

Max Planck Institute of Colloids and Interfaces

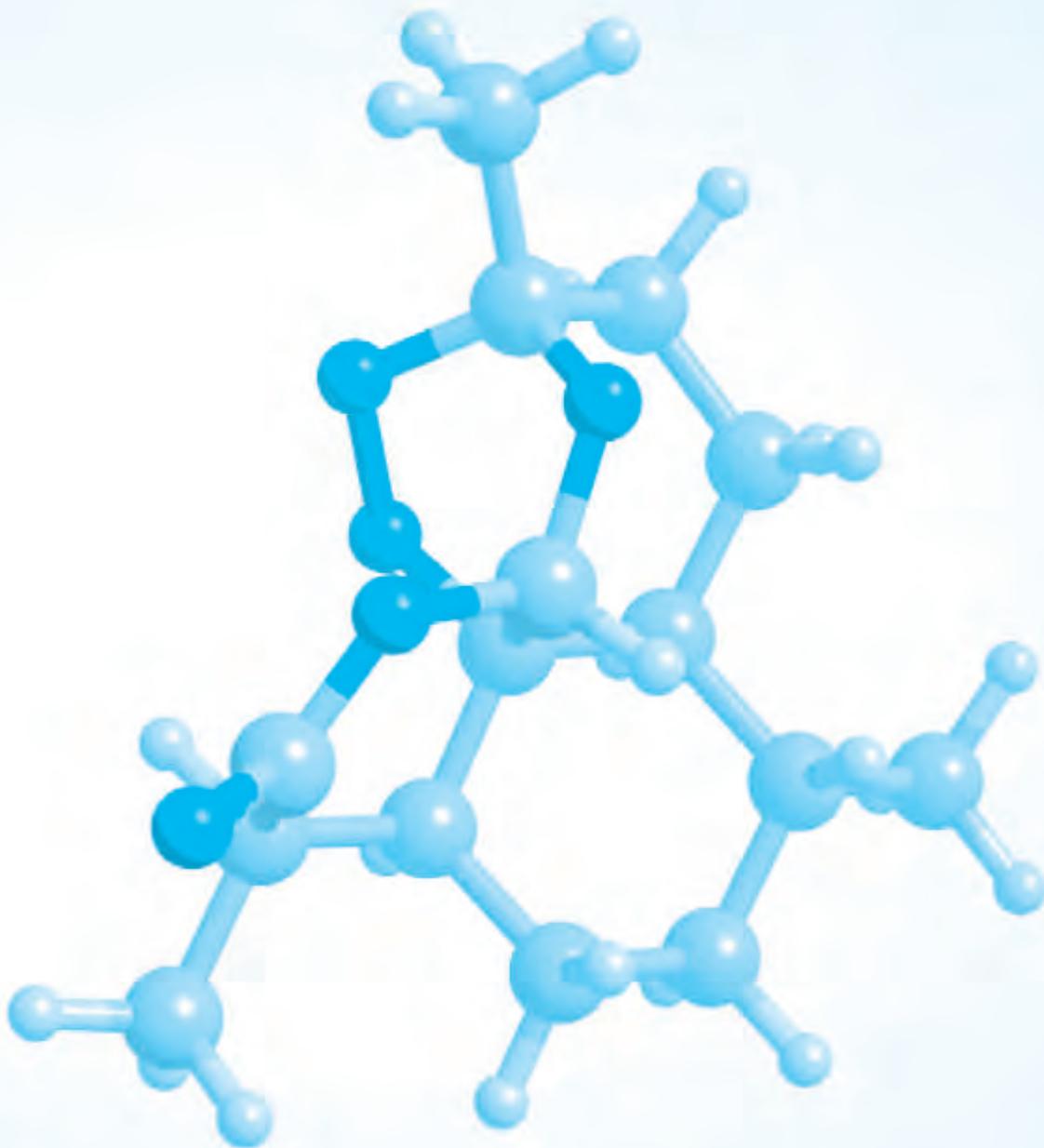
**REPORT
2011-2012**



Artemisinin ist derzeit der wichtigste Wirkstoff gegen Malaria. Jährlich werden ca. 200 t davon aus Pflanzen gewonnen. Mit einem am MPI entwickelten Verfahren ist es möglich, dieses wichtige Medikament aus Pflanzenabfall preiswert herzustellen.

Artemisinin is the most important anti-malarial drug. 200 t of the compound are extracted from plants every year. A new process, developed at the MPI, now allows to produce this important drug very cost-efficient from plant waste

Picture: © Max Planck Institute of Colloids and Interfaces





**Max Planck Institute
of Colloids and Interfaces**

RESEARCH REPORT 2011-2012

Imprint

Publisher: Max Planck Institute of Colloids and Interfaces
Address: Science Park Potsdam-Golm, Am Mühlenberg 1, 14476 Potsdam
Phone: +49 (0) 331/567-7814
Fax: +49 (0) 331/567-7875
Email: info@mpikg.mpg.de
Internet: www.mpihg.mpg.de
Editorial: Katja Schulze
Design and Illustration: www.pigurdesign.de
Printed by: optimal media GmbH
Potsdam, Juni 2013



INHALTSVERZEICHNIS

TABLE OF CONTENTS

Vorwort	6
Preface	8
Prof. P. H. Seeberger	
Das Institut in Zahlen	10
The Institute in Numbers	12
Prof. H. Möhwald	
Das Forschungsprogramm des Max-Planck-Instituts für Kolloid- und Grenzflächenforschung (MPIKG) ...	14
The Research Program of the Max Planck Institute of Colloids and Interfaces (MPICI)	17
Prof. M. Antonietti, Prof. P. Fratzl, Prof. H. Möhwald, Prof. R. Lipowsky, Prof. P. H. Seeberger	
Wissenschaftliche Beziehungen	20
Scientific Relations	22
Internationale Max Planck Research School (IMPRS) über Biomimetische Systeme	24
International Max Planck Research School (IMPRS) on Biomimetic Systems	25
Prof. R. Lipowsky · Dr. A. Valleriani	
Presse- und Öffentlichkeitsarbeit	26
Press and Public Relations	27
K. Schulze	

BIOMATERIALS

Research in the Department of Biomaterials · Prof. P. Fratzl	30
Biological Materials	
Evolutionary Perspectives on Vertebrate Hard Tissues · Dr. M. Dean	33
Biochemical Strategies in Load-Bearing Natural Materials · Dr. M. J. Harrington	34
Biological Chitin-Based Tools and Sensors · Dr. Y. Politi	36
Advanced Raman Spectroscopic Imaging of Biological Tissues · Dr. A. Mašić	38
In-Situ Mechanical Characterization of Internal Interfaces in Biomaterials · Dr. I. Zlotnikov	39
Mechanobiology · Dr. R. Weinkamer	40
Biological and Bio-inspired Materials	
Plant Material Adaptation · Dr. M. Eder	42
Hierarchical Structure of Biological and Biomimetic Materials · Dr. W. Wagermaier	44
Synthesis and Thermodynamic Stability of Amorphous Minerals · Dr. W. Habraken	46
Water Interactions in Complex Biological Materials · Dr. L. Bertineti	47
Magnetite Formation and Organization · Dr. D. Faivre	48
Biomimetic Actuation and Tissue Growth · Dr. J. Dunlop	50

BIOMOLECULAR SYSTEMS

Research in the Department of Biomolecular Systems · Prof. P. H. Seeberger	54
Carbohydrate Synthesis	
Automated Solid Phase Oligosaccharide Synthesis · Dr. M. Hurevich	56
Synthetic Carbohydrate Antigens · C. L. Pereira	58
Host Microbe Interactions	
Glycobiology of Cell Surface Glycans · Dr. C. Anish	60
(GPIs) AND GLYCOPROTEINS	
Synthesis and Properties of GPI-Anchors · Dr. D. V. Silva	62

Biomolecular Systems	
Microreactors as Tools for Organic Chemists · Dr. D. T. McQuade	.64
Precision Polymers and Polymeric Biomimetics	
Precision Glycopolymers for Receptor Targeting and Drug Development · Dr. L. Hartmann	.66
Glycoimmunology	
C-type Lectin Receptors: From Glycan Arrays to Murine Studies · Dr. B. Lepenies	.68
Structural Glycobiology	
Specific C-type Lectin Receptor Ligands · Dr. C. Rademacher	.70
Glycoproteomics	
Deciphering the Glycocode for Understanding Intercellular Communication · Dr. D. Kolarich	.72

COLLOID CHEMISTRY

Research in the Department of Colloid Chemistry · Prof. M. Antonietti	.76
Heterophase Polymerization	
Polymer Dispersions / Heterophase Polymerizations · Dr. K. Tauer	.80
Porous Polymers	
From Polymer Synthesis to Porosity Analysis · Dr. J. Weber	.82
Chimera Polymers and Novel Synthetic Methods	
Smart Biohybrid Polymers · Dr. H. Schlaad	.84
Modern Techniques of Colloid Analysis	
Electron Microscopic Studies of Colloidal Systems and Interfaces · Dr. J. Hartmann	.86
Hydrothermal Carbon Nanostructures and Coatings	
Carbon Materials from Renewable Resources · Dr. M. Titirici	.88
De Novo Nanoparticles	
Novel Synthetic Routes for Nanoparticles Production · Dr. C. Giordano	.90
International Joint Laboratory	
Poly(ionic liquid)s: Synthesis and Materials Application · Dr. Jiayin Yuan	.92
International Joint Laboratory	
Design of 3D-Conjugated Polymers as Heterogeneous Photocatalysts · Dr. F. Vilela	.94

INTERFACES

Research in the Department of Interfaces · Prof. H. Möhwald	.98
Independent Researchers	
Peptide Optical Waveguiding · Dr. Xuehai Yan	.101
Surface Nanoarchitecture for Self-Regulated Intelligent Interfaces · Dr. E. Skorb	.102
Ultrasonic Cavitation on Particle Surfaces · Dr. Lu Zhang	.103
(Quasi) Planar Interfaces – Fluid Interface	
Langmuir Monolayers as Model Systems to Study Interactions at Interfaces · Prof. G. Brezesinski	.104
Interfacial Layer Structure of Adsorbed Ionic Surfactants at the Water-Hexane Interface · Dr. R. Miller	.106
Solid Interfaces	
Phase Transitions and Transport Phenomena in Thin Films at Solid/Air Interfaces · Dr. H. Riegler	.108

Non-Planar Interfaces

Active Interfaces and Coatings · Dr. D. Shchukin	110
Nanotechnology and Optical Manipulations of Capsules and Films · Dr. A. Skirtach	112

THEORY & BIO-SYSTEMS

Research in the Department of Theory & Bio-Systems · Prof. R. Lipowsky	116
--	-----

Biopolymers

Glycans as Universal Tools for Proteins and Lipids · Dr. M. Santer	120
Conformational Changes in Protein Function · Dr. T. Weikl	122

Molecular Motors and Filaments

Cargo Transport by Teams of Molecular Motors:	
Elastic Coupling and Interference Regimes · Dr. F. Berger, Dr. C. Keller	124
Depolymerization of Actin Filaments · Dr. T. Niedermayer	126

Membranes and Vesicles

Stability of Lipids and Lipid Bilayers · Dr. A. Grafmüller	128
Lipid Membranes in Contact with Aqueous Phases of Polymer Solutions · Dr. R. Dimova	130
Interplay of Curvature and Composition in Membranes · Dr. T. Weikl	132
Vesicles in contact with two aqueous phases · Prof. R. Lipowsky	134

Interfacial Phenomena

Anchored Polymers – Self-Organization & Response to Perturbations · Dr. C. Seidel	134
---	-----

Complex Systems

Stochastic Processes in Complex Bio-Systems · Dr. A. Valleriani	136
Regulation of Bio-Processes · Dr. S. Klumpp	138

APPENDIX

Organigramm

Organization Chart	142
--------------------------	-----

Fachbeirat/Kuratorium

Scientific Advisory Board / Board of Trustees	144
---	-----

Drittmittelprojekte

Third Party Funds	145
-------------------------	-----

Ausgewählte Veranstaltungen

Selected Events	158
-----------------------	-----

Wissenschaftliche Abschlüsse

Scientific Degrees	159
--------------------------	-----

Personalien

Appointments and Honors	162
-------------------------------	-----

Wissenschaftliche Veröffentlichungen und Patente

Publications and Patents	163
--------------------------------	-----

Vorwort



von links:
Peter Fratzl,
Markus Antonietti,
Peter H. Seeberger,
Helmut Möhwald,
Reinhard Lipowsky

Dieser Bericht beschreibt die Aktivitäten des Max-Planck-Instituts für Kolloid- und Grenzflächenforschung (MPIKG), das 1992 gegründet wurde und seit 1999 in Potsdam angesiedelt ist. Das MPIKG besteht derzeit noch aus fünf Abteilungen, wobei die Abteilung „Biomolekulare Systeme“ (Peter Seeberger) bis zur Fertigstellung des Erweiterungsgebäudes an der Freien Universität Berlin untergebracht ist.

Dieses Vorwort gibt zunächst eine kurze Einführung in das Forschungsgebiet des MPIKG und einen Überblick über die aktuellen Schwerpunkte der einzelnen Abteilungen. Die Forschungsaktivitäten der fünf Abteilungen sind eng miteinander verknüpft.

Die Kolloid- und Grenzflächenforschung beschäftigt sich mit sehr kleinen bzw. sehr dünnen Strukturen im Nano- und Mikrometerbereich. Einerseits handelt es sich bei diesen Strukturen um eine ganze „Welt der versteckten Dimensionen“, andererseits bestimmt die komplexe Architektur und Dynamik dieser Strukturen das Verhalten von sehr viel größeren Systemen, wie z. B. Organismen.

Ein tieferes Verständnis von Kolloiden und Grenzflächen ist deshalb Schlüssel für zahlreiche Neuerungen, wie z. B. die Entwicklung von „intelligenten“ Wirkstoffträgern und Biomaterialien. Dazu ist ein interdisziplinärer Zugang notwendig, der chemische Synthese und biomimetische Materialentwicklung mit physikalischer Charakterisierung und theoretischer Modellierung verknüpft.

Die Nano- und Mikrostrukturen, die am MPIKG erforscht werden, sind aus speziellen Molekülen aufgebaut, die nach dem Prinzip der Selbstorganisation „von selbst“ geordnete Strukturen aufbauen. Die Abteilungen „Biomolekulare Systeme“ (Peter H. Seeberger) und „Kolloidchemie“ (Markus Antonietti) beschäftigen sich schwerpunktmäßig mit der Chemie dieses Systemaufbaus.

In der Abteilung „Biomolekulare Systeme“, die im Jahr 2008 neu eingerichtet wurde, werden z. B. „maßgeschneiderte“ Zuckermoleküle synthetisiert und mit anderen molekularen Gruppen verknüpft. Diese komplexen Kohlehydrate können andere Kohlehydrate sowie Proteine und Antikörper an

ihrem molekularen Aufbau erkennen und diskriminieren. Ein langfristiges Ziel ist dabei die Entwicklung von neuartigen Impfstoffen auf Zuckerbasis.

Die Abteilung „Kolloidchemie“ setzt wiederum verschiedenartige Makromoleküle ein, um daraus mesoskopische Verbundsysteme und Hybridmaterialien mit unterschiedlicher Architektur aufzubauen. Der Schwerpunkt liegt dabei auf der gezielten Kodierung von Strukturbildung und Selbstorganisation, d. h. die Moleküle enthalten bestimmte Muster, die die Strukturbildung steuern und die Zielstruktur weitgehend festlegen. Ein weiterer Schwerpunkt dieser Abteilung ist die Umwandlung von Biomasse in Kohle mittels der hydrothermalen Karbonisierung, ein Prozess, der einen wichtigen Beitrag zur Fixierung von CO₂ liefern könnte.

Weitere Nanostrukturen, die sich „von selbst“ organisieren, sind molekulare Monoschichten sowie Multischichten aus positiv und negativ geladenen Polymeren, zwei Schwerpunkte der Abteilung „Grenzflächen“ (Helmut Möhwald). Die Nanostrukturen werden dabei an mesoskopischen und makroskopischen Grenzflächen befestigt und können dann mit physikalischen Untersuchungsmethoden sehr präzise vermessen werden. Die Multischichten von geladenen Polymeren lassen sich für die Verkapselung von ganz unterschiedlichen Wirkstoffen einsetzen, von biologischen Wirkstoffen hin bis hin zum Korrosionsschutz.

Viele Nano- und Mikrostrukturen sind hierarchisch aufgebaut. Besonders eindrucksvolle Beispiele für diesen „verschachtelten“ Systemaufbau finden sich in mineralisierten Geweben, wie Knochen, Zähnen oder Muschelschalen, sowie in Pflanzen und deren Zellwänden. Diese Systeme werden in der Abteilung „Biomaterialien“ (Peter Fratzl) mit physikalischen Methoden erforscht. Dabei wird z. B. die Methode der fokussierten Synchrotronstrahlung eingesetzt, die es erlaubt, die Struktur von Mikrodomeänen des Materials sichtbar zu machen. Im Zentrum des

Interesses stehen die Struktur-Funktions-Beziehungen dieser natürlichen Materialien, insbesondere ihre außergewöhnlichen mechanischen Eigenschaften, die sich ständig wechselnden äußeren Bedingungen anpassen.

Die Aktivitäten der vier experimentellen Abteilungen werden durch theoretische Untersuchungen in der Abteilung „Theorie & Bio-Systeme“ (Reinhard Lipowsky) ergänzt. Aktuelle Schwerpunkte der Theorie sind molekulare Maschinen und mehrkomponentige Membranen. Zur Abteilung gehört auch ein Labor für die experimentelle Untersuchung von Lipid-Membranen und -Vesikeln. Diese theoretischen und experimentellen Aktivitäten verfolgen das langfristige Ziel, die grundlegenden Mechanismen und generellen Prinzipien aufzuklären, die die Selbstorganisation von Bio-Systemen im Nanobereich bestimmen.

Alle Forschungsgebiete sind hier natürlich nur plakativ dargestellt und werden im Hauptteil dieses Berichts detaillierter beschrieben. Dieser Hauptteil ist nach den fünf Abteilungen des Institutes gegliedert und setzt sich aus den Forschungsberichten der einzelnen Arbeitsgruppen zusammen.

Neben der intensiven Forschungstätigkeit hat das MPIKG auch seine erfolgreiche Nachwuchsförderung weiter fortgesetzt. Inzwischen sind mehr als 50 ehemalige Gruppenleiter des MPIKG auf Professuren an Universitäten berufen worden.

Die Planung des Erweiterungsgebäudes ist abgeschlossen und wir rechnen, nach einiger Verzögerung, für Mitte 2015 mit seiner Fertigstellung. Diese Erweiterung beseitigt dann den wohl dringendsten Engpass des Institutes, Arbeitsplatz, da die Zahl unserer Mitarbeiter mit dem Erfolg und durch die erfolgreiche Einwerbung von Drittmitteln in den vergangenen Jahren stetig gewachsen ist.

An dieser Stelle möchte ich allen Kollegen und Mitarbeitern des MPIKG für ihre tatkräftige Unterstützung während der letzten beiden Jahre danken. Mein Dank gilt auch unserem wissenschaftlichen Beirat, der unsere Arbeit sehr kompetent und konstruktiv begleitet, und nicht zuletzt der Leitung der Max-Planck-Gesellschaft für die nachhaltige Unterstützung über die vielen Jahre hinweg.

Peter H. Seeberger
Geschäftsführender Direktor 2011-2012



Preface

This report describes the recent activities of the Max Planck Institute of Colloids and Interfaces (MPICI), which was founded in 1992 and is located in Potsdam-Golm since 1999. The MPICI currently consists of five departments. The department on „Biomolecular Systems“ (Peter Seeberger) is temporarily accommodated at the FU Berlin until the extension of our building will be completed.

This preface provides a brief introduction to some basic aspects of the science of colloids and interfaces and a summary of the main research topics that are pursued in the different departments. The strong interconnections between all research activities within the institute will be emphasized.

Colloids and interfaces consist of very small or thin structures with linear dimensions between nanometers and micrometers. On the one hand, the possible structures represent a „world of hidden dimensions“. On the other hand, the dynamics and structures of these small entities determine the behaviour of much larger systems such as organisms.

A more systematic understanding of colloids and interfaces is a prerequisite for many innovations, such as „smart“ drug delivery systems and biomaterials. Such a deeper understanding can only arise from an interdisciplinary approach that combines chemical synthesis and biomimetic materials science with physical analysis and characterization as well as theoretical modelling.

The nano- and microstructures that are investigated at the MPICI are built up from special, even smaller molecules, which are using the principle of „self assembly“ to construct ordered structures. The two departments on „Biomolecular Systems“ (Peter H. Seeberger) and „Colloid Chemistry“

(Markus Antonietti) put a focus of activity onto this „chemistry of system design“.

The department „Biomolecular Systems“ was newly established in 2008 and synthesizes and designs glycans of well-defined architecture. These complex macromolecules are able to specifically recognize and discriminate other macromolecules such as proteins and antibodies. A long-term goal of this research is to develop novel vaccines based on such sugar molecules.

In the department „Colloid Chemistry“, a variety of macromolecules is used to construct mesoscopic compound systems and hybrid materials. One important aspect of this activity is the molecular encoding of self-assembly and self-organization by specific molecular groups that guide these processes towards a certain target structure. Another recent focus of the department is the transformation of biomass into coal using the process of hydrothermal carbonization. The latter process could provide an important contribution to carbon fixation and, thus, to the reduction of CO₂.

Additional nanostructures that arise via self-organization are monolayers of organic molecules and multilayers of positively and negatively charged polymers, two priorities of the department „Interfaces“ (Helmuth Möhwald). These nanostructures are suspended at mesoscopic and macroscopic interfaces and, in this way, become accessible to a wide spectrum of imaging and scattering methods. The multilayers of polyelectrolytes can be used to encapsulate a variety of different molecules and nanoparticles covering applications in chemical engineering and pharmacology.



Nano- and microstructures are built up in a hierarchical fashion. Especially impressive examples for this „nested“ system architecture are found in mineralized tissues such as bone, teeth, and seashells as well as in plants and their cell walls. These systems are studied in the department „Biomaterials“ (Peter Fratzl) using a variety of experimental characterization methods. One particularly powerful method is microfocussed synchrotron radiation, by which one can determine the structure of micrometer domains with atomic resolution and determine the structure-function relationships of these natural materials. One important aspect is their extraordinary mechanical properties, which can adapt to changing environmental conditions.

The activities of the four experimental departments are complemented by theoretical investigations in the department „Theory & Bio-Systems“ (Reinhard Lipowsky). Current priorities of this department are molecular machines as well as bio-membranes and vesicles that are also studied experimentally using optical microscopy. The long-term goal of these research activities is to elucidate the fundamental principles and generic mechanisms that govern the self-organization of biomimetic and biological systems in the nano-regime.

All research topics that have been mentioned here will be described in more detail in the main body of this report, which is organized according to the five departments of the MPICL. Each department consists of several research groups, each of which will present its research results as obtained during the past two years.

Apart from its many research activities, the institute also continued its successful higher academic education of young faculty. Indeed, more than 50 former group leaders of the MPICL have now taken up professorships in Germany and abroad.

Planning of our extension building has been completed and we expect to move into the new space by the middle of 2015 following a significant delay. This extension will resolve our main problem, the shortage of space at the institute, as the number of staff was continuously rising with the success, for instance measured in larger external funding.

I take this opportunity to thank all of my colleagues and associates at the MPICL for their active support during the past two years. It is also my pleasure to acknowledge the comprehensive advice that we again obtained from our scientific advisory board. Last not least, I am grateful to the Direction board of the Max Planck Society for their continuous support of our institute.

Peter H. Seeberger
Managing Director 2011-2012



Das Institut in Zahlen

Personal

Die Entwicklung der Zahlen ist wesentlich dadurch beeinflusst, dass ab 2009 die neue Abteilung „Biomolekulare Systeme“ voll funktionsfähig wurde und 2011 die Schrumpfung der Abteilung „Grenzflächen“ begann. Damit einher ging eine Umverteilung des Stammpersonals, aber nur geringe Änderungen dessen Umfangs wie **Abb. 1** zeigt. Andererseits stieg die Zahl der über kürzere Zeit Beschäftigten mit Einrichtung der 5. Abteilung sprunghaft an und blieb von da an stabil. Diese Zahl wird auch begrenzt durch den verfügbaren Raum, und in diesem Punkt wird erst 2015 Entspannung eintreten, wenn der Umzug in den Erweiterungsbau stattfindet. Als Nebenbemerkung, 70% der Institutsangehörigen sind jünger als 35 Jahre, die übrigen verteilen sich etwa gleichmäßig über alle Altersklassen.

Mit Einrichtung der Abteilung Biomolekulare Systeme 2009 stieg die Zahl der Doktoranden drastisch an, (**Abb. 2**) aber seit 2011 sinkt sie mit der Schrumpfung der Abteilung „Grenzflächen“. Die Zahl der Postdoktoranden blieb auf der anderen Seite relativ stabil, da in diesem Punkt die Abteilung Grenzflächen kaum schrumpfte. Bei den Postdoktoranden bleibt der Anteil der Ausländer um 85% (**Fig. 3**), während er bei den Doktoranden über 50% stieg. Daher ist ihr Anteil an allen Wissenschaftlern ebenfalls etwa 50%. Die Verteilung nach Regionen blieb in den letzten Jahren etwa konstant mit etwa 50% Europäern und einer Mehrheit aus Westeuropa. (**Abb. 4**)

Fig. 1

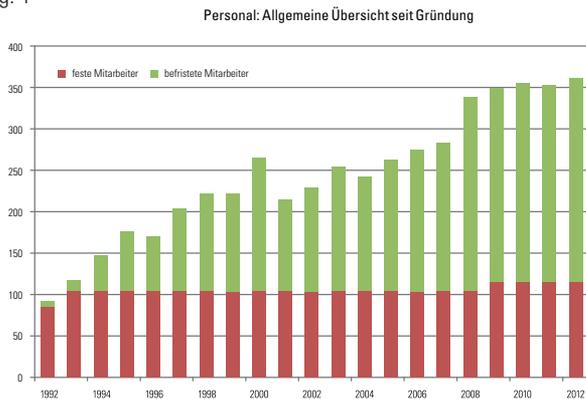


Fig. 3

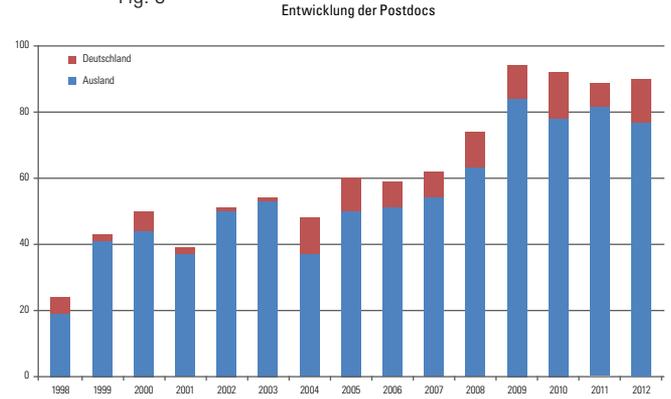


Fig. 2



Fig. 4



Haushalt

Der institutionelle Etat, der 2009 einen Sprung wegen vieler Investitionen und Baumaßnahmen mit Einrichtung der Abteilung „Biomolekulare Systeme“ verzeichnete (Abb. 5), nahm in den letzten 2 Jahren etwas ab wegen der Schrumpfung der Abteilung Grenzflächen. Andererseits hat sich das Drittmittel aufkommen stetig erhöht und überschreitet mittlerweile einen Anteil von 28%. Bei diesen Drittmitteln blieb der Anteil des BMBF und der DFG auf einem hohen Niveau, und der wesentliche Anstieg resultiert von Beiträgen der EU, insbesondere des European Research Council (Abb. 6). Dies ist insofern bemerkenswert, da der hohe Drittmittelanteil nicht die Mission des Instituts gefährdet: Grundlagenforschung. Im Gegenteil, der größte Teil der Drittmittel resultiert von Organisationen der Grundlagenforschung (DFG, ERC, VW-Stiftung), und er unterstützt damit direkt die Mission des Instituts. Da das Institut keine Auftragsforschung durchführen will und darf, ist der Anteil direkter Industrieförderung mit weniger als 2% des Etats relativ gering, aber konstant. Dieses ist wünschenswert für ein Institut der Grundlagenforschung.

Wissenschaftliche Ergebnisse und deren Einfluss

Wir sind zwar ein Forschungsinstitut und keine Universität, dennoch betrachten wir als wichtigsten Ertrag nicht Papier, sondern sehr gut ausgebildete junge Wissenschaftler. Jährlich verlassen mehr als 5 Wissenschaftler das Institut auf Professoren- oder äquivalente Stellen, 25-30 Doktoranden schließen ihre Arbeit ab und etwa 50 Postdoktoranden wechseln auf neue Stellen. Die Zahl der Publikationen hat mit etwa 350 einen Höchstwert erreicht und nimmt nun leicht ab wegen des Abbaus der Abteilung Grenzflächen (Abb. 7a). Diese Zahl ist gut, aber nicht überragend für ein Institut mit dem Anspruch, an der Weltspitze zu stehen. Hervorragend jedoch ist die Zahl der Zitationen mit 20.000 (Abb. 7b), mit denen sich das Institut mit jeder Institution vergleichbarer Größe weltweit vergleichen kann. Dies ist zudem bemerkenswert für ein junges Institut, da Zitationen auch auf Reputation beruhen und diese mit dem Alter wächst. Diese Zahlen sind letztlich auch dafür verantwortlich, dass Wissenschaftler hochkompetitive Preise und Projekte gewannen und dass das Institut in Rankings wie denen der Alexander-von-Humboldt Stiftung einen Spitzenplatz einnimmt.

Fig. 5

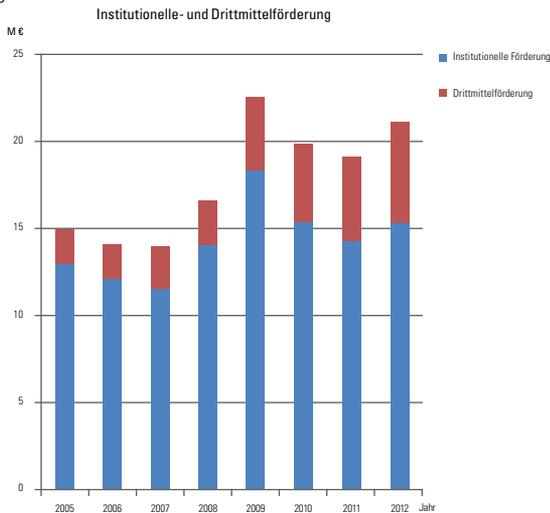


Fig. 7a

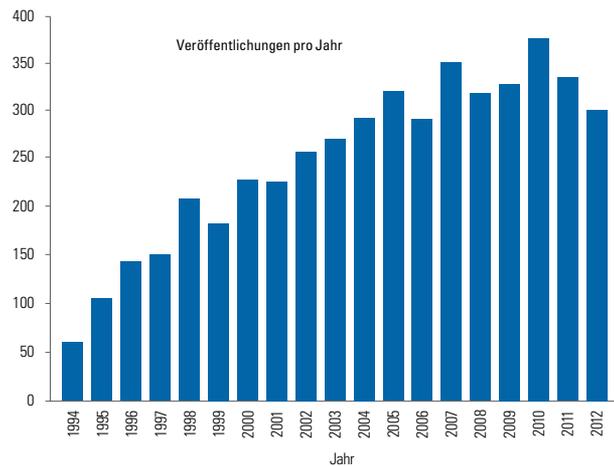


Fig. 6

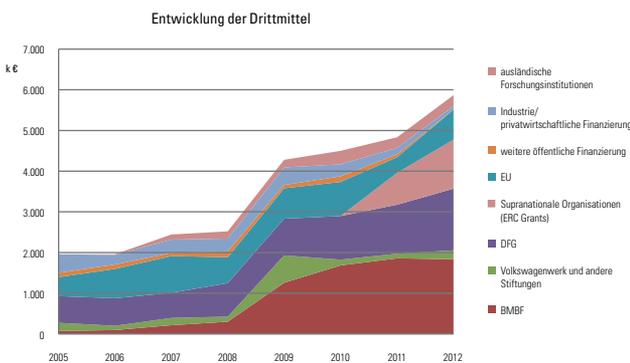
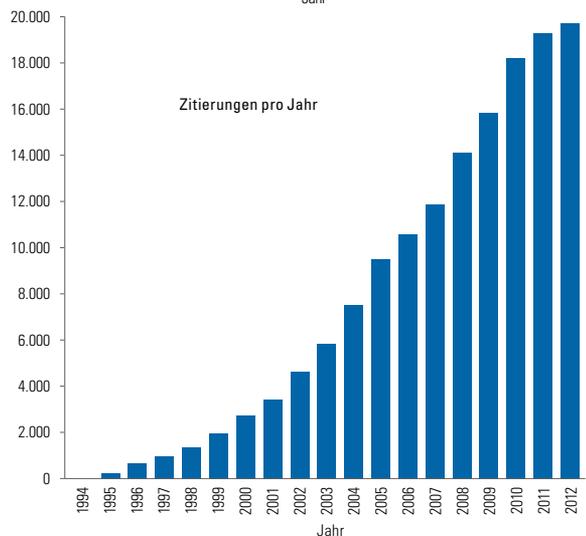


Fig. 7b



The Institute in Numbers

Personell

The development of numbers is largely influenced by the fact that from 2009 the new department "Biomolecular Systems" came into full operation and that the downsizing of the department "Interfaces" began in 2010. This was accompanied by a redistribution of staff, but only by minor changes in size as seen in **Fig. 1**. However, the number of short term employees encountered a step-wise increase paralleling the establishment of the fifth department, and from then remained on a stable level. This level is also determined by the available space, and this problem will only be solved by 2015 with the move into an extension of the Golm site. As a side note 70% of the institute members are aged below 35, the others rather-evenly distributed over all ages. With establishment of

the Biomolecular Systems department in 2009 the number of graduate students increased drastically (**Fig. 2**), but since 2011 it decreases with the downsizing of the Interface department. The number of postdocs on the other hand has remained rather stable, as in this respect the Interface department has not yet been shrinking. Among the postdocs the fraction of foreigners remains around 85% (**Fig. 3**), whereas that among the graduate students is increasing above 50%. Hence their fraction concerning all scientists is around 50%. The distribution among regions in the last years remained largely constant with about 50% Europeans and a majority from Western Europe (**Fig. 4**).

Fig. 1

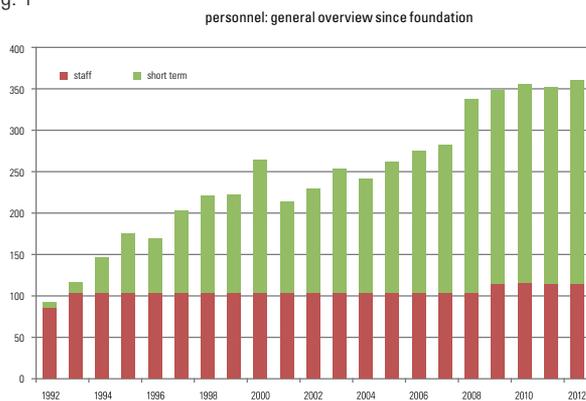


Fig. 3

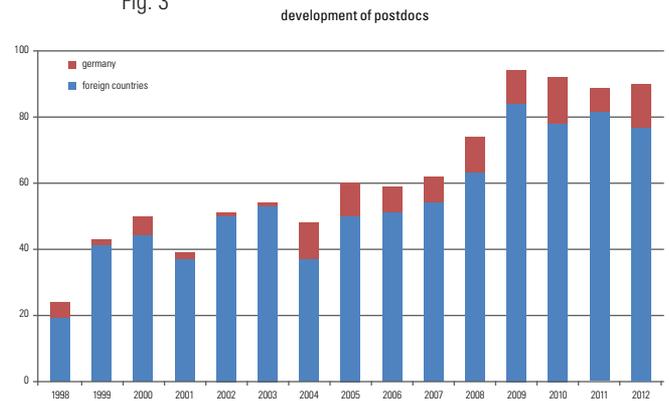


Fig. 2

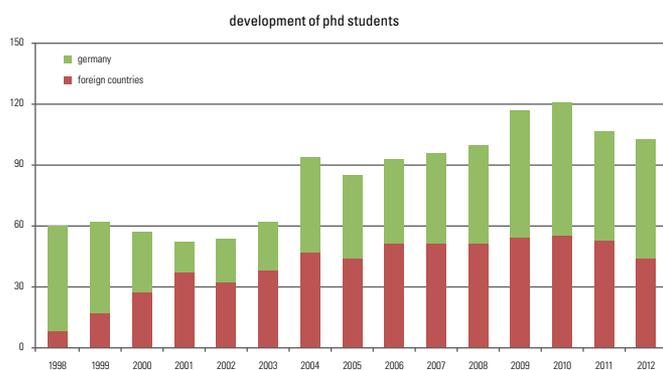
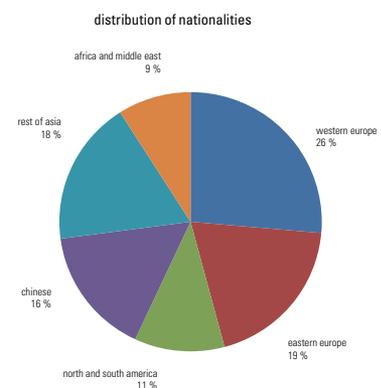


Fig. 4

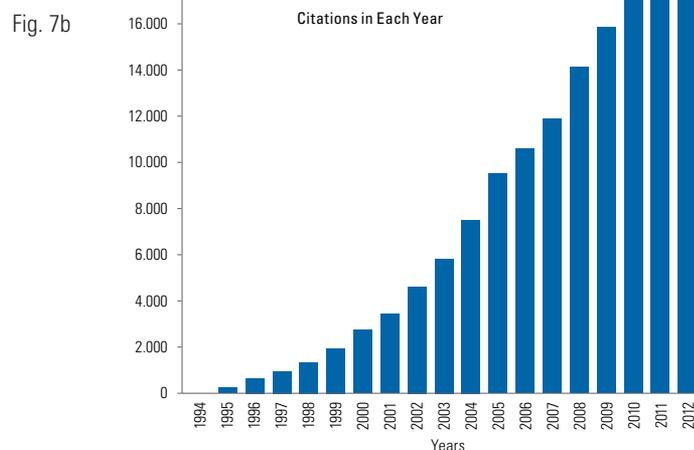
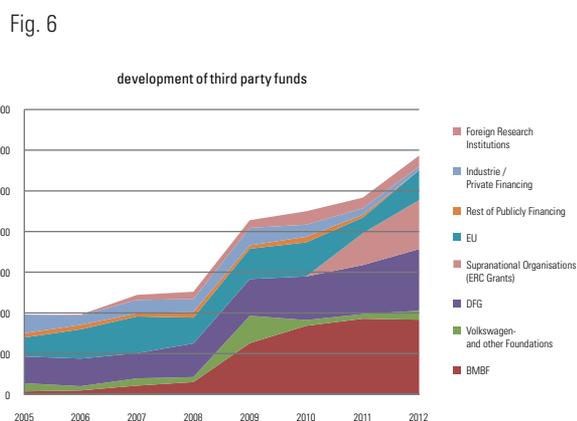
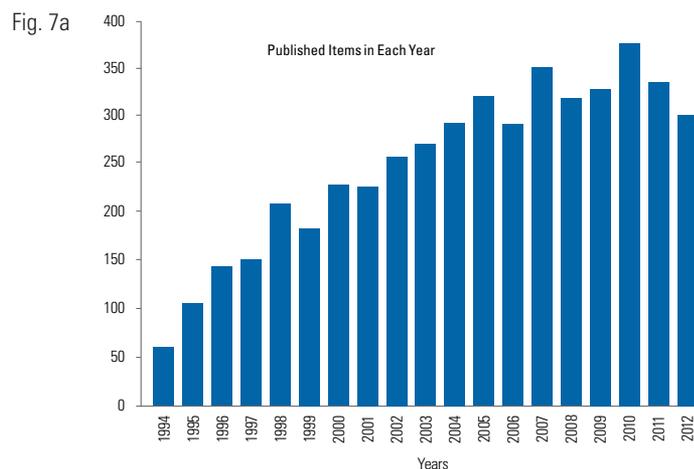
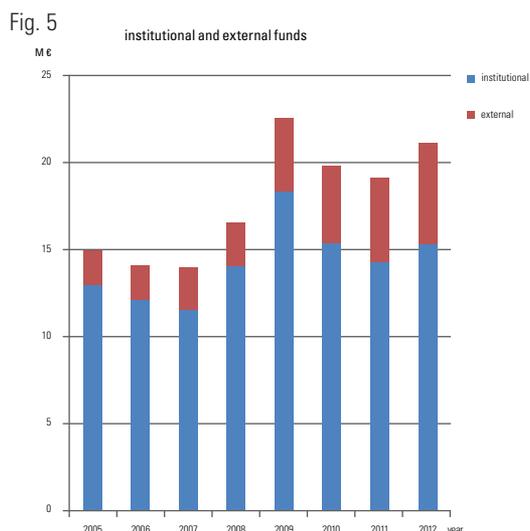


Budget

The institutional budget that had developed a step in 2009 because of many investments and construction measures to establish the department “Biomolecular Systems” has experienced some reduction because of the shrinkage of the Interface department in the last two years (Fig. 5). On the other hand third party funding has increased steadily and meanwhile exceeds a fraction of 28%. Among them the fraction of the Federal Ministry of Education and Technology (BMBF) and of the German Science Foundation (DFG) have remained on a high level, and the major increase results from European contributions, especially from the European Research Council (Fig. 6). This is important to note, as the high level of funding thus does not impede the mission of the institute: basic science. On the contrary, most of third party funding stems from basic science funding agencies (DFG, ERC, VW foundation) and therefore supports directly the institute’s mission. Because the institute does not want and is not allowed to perform contractual research for industry, their contribution is below 2% of the budget, which is rather low and stable. This is desirable for an institute with a basic science mission.

Scientific Results and Impact

Although being a research institute and no university we consider the most important result not paper but well-trained young scientists. Annually more than five scientists leave the institute on professor positions or equivalent ones, 25-30 PhD students finish their theses and about 50 Postdocs leave on new positions. The number of publications has arrived at a maximum value around 350 (Fig. 7a) and now slightly decays because of the downsizing of the interface department. This is a good but not an overwhelming number for an institute that claims to be world-top. Overwhelming, however is the number of annual citations of around 20.000 (Fig. 7b) with which the institute need not fear a comparison with any unit of comparable size world-wide. This is in addition remarkable for a rather young institute since citations are also based on reputation, and this increases with age. These numbers are basically the reason that scientists win highly competitive awards and projects and that the institute is top-seeded in rankings like those of the Alexander-von-Humboldt Foundation.



Das Forschungsprogramm des Max-Planck-Instituts für Kolloid- und Grenzflächenforschung (MPIKG)

Vision und Mission

Kolloide sind winzige Bausteine, welche die grundlegenden Einheiten von lebenden Organismen und vielen anderen nützlichen Materialien bilden. Das Verständnis des Aufbaus sowie die erfolgreiche Synthese dieser kleinen Teilchen könnten in Zukunft helfen, drängende Probleme u.a. in den Bereichen Gesundheit, Energie und Transport zu lösen. Das Forschungsprogramm des MPIKG beschäftigt sich deshalb auch primär mit den fundamentalen wissenschaftlichen Problemen von Kolloiden und deren Grenzflächen. Die wissenschaftliche Vision des Instituts ist auf zwei Kernbereiche ausgelegt: zum einen auf das Herstellen, Visualisieren, Messen und das Verständnis dieser winzigen organischen und anorganischen Bausteine und zum anderen auf deren vielfältige Wechselwirkungen und Anordnungen (Abb.1). Unsere Grundlagenforschung untersucht daher sowohl biologische und medizinische Fragestellungen als auch Materialien und deren verschiedenste Anwendungen. Die bioinspirierte Materialforschung schlägt dabei die Brücke zwischen den beiden Ausrichtungen, indem sie Materialstrukturen, die in der Natur vorkommen, in Konzepte für technische Materialien übersetzt.

Das MPI für Kolloid- und Grenzflächenforschung nimmt bereits jetzt eine führende Rolle in verschiedenen innovativen Wissenschaftsfeldern ein. Diese Forschungsgebiete – geordnet von kleinen nach größer werdenden Objekten – reichen von der Synthese, Charakterisierung und theoretischen Beschreibung von Oligosacchariden und Kohlehydraten über funktionalisierte Nanopartikel und Hybridmaterialien, Polyelektrolyt-Multischichten, der Selbstorganisation von komplexen Grenzflächen und Mehrkomponentenmembranen bis hin zu hierarchischen Biomaterialien basierend auf Polysacchariden, Proteinen oder mineralisierten Geweben wie Knochen und Zähnen. In all diesen Bereichen bürgt der Name des MPIKG für ausgewiesene Expertise.

Das Institut verfolgt zwei generelle Strategien um seine Spitzenposition in diesem Bereich zu etablieren und weiter auszubauen: (i) Es identifiziert und wählt fortwährend neue interdisziplinäre Forschungsthemen, die eine höchstmögliche Relevanz für Wissenschaft und Gesellschaft aufweisen; (ii) es ist sehr aktiv in der Ausbildung von Doktorandinnen und Doktoranden und der Förderung junger WissenschaftlerInnen. So wird das MPIKG zum idealen Ausgangspunkt für erfolgreiche akademische Karrieren.

Aktuell werden neue Themen, welche unmittelbar mit biomimetischen und biologischen Systemen verknüpft sind, in die Forschungsarbeit aufgenommen. So gibt es vier neue Schwerpunktgebiete: Molekulare Erkennung von Kohlehydraten, fotoinduzierte molekulare Prozesse, Transportprozesse auf Basis von molekularen Motoren, und biomimetische Bewegungssysteme. Ein besseres Verständnis von mehrskaligen Biosystemen ist dabei Wissensgrundlage für eine Vielzahl möglicher Anwendungen wie z.B. der Entwicklung von intelligenten Wirkstoffträgern und Biomaterialien.

Diese vier Kernbereiche werden deshalb auch innerhalb des Netzwerks der neuen Internationalen Max Planck Research School (IMPRS) über „mehrskalige Biosysteme: Von molekularer Erkennung bis zum mesoskopischen Transport“ behandelt. Eine erste Förderperiode wurde von 2013 bis 2019 bewilligt.

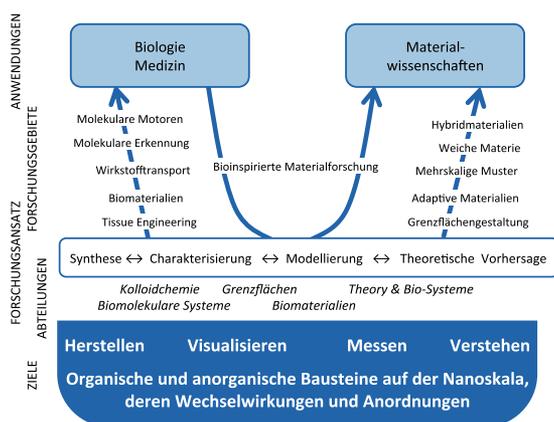


Abb. 1: Wissenschaftliche Strategie des MPIKG

Dies ist aber nur möglich durch die Kombination von wissenschaftlicher Exzellenz und außergewöhnlichem Engagement, die vor allen Dingen in die Betreuung und Unterstützung von jungen Wissenschaftlerinnen und Wissenschaftlern fließen.

Unsere Mission ist es, mit wissenschaftlicher Exzellenz eine Brücke von Molekülen zu mehrskaligen Materialien und Biosystemen zu schlagen und dabei NachwuchswissenschaftlerInnen bestmöglich zu fördern.

Interdisziplinäre Expertise

Die komplexe und vielfältige Welt der Kolloide und Grenzflächen bietet eine große Anzahl an räumlichen und zeitlichen Organisationseinheiten, welche von molekularen bis hin zu mesoskopischen Skalen reichen. Für eine umfassende Untersuchung dieser vielskaligen Systeme und Prozesse bieten die einzelnen Abteilungen des Instituts eine komplementäre Methodik und ausgesprochene Fachkenntnis in den Bereichen Chemie, Physik und Materialwissenschaften. Die Abteilungen „Biomolekulare Systeme“ (Seeberger) und „Kolloidchemie“ (Antonietti) besitzen spezielle Expertise bei der chemischen Synthese von Molekülen und Materialien. Die Abteilungen



„Biomaterialien“ (Fratzl) und „Grenzflächen“ (Möhwald) fokussieren ihre Arbeit dagegen auf die strukturelle Analyse und physikalische Charakterisierung dieser Systeme. Wenn es um das Verständnis und die Modellierung geht, ist die Abteilung „Theorie & Bio-Systeme“ federführend.

Während des letzten Jahrzehnts hat das Institut seine Aktivitäten auf dem Gebiet der Biosysteme mit der Gründung der Abteilung „Biomaterialien“ unter Peter Fratzl im Jahr 2003 und der Abteilung „Biomolekulare Systeme“ unter Peter H. Seeberger im Jahr 2009 stark erweitert. Aber auch die Kernkompetenz der strukturellen Analyse und physikalischen Charakterisierung soll weiterhin gefestigt und ausgebaut werden. Nach der Emeritierung von Helmut Möhwald im Jahr 2014, wird eine unabhängige Arbeitsgruppe (W2-Professur) zu diesem Thema am Institut etabliert. Die Suche nach einem/einer herausragenden wissenschaftlichen LeiterIn für diese Gruppe hat bereits begonnen. Ferner wird das MPIKG seine Bestrebungen, eine fünfte Abteilung zu diesem wichtigen Forschungsbereich einzurichten, nicht aufgeben.

Langfristige Ziele

Jede Abteilung des MPIKG hat sich langfristig anspruchsvolle Ziele gesetzt: Die Seeberger-Abteilung charakterisiert die komplexen Kohlehydratmischungen in der Glycocalix von eukariotischen und prokariotischen Zellen. Auf diese Weise sollen auf Kohlehydrate basierende Impfstoffe hergestellt werden. Die WissenschaftlerInnen um Markus Antonietti sind auf dem Weg, enzymähnliche Nanokatalysatoren und die künstliche Photosynthese zu entwickeln und so einen Meilenstein für die grüne Energiegewinnung zu setzen. In der Abteilung von Helmut Möhwald wurden bislang die molekularen und supramolekularen Wechselwirkungen an Grenzflächen erforscht. Im Mittelpunkt der Abteilung von Peter Fratzl stehen das Verständnis und die Nachahmung von Pflanzenbewegung und Knochenwachstum. Schließlich möchte die Abteilung um Reinhard Lipowsky zunächst verstehen und dann charakterisieren, was es mit der komplexen Lücke zwischen künstlichen und natürlichen Systemen auf sich hat.

Neue Forschungsperspektiven

Während der letzten Jahre haben sich, wie vorher erwähnt, vier neue zukunftsweisende Forschungsthemen herausgebildet. Diese sollen nachfolgend etwas ausführlicher dargestellt werden, um auch die Verknüpfung zwischen den Abteilungen sichtbar zu machen.

Bei der molekularen Erkennung von Kohlehydraten handelt es sich um ein Arbeitsgebiet aus der Abteilung Seeberger, welches aber mit aktuellen Untersuchungen aus den

Abteilungen Antonietti, Möhwald und Lipowsky Schnittmengen aufweist. Die Forschung in diesem Kernbereich basiert im Wesentlichen auf der Synthese von Polysacchariden und Kohlehydraten, die eine sehr definierte molekulare Architektur besitzen (Abt. Seeberger). Diese Kohlehydrate werden sowohl mit Nanopartikeln (Abt. Antonietti), lipiden Monoschichten (Abt. Möhwald) als auch mit lipiden Doppelmembranen (Abt. Lipowsky) verankert. Auf diese Weise sind sie zugänglich für verschiedene experimentelle- und Rechenmethoden. Darüber hinaus werden die Systeme mit hoher räumlicher und zeitlicher Auflösung untersucht.

Fotoinduzierte molekulare Prozesse stehen im Fokus der Abteilung Antonietti, wobei es hier gemeinsame Interessen mit den Abteilungen Seeberger, Möhwald und Lipowsky gibt. Die größte Herausforderung für die fotoinduzierte Aufspaltung von Wasser ist es, geeignete Katalysatoren zu finden. Ein neuer Katalysator auf synthetischer Polymerbasis wurde erst kürzlich vorgestellt und wird nun weiter entwickelt bzw. optimiert (Abt. Antonietti). Andere fotoinduzierte Prozesse beinhalten die Synthese von Polymeren unter Zuhilfenahme von beschleunigenden Radikalen (Abt. Seeberger, Abt. Antonietti), die fotoinduzierte Permeation von Polyelektrolytkapseln (Abt. Möhwald) und fotoinduzierte konformelle Änderungen von supramolekularen Strukturen (Abt. Lipowsky).

Die Abteilung Lipowsky beschäftigt sich schwerpunktmäßig mit dem (intrazellulären) Transport durch molekulare Motoren. Aber auch die Abteilungen Fratzl und Möhwald bearbeiten angrenzende Thematiken. Intrazelluläre Partikel zeigen komplexe Muster beim Transport und reflektieren so die Zusammenarbeit der molekularen „Motorteams“ (Abt. Lipowsky). Diese Motoren können auch synthetische Multischichtkapseln transportieren, die mit einem Peptid gefüllt sind oder auch mit anderen chemischen Stoffen (Abt. Möhwald). Ein faszinierender natürlicher Prozess, bei dem die Rolle des aktiven Transports noch erforscht werden muss, ist die spezielle Anordnung von Magnetosomen in magnetotaktischen Bakterien (Abt. Fratzl, Lipowsky).

Biomimetische Bewegung und Gewebewachstum sind Kernthemen innerhalb der Abteilung Fratzl. Hier gibt es einige überschneidende Interessen mit der Abteilung Lipowsky. Formänderungen in Geweben werden ausgelöst durch die Erzeugung von ungleichmäßigen, internen Belastungen. Diese werden durch die Wasseraufnahme in Zellwänden und durch Zellproliferation in Knochen und Hautgewebe erzeugt (Abt. Fratzl). Weiterführende Studien dieser belastungsauslösenden Prozesse werden mittels mehrskaligen Computersimulationen durchgeführt. Sie sollen die dahinter liegenden molekularen Mechanismen aufdecken (Abt. Lipowsky).

Programme für Doktorandinnen und Doktoranden

Ein starkes Engagement für die Ausbildung von DoktorandInnen ist Markenzeichen unseres Instituts. Die erste Max Planck Research School (IMPRS) über „Biomimetische Systeme“ wurde über zwölf Jahre erfolgreich koordiniert und beendete ihre Arbeit im Herbst 2012. Nun folgt die zweite IMPRS über „Multiskalige Biosysteme“. Die Förderperiode wurde kürzlich von 2013-2019 bewilligt. Die Schule integriert die zuletzt genannten Kernbereiche der einzelnen Abteilungen in ihr Programm. Hauptziel der IMPRS ist es, dass die teilnehmenden DoktorandInnen effizient und erfolgreich an einem zukunftsweisenden Forschungsprojekt arbeiten können. Für die interdisziplinäre Forschung an mehrskaligen Systemen müssen die DoktorandInnen verschiedene unterschiedliche Disziplinen erlernen. Ferner sollen sie befähigt werden, das Wesentliche aus der hohen Anzahl an wissenschaftlicher Literatur zu extrahieren und auf die verschiedenen Bereiche anzuwenden. Die Ausbildung ist auch für BewerberInnen interessant, die eine nichtakademische Karriere anstreben: beispielsweise in der Pharmazie, den Bioingenieurwissenschaften und der Medizin. Das Institut ist zudem an der International Graduate Research and Training Group "Self Assembled Soft Nanostructures at Interfaces", koordiniert von der TU Berlin, beteiligt. Darüber hinaus ist das MPIKG auch noch in zwei weiteren Graduiertenschulen aktiv, die aus der Exzellenzinitiative der Deutschen Forschungsgemeinschaft (DFG) entstanden sind. Das ist zum einen die Berlin-Brandenburg School for Regenerative Therapies (BSRT), koordiniert von der Charité - Universitätsmedizin Berlin und zum anderen die SALSA, School of Analytical Sciences Adlershof, koordiniert von der Humboldt-Universität zu Berlin.

Förderung von jungen WissenschaftlerInnen

Das Institut ist und war schon immer ein guter Nährboden für junge WissenschaftlerInnen, die eine akademische Karriere anstreben. Viele der früheren MitarbeiterInnen und Postdocs sind jetzt ProfessorInnen an deutschen oder ausländischen

Universitäten. Während der letzten zehn Jahre haben 33 früh-

ere ArbeitsgruppenleiterInnen Spitzenpositionen eingenommen, die vergleichbar sind mit den deutschen W3 oder W2 Professuren. Die meisten dieser WissenschaftlerInnen haben zuvor innerhalb des Netzwerks der alten IMPRS über „Biomimetische Systeme“ unterrichtet. In der neuen IMPRS über „Multiskalige Biosysteme“, werden alle ArbeitsgruppenleiterInnen, welche an verwandten Themen arbeiten, zu Mitgliedern der Fakultät und nehmen an der Auswahl und Zulassung der StudentInnen teil.

Gesellschaftliche Relevanz

Viele Forschungsaktivitäten am MPIKG haben potentielle Anwendungen, die nützlich und förderlich sein können für andere Disziplinen, aber auch für die Gesellschaft als Ganzes. Die Entwicklung von Impfstoffen auf der Basis von Kohlenwasserstoffen und die Möglichkeit große Mengen dieser Moleküle zu produzieren, ist vielversprechend und wegweisend für die Prävention von vielen Tropenkrankheiten wie Malaria oder Leishmaniose. Diese Impfstoffe sind speziell für Entwicklungsländer sehr bedeutsam. Funktionelle Nanopartikel und Materialien können dagegen für die verbesserte fotoinduzierte Aufspaltung von Wasser und für neue Methoden der CO₂-Bindung eingesetzt werden. Darüber hinaus besitzen diese Systeme ein breites Anwendungsspektrum in Bezug auf den intelligenten Wirkstofftransport, da sie die molekulare Erkennung und Bewegung mit der gezielten Wirkstofffreigabe kombinieren. Ferner könnten selbstreparierende Beschichtungen entscheidend dazu beitragen, den Materialverbrauch zu verringern, indem sie helfen, Korrosion und bakteriellen Bewuchs zu vermeiden. Biosysteme, die am Institut untersucht werden, könnten in Zukunft zu neuen Materialkonzepten führen, die auf bioinspirierten Designs basieren oder zur Organregeneration beitragen. Letztendlich und vor allem wird die Gesellschaft als Ganzes sehr stark von den jungen WissenschaftlerInnen profitieren, die ihre breite interdisziplinäre Ausbildung am MPIKG erhalten haben und das Institut verlassen, um ihr Wissen in anderen Wissenschafts- und Ingenieurbereichen anzuwenden.

Markus Antonietti,
Peter Fratzl,
Reinhard Lipowsky,
Helmuth Möhwald,
Peter H. Seeberger



The Research Program of the Max Planck Institute of Colloids and Interfaces (MPCI)

Colloids are small building blocks which constitute the basic units of living organisms and of many useful materials. Mastering their synthesis and assembly will solve pressing problems in health, energy, transport and many other important areas. The research strategy of the MPCI is to address fundamental scientific problems relating to colloids and to the interfaces between them. Thus the scientific vision of the institute is to lead the effort in making, visualizing, measuring and understanding these organic and inorganic nano-scale building blocks, as well as their interaction and assembly (see Fig. 1). This is guiding our basic scientific research related to biological or medical questions, as well as to materials for various applications. Bioinspired materials research is bridging between the two directions by translating materials structures found in nature into concepts for engineering materials.

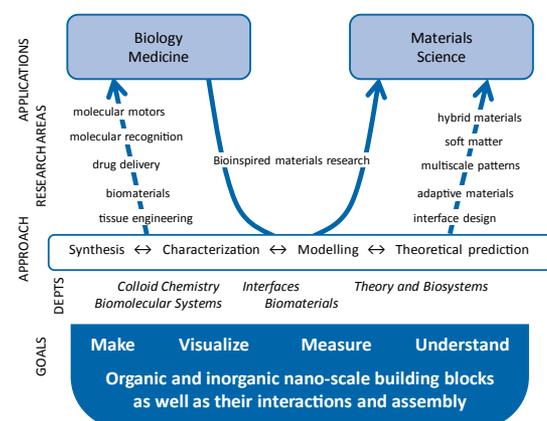


Fig. 1: Scientific strategy of the MPCI

To achieve these goals, we are convinced that scientific excellence must be combined with an exceptional commitment to mentoring and supporting young scientists.

Thus, our mission statement is: **Bridging the gap between molecules and multiscale materials and biosystems through excellence in science and in the support of young researchers.**

Over the last years the MPI of Colloids and Interfaces has attained a leadership position in several cutting edge research areas within the field of colloids and interfaces. These areas – ordered from smaller to increasingly larger objects – include the synthesis, characterization and theo-

retical description of oligosaccharides and carbohydrates, of functionalized nanoparticles and hybrid materials, of polyelectrolyte multilayers, the self-organization of complex interfaces and multi-component membranes, as well as hierarchical biomaterials based on polysaccharides, proteins or mineralized tissues such as bone and teeth. In all of these areas, the name of the MPCI serves as a trademark.

The MPCI pursues two general strategies in order to keep and strengthen its leading role in the field: (i) The MPCI constantly identifies and selects new interdisciplinary research topics with the highest potential impact on science and society; and (ii) the MPCI is very active in the training of graduate students and the support of young scientists and, thus, continues to be a hotbed for academic careers.

Recently, several new topics related to biomimetic and biological systems have been taken up. Four new focus areas are: molecular recognition of carbohydrates, photo-induced molecular processes, transport processes based on molecular motors, and biomimetic actuation and motility. These areas will also be pursued in the framework of the new International Max Planck Research School (IMPRS) on “Multiscale Biosystems: From molecular recognition to mesoscopic transport” during its first funding period from 2013 to 2019.

An improved understanding of multiscale biosystems provides the knowledge base for many possible applications such as the development of intelligent drug carriers and biomaterials.

Interdisciplinary Expertise

The complex and versatile world of colloids and interfaces provides many levels of spatial and temporal organization, from molecular to mesoscopic scales. In order to address these multiscale systems and processes, the departments at the MPCI provide complementary methodology and core expertise from chemistry, physics, and materials science. The departments of “Biomolecular Systems” (Seeberger) and “Colloid Chemistry” (Antonietti) have their core expertise in the chemical synthesis of molecules and materials. The departments of “Biomaterials” (Fratzl) and “Interfaces” (Möhwald) focus on structural analysis and physical characterization. The department of “Theory & Bio-Systems” (Lipowsky) provides expertise in theory and modeling. During the last decade, the MPCI has strongly enhanced its activities on biosystems by establishing the Fratzl department on “Biomaterials” in 2003 and the Seeberger department on





“Biomolecular Systems” in 2009. In order to strengthen its core expertise on structural analysis and physical characterization after the retirement of Helmut M \ddot{o} hwald in 2014, the MPICI will immediately establish an independent research group (W2 professor level) in this area. The search for an outstanding scientist to lead this group is under way. Moreover, the MPICI strives to establish a fifth department in the future to cover this area.

Long-term Objectives

Each department of the MPICI pursues challenging long-term objectives. The Seeberger department characterizes the complex mixture of carbohydrates in the glycocalyx of eukaryotic and prokaryotic cells in order to develop carbohydrate based vaccines. The Antonietti department wants to establish enzyme-like nanocatalysts and artificial photosynthesis as milestones for green energy production. The M \ddot{o} hwald department has been focusing on molecular and supramolecular interactions at interfaces. The Fratzl department wants to understand and mimic plant motility and bone tissue growth. The Lipowsky department wants to understand and characterize the complexity gap between artificial and natural biosystems.

New Focus Areas

During the last years, as mentioned above, four new promising focus areas have appeared. These shall be described below in more detail, also to visualize the links between the departments. Molecular recognition of carbohydrates is a focus area of the Seeberger department, with overlapping interests of the Antonietti, M \ddot{o} hwald, and Lipowsky departments. Research in this core area is based on the synthesis of polysaccharides and carbohydrates with a well-defined molecular architecture (Dept. Seeberger). These carbohydrates are then anchored to nanoparticles (Dept. Antonietti), lipid monolayers (Dept. M \ddot{o} hwald), and lipid bilayers (Dept. Lipowsky). In this way, they become

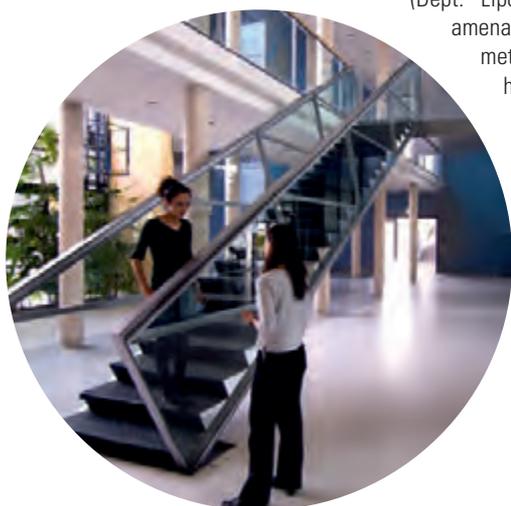
amenable to experimental and computational methods that probe these systems with high spatial and temporal resolution. Photo-induced molecular processes are a focus area of the Antonietti department, with overlapping interests of the Seeberger, M \ddot{o} hwald and Lipowsky departments. The main challenge for the photo-

induced cleavage of water is to find appropriate catalysts. A new type of catalyst based on a synthetic polymer has been recently introduced and will be further developed and optimized (Dept. Antonietti).

Other photo-induced processes include the synthesis of polymers using snowballing radical generation (Dept. Seeberger, Dept. Antonietti), photo-induced permeation of polyelectrolyte capsules (Dept. M \ddot{o} hwald), and photo-induced conformational changes of supramolecular assemblies (Dept. Lipowsky). Cargo transport by molecular motors is a focus area of the Lipowsky department, with overlapping interests of the Fratzl and M \ddot{o} hwald departments. Intracellular cargo particles exhibit complex patterns of transport reflecting the cooperative activity of molecular motor teams (Dept. Lipowsky). These motors can transport synthetic multilayer capsules filled with peptides and other chemical agents (Dept. M \ddot{o} hwald). One intriguing process for which the role of active transport remains to be elucidated is the assembly of magnetosomes in magnetotactic bacteria (Dept. Fratzl, Dept. Lipowsky). Biomimetic actuation and growth of tissues is a focus area of the Fratzl department, with overlapping interests of the Lipowsky department. Shape changes in tissues are caused by the generation of non-uniform, internal stresses. These stresses are generated by water absorption in the cell walls of plant tissues and by cell proliferation in bone or skin tissues (Dept. Fratzl). The ongoing experimental studies of these stress-generating processes will also be addressed by multi-scale computer simulations in order to elucidate the underlying molecular mechanisms (Dept. Lipowsky).

Graduate Programs

The MPICI will continue its strong engagement in the training of graduate students. The first International Max Planck Research School (IMPRS) on “Biomimetic Systems” has now been successfully operated for twelve years and will end in fall 2012. The second IMPRS on “Multiscale Biosystems” has been recently approved for the first funding period from 2013 until 2019. The main objective of the IMPRS curriculum is to enable the participating doctoral students to work on their research projects, which are at the forefront of current research, in an efficient and fruitful manner. In order to participate in the interdisciplinary research area of multiscale biosystems, doctoral students must learn the different languages as used in these different disciplines and need to understand how to extract useful information from the vast scientific literature that is published in these disciplines. The



training will also be useful for doctoral students, who intend to pursue a career outside academia in pharmacology, bio-engineering, and medicine. In addition the institute is active in the International Graduate research and Training Group on "Self Assembled Soft Nanostructures at Interfaces" coordinated by TU Berlin. The MPICI is also engaged in two other graduate schools which emerged from the excellence initiative of the German Science Foundation (DFG): the "Berlin-Brandenburg School of Regenerative Therapies" (coordinated by the Charité Hospital, Berlin) and the "School of Analytical Sciences Adlershof" (coordinated by the Humboldt University Berlin).

Support of Young Scientists

The MPICI will continue to be a hotbed for young scientists who pursue a career in academia. A large number of former associates and postdocs are now professors at German or foreign universities. In particular, during the last ten years, 33 former research group leaders of the MPICI have taken up offers for professorships that are equivalent to German W3 or W2 positions. Most of these research group leaders were teaching in the framework of the old IMPRS on "Biomimetic Systems". In the new IMPRS on "Multiscale Biosystems", all research group leaders, who work on topics related to the school, will be members of the school's associate faculty and will also take part in the recruitment and admission of the students.

Potential Applications and Impact on Society as a Whole

Many research activities at the MPICI have applications that will be useful and beneficial for research in other disciplines and for society as a whole. The development of vaccines based on hydrocarbons in connection with the possibility to produce large amounts of these molecules represents a very promising route for the prevention of many

tropical diseases such as malaria or leishmaniasis. These vaccines would be particularly beneficial for developing countries. Functionalized nanoparticles and materials can be used for improved photoinduced cleavage of water and for new methods of CO₂ fixation. Likewise, these systems have a wide range of applications in the context of smart drug delivery systems, which combine molecular recognition and activation with triggered drug release. Self-repairing coatings may lead to less materials consumption by avoiding corrosion and biofouling. The biosystems studied at the MPICI are also likely to lead to new materials concepts based on bio-inspired designs as well as new concepts for material-supported organ regeneration. Finally, the society as a whole will strongly benefit from the many young scientists that have received a broad interdisciplinary training at the MPICI and leave the institute in order to apply their knowledge in other branches of science and engineering.

Markus Antonietti,
Peter Fratzl,
Reinhard Lipowsky,
Helmuth Möhwald,
Peter H. Seeberger



Wissenschaftliche Beziehungen

Nationale Kooperationen:

Zwischen dem Max-Planck-Institut für Kolloid- und Grenzflächenforschung (MPIKG) und der Universität Potsdam besteht seit Institutsgründung eine intensive und gute Zusammenarbeit. Alle fünf Direktoren sind Honorarprofessoren an der Universität Potsdam. Dies spiegelt sich in einer intensiven Lehrtätigkeit sowohl in Bereichen des Grundstudiums als auch in den Wahlpflichtfächern wieder. Prof. Fratzl und Prof. Lipowsky sind zudem Honorarprofessoren an der Humboldt Universität zu Berlin und Prof. Seeberger an der Freien Universität Berlin. Darüber hinaus wurde Prof. Rabe vom Institut für Physik der Humboldt-Universität 2005 als Auswärtiges Wissenschaftliches Mitglied an das MPI für Kolloid- und Grenzflächenforschung berufen.

Die Aktivitäten über biomimetische Systeme wurden durch die gemeinsam vom Institut und der Universität Potsdam im Jahr 2000 ins Leben gerufene International Max-Planck Research School (IMPRS) on „Biomimetic Systems“ komplettiert, entscheidend gestärkt und unterstützt. Im Oktober 2012 beendete die Schule ihre erfolgreiche Arbeit. Ab Juni 2013 wird ihr eine neue International Max-Planck Research School (IMPRS) on „Multiscale Biosystems“ folgen. Diese befasst sich mit dem hierarchischen Aufbau von Biosystemen im Nanometer- und Mikrometerbereich. Sprecher ist Professor Lipowsky.

Zur weiteren Verstärkung der Zusammenarbeit wurden zwei Juniorprofessuren an der Universität Potsdam eingerichtet, besetzt durch Prof. Andreas Taubert (Kolloidchemie) und durch Prof. Matias Bargheer (Grenzflächen). 2009 wurden Matias Bargheer und 2011 Andreas Taubert zu W3-Professoren an der Universität Potsdam (UP) ernannt. Die Kooperation mit dem MPIKG bleibt bestehen.

Ferner beteiligt sich das Institut am Forschungsverbund „Unifying Concepts in Catalysis“ (UniCat), welcher im Rahmen der Exzellenzinitiative des Bundes und der Länder 2007 gegründet wurde und von der TU Berlin koordiniert wird. Prof. Antonietti ist hier seit 2009 Principal Investigator (PI). Über den SFB 760 „Musculoskeletal Regeneration“, der von der Charité - Universitätsmedizin Berlin koordiniert wird sowie den SFB 765 „Multivalenz als chemisches Organisations- und Wirkprinzip“, von der FU koordiniert, kooperiert es ferner mit der FU Berlin und dem Helmholtz-Zentrum Geesthacht (Institut für Polymerforschung). Darüber hinaus ist es auch Mitglied des vom Bundesministerium für Bildung und Forschung (BMBF) finanzierten Berlin-Brandenburger Zentrums für Regenerative Therapien (BCRT) sowie der von der DFG-Exzellenzinitiative geförderten Graduiertenschule Berlin-Brandenburg School of Regenerative Therapies (BSRT). Zudem koordiniert Prof. Fratzl das DFG-Schwerpunktprogramm SPP 1420 „Biomimetische Materialforschung“, an dem mehr als zehn Universitäten sowie Max-Planck-Institute beteiligt sind, das Bauprinzipien und Herstellung von neuartigen, hierarchisch strukturierten Materialien untersucht, die auf natürlichen Vorbildern basieren.

Eine Plattform für die Untersuchung biologischer Proben mit Synchrotronstrahlung wird in enger Kooperation mit der Universität Heidelberg am Helmholtz-Zentrum Berlin für Materialien und Energie betrieben. Großes Engagement gilt der Betreuung und dem Aufbau von Messplätzen an den Berliner Neutronen- und Synchrotronstrahlungsquellen sowie dem Deutschen Elektronen Synchrotron (DESY) in Hamburg.

Das Institut kooperiert mit dem Fraunhofer-Institut für Biomedizinische Technik IBMT und der Universität Potsdam seit 2009 in dem Projekt „Das Taschentuchlabor: Impulszentrum für Integrierte Bioanalyse“. Hier arbeiten vierzehn Partner aus Wissenschaft und Industrie an der Entwicklung von neuartigen Biosensoren, mit denen Krankheitserreger sofort und ohne komplizierte Aufreinigung detektiert werden können. Bis 2011 war das MPIKG gemeinsam mit dem Max-Planck-Institut für Molekulare Pflanzenphysiologie am vom BMBF geförderten Netzwerk GoFORSYS über Systembiologie beteiligt. Schließlich ist das Institut auch aktiv beteiligt an der International Graduate Research and Training Group on "Self Assembled Soft Nanostructures at Interfaces", koordiniert von der TU Berlin.

Internationale Kooperationen

Im Rahmen von europäischen Förderprogrammen, laufen zurzeit 21 EU-Projekte innerhalb des 7. Rahmenprogramms, davon 2 ERC Advanced Grants

Des Weiteren ist das Institut gemeinsam mit dem Max-Planck-Institut für molekulare Physiologie in Dortmund und dem Riken Advanced Science Institute (ASI) in Wako federführend beteiligt am neuen Riken-Max Planck-Joint Research Center. Beide Forschungseinrichtungen schaffen damit eine Plattform, auf der sie Wissen, Erfahrungen und Infrastruktur sowie neue Methoden und Techniken im Bereich der chemischen Systembiologie bündeln.

Das Indian Institute of Science and Education Research (IISER), Pune und das Institut haben zudem 2011 eine Max-Planck Partnergruppe ins Leben gerufen. In diesem Gemeinschaftsprojekt sollen innovative Nanosysteme entwickelt und hergestellt werden, die helfen sollen, Krebs besser behandeln zu können.

Bilaterale- und Kooperationsprojekte bestehen zur Zeit unter der Förderung der European Space Agency (ESA), der NATO, des Deutschen Akademischen Austausch Dienstes (DAAD), der Deutschen Forschungsgemeinschaft (DFG), der German Israel Foundation (GIF) for Scientific Research and Development, des National Institutes of Health (NIH), des Schweizer Nationalfonds, der Schweizerischen Eidgenossenschaft sowie der VW-Stiftung mit China, Frankreich, Griechenland, Großbritannien, Irland, Italien, Israel, Japan, Niederlande, Norwegen, Portugal, Polen, Russland, Schweiz, Schweden und Spanien und den USA. Darüber hinaus wird in enger Zusammenarbeit mit dem Ludwig-Boltzmann Institut für Osteologie in Wien (Österreich) an klinisch orientierter Knochenforschung gearbeitet.

Ferner betreibt die Abteilung Grenzflächen seit 2008 ein „Laboratoire Européen Associé über „Sonochemie“ mit dem CEA-Institut für Separationschemie in Marcoule.

Industriekooperationen, Verwertungsverträge, Ausgründungen

Industriekooperationen bestehen unter anderem mit Merck, der Beiersdorf AG, AstraZeneca UK, LAM Research, Lanxess und Ancora Pharmaceuticals. Das Institut hält gegenwärtig 41 Patente. Im Zeitraum von 1993-2012 erfolgten insgesamt acht Ausgründungen: ArtemiFlow, Capsulation Nanoscience AG, Colloid GmbH, GlycoUniverse, Nanocraft GmbH, Optrel, Riegler & Kirstein und Sinterface.

Editorial Boards

Unsere Wissenschaftler fungieren als Gutachter und Berater von fachspezifischen Zeitschriften und Journalen. In der folgenden Liste sind nur die Wissenschaftler angeführt, die entweder Herausgeber oder Mitglied eines Editorial Boards sind. Des Weiteren informieren wir Sie über Mitgliedschaften in Fachbeiräten.

Editorial Boards

- ACS Chemical Biology (P. H. Seeberger)
- Advanced Engineering Materials (P. Fratzl)
- Advanced Functional Materials (P. Fratzl)
- Advanced Healthcare Materials (P. Fratzl)
- Advances in Carbohydrate Chemistry and Biochemistry (P. H. Seeberger)
- Advances in Colloid and Interface Science (R. Miller, Editor)
- Applied Rheology (M. Antonietti)
- Beilstein J. of Organic Chemistry (P. H. Seeberger, Editor-in-Chief)
- Bioinspiration & Biomimetics (P. Fratzl)
- Bionterphases (P. Fratzl)
- Biomacromolecules (H. Möhwald)
- Biophysical Review Letters (P. Fratzl, R. Lipowsky, Editor)
- Bioorg. & Med. Chem. Letters (P. H. Seeberger)
- Bioorganic & Medicinal Chemistry (P. H. Seeberger)
- Biophysical Journal (R. Lipowsky)
- Calcified Tissue International (P. Fratzl)
- ChemBioChem (P. H. Seeberger)
- Chemistry of Materials (M. Antonietti, H. Möhwald)
- Colloid & Polymer Science (M. Antonietti)
- Current Opinion in Colloid & Interface Science (H. Möhwald)
- Current Opinion in Chemical Biology (P. H. Seeberger)
- Journal of Biotechnology (P. H. Seeberger)
- Journal of Carbohydrate Chemistry (P. H. Seeberger)
- Journal of Flow Chemistry (P. H. Seeberger)
- Journal of Materials Chemistry (H. Möhwald)
- Journal of Structural Biology (P. Fratzl)
- Journal of Statistical Physics (R. Lipowsky)
- Langmuir (H. Möhwald, M. Antonietti)
- Macromolecular Biosciences (P. H. Seeberger)
- Macromolecular Chemistry and Physics (H. Möhwald)
- Macromolecular Journals of Wiley-VCH (M. Antonietti)
- Macromol. Rapid Commun. (H. Möhwald)
- Nach. Chem. Lab. Tech. (M. Antonietti)
- Nano-Letters (H. Möhwald)
- Nature Communications (P. Fratzl)
- New Journal of Chemistry (M. Antonietti)
- Journal of Rheology (M. Antonietti)
- Physical Chemistry Chemical Physics (H. Möhwald)
- Polymer (M. Antonietti)
- Progress in Polymer Science (M. Antonietti)
- Review in Molecular Biotechnology (M. Antonietti)
- Science Magazine (P. Fratzl)
- Soft Matter (H. Möhwald)

Fachbeirat:

- Alberta Ingenuity Centre for Carbohydrate Science, Canada (P. H. Seeberger)
- Adolphe Merkle Institute (AMI) Fribourg (H. Möhwald)
- Austrian Nano Initiative (H. Möhwald, Board and Jury)
- Bayreuther Zentrum für Kolloid- und Grenzflächenforschung (H. Möhwald)
- Berlin-Brandenburg School of Regenerative Therapies, BSRT (P. Fratzl)
- Biofibres Materials Centre, Stockholm (H. Möhwald)
- Bionic Center Freiburg (P. Fratzl)
- CIC biomaGUNE, San Sebastian, Spain (P. H. Seeberger)
- DECHEMA Research Group on "Chemical Nanotechnology" (H. Möhwald)
- DFG Standing Review Board Materials Science (P. Fratzl, Chair)
- Elitenetzwerk Bayern (R. Lipowsky)
- Fondation ICFRC, International Center for Frontier Research in Chemistry, Strasbourg (H. Möhwald)
- Fraunhofer-Institute of Applied Polymer Research (H. Möhwald)
- German Colloid Society (H. Möhwald)
- Heinz Maier-Leibnitz Center Munich (P. Fratzl, Chair)
- The Helmholtz Centre Berlin for Materials and Energy (Peter Fratzl, Supervisory Board)
- FWF Austrian Science Fund (Peter Fratzl, Supervisory Board)
- IdEx Bordeaux (Initiative of Excellence of Bordeaux (M. Antonietti, Scientific Advisory Board)
- Institute of Biophysics and Nanosystems Research of the Austrian Academy of Science (ÖAW), Graz (H. Möhwald, Chair)
- Institute for Science & Technology Austria (P. Fratzl, Scientific Advisory Board)
- Institute of Theoretical Physics, CAS (R. Lipowsky)
- Material Science in Gothenborg (H. Möhwald)
- Minerva Foundation, Centers Committee (P. Fratzl, Chair)
- National Science and Technology Development Agency (NSTDA), Thailand (M. Antonietti, International Advisory Committee)
- National Nanotechnology Center (NANOTEC), Thailand (M. Antonietti, Scientific Advisory Board)
- Pôle chimie Balard Montpellier (H. Möhwald)
- WYSS Institute for Bioinspired Engineering at Harvard University (P. Fratzl, Scientific Advisory Board)

Scientific Relations

National Co-operations

The Max Planck Institute of Colloids and Interfaces (MPICI) and the University Potsdam maintain since its foundation intense and well-connected research co-operations. All five directors hold Honorary Professorships at the University Potsdam which reflect intensive teaching in basic studies as well as in specialized subjects. In addition to this Prof. Fratzl and Prof. Lipowsky hold Honorary Professorships at the Humboldt University Berlin and Prof. Seeberger at the Free University Berlin. In 2005 Prof. Rabe of the Humboldt University Berlin (Institute of Physics) was appointed as Foreign Member of the Max Planck Institute of Colloids and Interfaces.

In order to support and enhance its activities on biomimetic systems, and to improve the training of young researchers in this emerging field, the MPICI had created the International Max-Planck Research School (IMPRS) on Biomimetic Systems, followed by the new International Max Planck Research School (IMPRS) on "Multiscale Biosystems" starting in July 2013. The school is supported by the Max Planck Society and the partner universities, which are all Berlin Universities and the University Potsdam. The program lasts at least six years but it can be extended up to twelve years, can take on up to 20 students every year and leads to a doctor's degree in physics, chemistry or biology.

For additional intensification of the collaboration two Junior Professorships were established at the University Potsdam: Prof. Matias Bargheer (Department of Interfaces) and Prof. Andreas Taubert (Department of Colloid Chemistry who meanwhile were appointed as W3 professors at the University Potsdam (UP). The cooperation with the institute will thus go on.

The institute is also involved in the Cluster of Excellence "Unifying Concepts in Catalysis", which is co-ordinated by the Technical University Berlin. Since 2009 Prof. Antonietti has been principal investigator (PI) there. It was founded in 2007 within the framework of the Excellence Initiative launched by the German Federal and State Governments. Furthermore the MPICI cooperates in the new SFB program "Musculoskeletal Regeneration" (co-ordinated by Charité, Medical University, Berlin) and the by the FU coordinated SFB 765 "Multivalent Display" with the Free University Berlin and the Institute of Polymer Research at the Helmholtz-Zentrum Geesthacht.

It is also a member of the BMBF financed Berlin-Brandenburg Center for Regenerative Therapies (BCRT) and the Berlin-Brandenburg School of Regenerative Therapies (BSRT), funded by the Excellence Initiative of the DFG. On top of this Prof. Fratzl co-ordinates the DFG priority program SPP 1420 "Biomimetic Materials Research", in which more than ten universities as well as Max Planck Institutes take part. The aim is to explore the possibility of generating new material classes of great potential by combining the degrees of freedom of hierarchical structuring inspired by nature with the variety of materials offered by engineering.

In addition a platform for investigating biological specimens at Synchrotrons is set up together with the University Heidelberg and is run by the Helmholtz Centre Berlin for Materials and Energy. Big engagement required also the maintenance and build-up of beam-lines at the neutron- and

synchrotron radiation sources in Berlin and the German electron synchrotron (DESY) in Hamburg.

Since 2009 the institute also co-operates in the project "The Lab in a Hankie" – Impulse Centre for Integrated Bioanalysis with the Fraunhofer Institute of Biomedical Engineering IBMT, the University Potsdam and others. The project aims at the development of new biosensors for the direct detection of pathogens without complicated purification steps. Beyond that it took part in the systems biology network GoFORSYS, which was funded by the BMBF and the international graduate program "Self-assembled Soft Matter Nanostructures", together with the Berlin universities, which is funded by the DFG.

International Co-operations

Within the framework of European programs in total there are 21 EU projects within 7th framework program, including two ERC Advanced Grants.

Furthermore the Institute is principal partner together with the Max Planck Institute of Molecular Physiology in Dortmund and the Riken Advanced Science Institute (ASI) in Wako of the new Riken Max Planck Joint Research Center. The new research center is able to promote the more effective use of research resources as well as information and technology in the field of systems chemical biology.

The Indian Institute of Science and Education Research (IISER), Pune and the Max Planck Institute (MPI) of Colloids and Interface, Germany have entered 2011 into a research collaboration to design and construct nanodevices to improve treatment of cancer. The Max Planck Partner Group is funded by the Department of Science & Technology, Govt. of India and the Max Planck Society, Germany.

Beyond the collaborations described there exist bilateral and co-operation projects under assistance of the European Space Agency (ESA), the NATO, the German Academic Exchange Service (DAAD), the German Research Foundation (DFG), German Israel Foundation (GIF) for Scientific Research and Development, the National Institutes of Health (NIH), Swiss National Science Foundation (SNSF) and the VW-Stiftung with Commonwealth of Independent States (CIS), China, France, Greece, Ireland, Italy, Israel, Japan, the Netherlands, Norway, Poland, Portugal, Switzerland, Sweden, United Kingdom (UK) and the USA. Clinically oriented bone research is carried out in close collaboration with the Ludwig Boltzmann Institute of Osteology in Vienna (Austria).

Moreover the Department of Interfaces has established a Laboratoire Européen Associé about „Sonochemistry“. It is run since 2008 together with the CEA Institute of Separation Chemistry in Marcoule.

Co-operations with Industry, Application Contracts, Spin-Offs

Among many industry contacts co-operations with well-defined targets have been with Merck, Beiersdorf AG, AstraZeneca UK, LAM Research, Lanxess and Ancora Pharmaceuticals. At present the MPIKG upholds 41 patents. In the period from 1993-2012 eight spin-offs have been launched: ArtemiFlow, Capsulation Nanoscience AG, Colloid GmbH, GlycoUniverse, Nanocraft GmbH, Optrel, Riegler & Kirstein and Sinterface.

Editorial and Advisory Boards

Scientists serve as reviewers and advisors for many journals. Therefore listed are only activities as editor and member of an editorial board. Moreover you will find a list where you can find memberships in advisory boards.

Editorial Boards

- ACS Chemical Biology (P. H. Seeberger)
- Advanced Engineering Materials (P. Fratzl)
- Advanced Functional Materials (P. Fratzl)
- Advanced Healthcare Materials (P. Fratzl)
- Advances in Carbohydrate Chemistry and Biochemistry (P. H. Seeberger)
- Advances in Colloid and Interface Science (R. Miller, Editor)
- Applied Rheology (M. Antonietti)
- Beilstein J. of Organic Chemistry (P. H. Seeberger, Editor-in-Chief)
- Bioinspiration & Biomimetics (P. Fratzl)
- Bionterphases (P. Fratzl)
- Biomacromolecules (H. Möhwald)
- Biophysical Review Letters (P. Fratzl, R. Lipowsky, Editor)
- Bioorg. & Med. Chem. Letters (P. H. Seeberger)
- Bioorganic & Medicinal Chemistry (P. H. Seeberger)
- Biophysical Journal (R. Lipowsky)
- Calcified Tissue International (P. Fratzl)
- ChemBioChem (P. H. Seeberger)
- Chemistry of Materials (M. Antonietti, H. Möhwald)
- Colloid & Polymer Science (M. Antonietti)
- Current Opinion in Colloid & Interface Science (H. Möhwald)
- Current Opinion in Chemical Biology (P. H. Seeberger)
- Journal of Biotechnology (P. H. Seeberger)
- Journal of Carbohydrate Chemistry (P. H. Seeberger)
- Journal of Flow Chemistry (P. H. Seeberger)
- Journal of Materials Chemistry (H. Möhwald)
- Journal of Structural Biology (P. Fratzl)
- Journal of Statistical Physics (R. Lipowsky)
- Langmuir (H. Möhwald, M. Antonietti)
- Macromolecular Biosciences (P. H. Seeberger)
- Macromolecular Chemistry and Physics (H. Möhwald)
- Macromolecular Journals of Wiley-VCH (M. Antonietti)
- Macromol. Rapid Commun. (H. Möhwald)
- Nach. Chem. Lab. Tech. (M. Antonietti)
- Nano-Letters (H. Möhwald)
- Nature Communications (P. Fratzl)
- New Journal of Chemistry (M. Antonietti)
- Journal of Rheology (M. Antonietti)
- Physical Chemistry Chemical Physics (H. Möhwald)
- Polymer (M. Antonietti)
- Progress in Polymer Science (M. Antonietti)
- Review in Molecular Biotechnology (M. Antonietti)
- Science Magazine (P. Fratzl)
- Soft Matter (H. Möhwald)

Advisory Boards:

- Alberta Ingenuity Centre for Carbohydrate Science, Canada (P. H. Seeberger)
- Adolphe Merkle Institute (AMI) Fribourg (H. Möhwald)
- Austrian Nano Initiative (H. Möhwald, Board and Jury)
- Bayreuther Zentrum für Kolloid- und Grenzflächenforschung (H. Möhwald)
- Berlin-Brandenburg School of Regenerative Therapies, BSRT (P. Fratzl)
- Biofibres Materials Centre, Stockholm (H. Möhwald)
- Bionic Center Freiburg (P. Fratzl)
- CIC biomaGUNE, San Sebastian, Spain (P. H. Seeberger)
- DECHEMA Research Group on "Chemical Nanotechnology" (H. Möhwald)
- DFG Standing Review Board Materials Science (P. Fratzl, Chair)
- Elitenetzwerk Bayern (R. Lipowsky)
- Fondation ICFRC, International Center for Frontier Research in Chemistry, Strasbourg (H. Möhwald)
- Fraunhofer-Institute of Applied Polymer Research (H. Möhwald)
- German Colloid Society (H. Möhwald)
- Heinz Maier-Leibnitz Center Munich (P. Fratzl, Chair)
- The Helmholtz Centre Berlin for Materials and Energy (Peter Fratzl, Supervisory Board)
- FWF Austrian Science Fund (Peter Fratzl, Supervisory Board)
- IdEx Bordeaux (Initiative of Excellence of Bordeaux (M. Antonietti, Scientific Advisory Board)
- Institute of Biophysics and Nanosystems Research of the Austrian Academy of Science (ÖAW), Graz (H. Möhwald, Chair)
- Institute for Science & Technology Austria (P. Fratzl, Scientific Advisory Board)
- Institute of Theoretical Physics, CAS (R. Lipowsky)
- Material Science in Gothenborg (H. Möhwald)
- Minerva Foundation, Centers Committee (P. Fratzl, Chair)
- National Science and Technology Development Agency (NSTDA), Thailand (M. Antonietti, International Advisory Committee)
- National Nanotechnology Center (NANOTEC), Thailand (M. Antonietti, Scientific Advisory Board)
- Pole Chimie Balard Montpellier (H. Möhwald)
- WYSS Institute for Bioinspired Engineering at Harvard University (P. Fratzl, Scientific Advisory Board)

Internationale Max Planck Research School (IMPRS) über Biomimetische Systeme

Im Jahre 2000 etablierte das Max-Planck-Institut für Kolloid- und Grenzflächenforschung (MPIKG) gemeinsam mit der Universität Potsdam die „Internationale Max Planck Research School (IMPRS) über „Biomimetische Systeme“. Zusammen mit seinen Partnern bot das Institut ausländischen und deutschen Studenten der Physik, Chemie, Biologie und Materialwissenschaften ein interdisziplinäres Lehr- und Forschungsprogramm über „Biomimetische Systeme“ an. Hauptziel des Graduiertenprogramms war es, grundlegende Kenntnisse über biologische und biomimetische Systeme zu vermitteln und damit eine fachübergreifende Ausbildung zu offerieren. Die auf Englisch gehaltenen Kurse, Seminare und Workshops wurden von international renommierten Dozenten des jeweiligen Forschungsgebietes gehalten. Die IMPRS über „Biomimetische Systeme“ beendete ihre Arbeit im Oktober 2012 und hatte eine Laufzeit von insgesamt zwölf Jahren.

Lehrprogramm

Die Schule organisierte mehrere Lehrveranstaltungen pro Semester. Zum einen gab es allgemeine Kurse, um ein gemeinsames wissenschaftliches Basiswissen zu etablieren. So vermittelten diese beispielsweise die fundamentalen Prinzipien theoretischer, numerischer und experimenteller Arbeit auf dem Gebiet biomimetischer Systeme. Zum anderen gab es mehrere Kompakt- und Laborkurse, die speziell auf bestimmte Themenbereiche ausgerichtet waren. Alle Vorlesungen und Aktivitäten waren grundsätzlich offen für alle Studenten der teilnehmenden Einrichtungen. Als erste Graduiertenschule im Bereich Potsdam leistete die Schule einen wichtigen Beitrag zur Ausbildung der hier ansässigen Doktoranden. Vom Wintersemester 2001/2002 bis zum Wintersemester 2010/2011 wurden folgende Kurse angeboten:

- 79 Semesterkurse mit insgesamt 2200 Stunden Lehrzeit. Ein Drittel der Stunden wurde von Nachwuchsgruppenleitern gehalten.
- 44 Kompakt- und Laborkurse, mit insgesamt mehr als 600 Stunden Lehrzeit.

Ungefähr die Hälfte der Vorlesungen wurde von Gruppenleitern und ca. ein Viertel von eingeladenen Gastwissenschaftlern absolviert.

Ferner wurde die Schule um ein European Early Stage Training (EST) und ein anderes Europäisches Netzwerk (STREP on "Active Bio-Systems") erweitert, welche beide von R. Lipowsky koordiniert wurden. In Zusammenarbeit mit diesen zwei Netzwerken organisierte die Schule eine internationale Konferenz und fünf Workshops. Gemeinsam mit der Chinesischen Akademie der Wissenschaften richtete die IMPRS zudem eine Sommerschule in Peking aus und unterstützte die Konferenz PhysCell2009. Auch an dem vom BMBF geförderten Systembiologieprojekt GoFORSYS sowie an der Potsdam Graduate School (PoGS) war die Schule beteiligt und bot in diesem Rahmen verschiedene Kurse innerhalb der Masterstudiengänge Physik und Biologie der Universität Potsdam an.

IMPRS über „Multiscale Biosystems“

Zu Beginn des Wintersemesters 2013/2014 nimmt eine neue IMPRS on "Multiscale Biosystems" ihre Arbeit auf. Sprecher der Schule ist R. Lipowsky, Vizesprecher R. Seckler und Koordinator A. Valleriani. Das Graduiertenprogramm setzt sich aus folgenden Partnern zusammen: Universität Potsdam, Freie Universität Berlin, Humboldt-Universität Berlin und Fraunhofer-Institut für Biomedizinische Technik IBMT.

Die Schule befasst sich mit dem hierarchischen Aufbau von Biosystemen im Nanometer- und Mikrometerbereich. So geht es z.B. um Makromoleküle wie Proteine in wässriger Lösung, die molekulare Erkennung zwischen diesen Bausteinen, die Übertragung freier Energie in molekularen Maschinen oder die Strukturbildung und den Transport in Zellen und Geweben. Die vier Forschungsschwerpunkte der IMPRS sind: molekulare Erkennung von Kohlenhydraten, Wechselwirkung von Biomolekülen mit Licht, gerichtete Prozesse in Zellen sowie gerichtete Formänderungen von Gewebe. Im Mittelpunkt der Untersuchungen steht die Frage, wie die Prozesse auf supramolekularen und mesoskopischen Skalen, im Bereich von wenigen Nanometern bis zu vielen Mikrometern, durch die Struktur und Dynamik der molekularen Bausteine bestimmt werden.

Rahmenbedingungen

Die neue IMPRS on „Multiscale Biosystems“ wurde zunächst für sechs Jahre bewilligt mit der Option einer Verlängerung für weitere sechs Jahre. Hauptsitz der Schule ist das MPI für Kolloid- und Grenzflächenforschung. Nach den allgemeinen Grundsätzen werden in den Research Schools der Max-Planck-Gesellschaft in der Regel je zur Hälfte deutsche und ausländische Nachwuchswissenschaftler gemeinsam ausgebildet.

Das englischsprachige Doktorandenprogramm bietet innovative und interdisziplinäre Forschung. Um ein quantitatives Verständnis der wissenschaftlichen Zusammenhänge zu erlangen, verbinden die interdisziplinären Forschungsaktivitäten der Schule Bottom-up mit Top-down Zugängen, die von mehreren Gruppen aus der theoretischen und experimentellen Biophysik, aus der physikalischen Chemie und Kolloidchemie, aus der Biochemie und Molekularbiologie, sowie aus den Materialwissenschaften eingesetzt werden. Gruppenleiter, Nachwuchsgruppenleiter und Professoren des MPI für Kolloid- und Grenzflächenforschung, der Universität Potsdam, FU Berlin, HU Berlin und des Fraunhofer-Instituts für Biomedizinische Technik IBMT nehmen an dem Programm teil und bilden die Doktoranden aus. Über die Wissenschaft hinaus bietet das Graduiertenprogramm eine Reihe von Soft-Skill-Seminaren wie z.B. Deutschkurse oder Vorlesungen zur beruflichen Orientierung.

Weitere Informationen finden Sie unter:
imprs.mpikg.mpg.de

Reinhard Lipowsky and Angelo Valleriani



International Max Planck Research School (IMPRS) on Biomimetic Systems

In the year 2000, the MPI of Colloids and Interfaces (MPICI), together with the University of Potsdam, established an International Max Planck Research School (IMPRS) on Biomimetic Systems. The IMPRS on Biomimetic Systems offered, together with its partner groups, an interdisciplinary curriculum on 'Biomimetic Systems' for foreign and German students from physics, chemistry, biology, and materials science. One major goal of this curriculum was to provide a common basis of knowledge in biological and biomimetic systems, which transcends the traditional boundaries between the different disciplines. The curriculum was based on courses, seminars and workshops with the participation of scientists, who work at the cutting edge of this field.

The IMPRS on Biomimetic Systems was running for twelve years until October 2012.

The curriculum delivered by the IMPRS on Biomimetic Systems

The curriculum of the IMPRS on Biomimetic Systems was based on semester courses, lab and compact courses, as well as seminars. The semester courses delivered general and fundamental background information to unify the knowledge among scientists from different disciplines. The lab and compact courses were intended to provide lectures on more advanced topics.

The courses of the IMPRS were held in English and open to all students of the participating institutions. As the first graduate school in the Potsdam area, the IMPRS contributed to the training of local doctoral students.

Starting with the winter semester 2001/2002 and until the winter semester 2010/2011, the following courses have been offered:

- 79 Semester Courses, with a total duration of about 2,200 hours of lectures. Junior group leaders held more than 1/3 of these lectures
- 44 Compact and Lab Courses, with a total duration of more than 600 hours of lectures

About half of the lectures have been delivered by group leaders and about one quarter by invited guest scientists.

In addition, the IMPRS on Biomimetic Systems was part of a large international research training network funded by the European Commission (EST on "Biomimetic Systems") and another European network (STREP on "Active Bio-Systems"), both coordinated by R. Lipowsky. Together with these two networks, one international conference and five workshops have been organized. Furthermore, the IMPRS also organized a summer school together with the Chinese Academy of Sciences, which was held in Beijing, and actively supported the conference PhysCell2009. The IMPRS on Biomimetic Systems was participating in the BMBF funded Systems Biology project GoFORSYS as well as in the Potsdam Association of all graduate schools (PoGS), and offered several courses shared with the MSc in Physics and Biology at the University of Potsdam.

IMPRS on Multiscale Biosystems

In collaboration with the University of Potsdam, the Free University Berlin, the Humboldt University Berlin, and the Fraunhofer Institute for Biomedical Engineering IBMT, the MPICI now offers a new IMPRS on "Multiscale Biosystems". The speaker of the school is R. Lipowsky, the vice-speaker is R. Seckler, and the coordinator is A. Valleriani. The new IMPRS will start its training activities in the winter semester 2013/2014.

Our new school addresses the fundamental levels of biosystems as provided by macromolecules in aqueous solutions, molecular recognition between these building blocks, free energy transduction by molecular machines as well as structure formation and transport in cells and tissues. The research activities are focused on four core areas: molecular recognition of carbohydrates, interaction of biomolecules with light, directed intracellular processes as well as directed shape changes of tissues. One general objective is to understand, in a quantitative manner, how the processes on supramolecular and mesoscopic scales between a few nanometers and many micrometers arise from the structure and dynamics of the molecular building blocks.

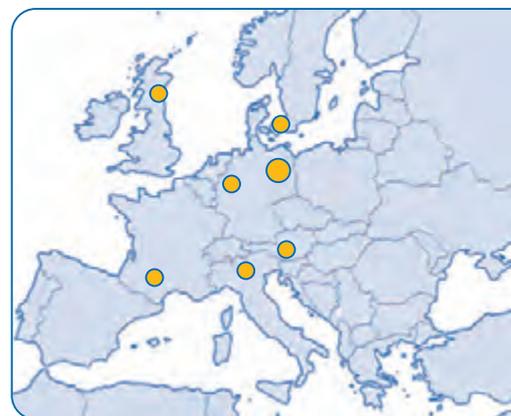
General Framework

The English-speaking doctoral program offers cutting edge and interdisciplinary research and has been approved for six years, with a possible extension for another six years. Headquarter of the school is the MPICI. In line with the general rules for all IMPRS, about half of the admitted students will be from Germany and from abroad, respectively. The interdisciplinary research combines bottom-up with top-down approaches, which are pursued by several groups from theoretical and experimental biophysics, from physical and colloid chemistry as well as from biochemistry and molecular biology. Furthermore, a variety of soft skills events will be offered, including German language courses as well as lectures on career possibilities.

Group leaders, junior group leaders and professors of the Max Planck Institute of Colloids and Interfaces, the Potsdam University, FU Berlin, HU Berlin, and the Fraunhofer Institute for Biomedical Engineering IBMT participate in the program and offer training and mentorship.

For further information see: imprs.mpikg.mpg.de

Reinhard Lipowsky and Angelo Valleriani



Presse- und Öffentlichkeitsarbeit

Das Max-Planck-Institut für Kolloid- und Grenzflächenforschung informiert innerhalb seiner Presse- und Öffentlichkeitsarbeit über die wissenschaftlichen Innovationen am Institut und deren Ergebnisse in Lehre, Forschung und Anwendung. Auf diese Weise möchten wir ein eigenständiges, positives Image und Vertrauen schaffen. Gleichzeitig soll dazu beigetragen werden eine Brücke von der Lehr- und Forschungsstätte in die Öffentlichkeit zu schlagen, aktuelle Impulse aufzunehmen, neue Ideen zu finden und umzusetzen. Ein Hauptziel ist es, unsere aktuelle Forschung in das Bewusstsein der allgemeinen Öffentlichkeit, der Politik, der Presse, unserer KooperationspartnerInnen, zukünftiger StudentInnen, ehemaliger Institutsangehöriger sowie der internen Gemeinschaft zu bringen. Aufmerksamkeit und Interesse für die Wissenschaft und damit letztendlich Akzeptanz, Sympathie und Vertrauen zu gewinnen, gehören zu unseren wichtigsten Anliegen.

Fach- und Publikumsjournalisten werden über das aktuelle Geschehen mit Hilfe von fundierten Nachrichten und Hintergrundwissen informiert. Regelmäßig veröffentlichen wir unseren Zweijahresbericht, Presse-Informationen, beantworten Presseanfragen und halten zu den Medienvertretern persönlichen Kontakt. Neben der klassischen Pressearbeit stellt die Konzeption, Organisation und Durchführung von Veranstaltungen den zweiten Tätigkeitsschwerpunkt des Referats dar.

Der alle zwei Jahre stattfindende Tag der Offenen Türen im Wissenschaftspark Potsdam-Golm ist dabei einer unserer Höhepunkte. Gemeinsam mit den Max-Planck-Instituten für Gravitationsphysik und Molekulare Pflanzenphysiologie, den Fraunhofer-Instituten für Angewandte Polymerforschung IAP sowie für Biomedizinische Technik IBMT, dem Golm Innovationszentrum GO:IN sowie dem Brandenburgischen Landeshauptarchiv bieten wir interessierten Besuchern aller Altersklassen einen faszinierenden Einblick in die Forschung. Das

vielfältige Programm mit Führungen, Experimenten, Vorträgen

und Mitmach-Aktionen bietet Jung und Alt Wissenschaft zum Anfassen und zahlreiche Möglichkeiten, High-Tech-Technologien hautnah zu erleben und zu begreifen. Der Tag der Offenen Türen wird 2013 am 14. September von 11.00 bis 17.00 Uhr stattfinden.

Mit dabei war das MPIKG auch beim großen Wissenschaftsfestival „Ideenpark 2012“ in der Messe Essen und im Gruga-Park vom 11. bis 23. August. Staunen, ausprobieren, Zusammenhänge verstehen – beim Ideenpark hatten Jung und Alt viel zu erkunden. Eine futuristische Stadtlandschaft auf 60.000 Quadratmetern mit über 400 Exponaten wartete in der Messe Essen und im Gruga-Park auf die Besucher. Mehr als 1.500 Forscher, Ingenieure, Studenten und Auszubildende stellten bei dieser Gelegenheit ihre Projekte vor.

In der BioWerkstatt in Halle 3 des IdeenParks lernten die Besucher zahlreiche Biomaterialien aus Wald und Meer kennen – immer scharfe Seeigelzähne, das unzerbrechliche Glaskelett eines Tiefseeschwammes und Weizensamen, die sich von ihrer Mutterpflanze entfernen können, sind nur einige Beispiele. Gemeinsam mit den Forschern erkundeten die zahlreichen Besucher das Prinzip des hierarchischen Aufbaus. Sie erfuhren dabei, warum die hier realisierte, sehr effiziente Nutzung der für den jeweiligen Organismus vorhandenen Ressourcen ein Vorbild für die Entwicklung neuer technischer Materialien sein kann.

Zudem werden am Max-Planck-Institut für Kolloid- und Grenzflächenforschung Führungen für Interessierte, insbesondere für Schulklassen sowie Vorträge an den Schulen selbst organisiert. Der Internetauftritt des Instituts, aber auch die interne Kommunikation stellen darüber hinaus weitere wichtige Bereiche der Öffentlichkeitsarbeit dar.

Wir sehen es als Aufgabe an, die Bedeutung der Grundlagenforschung und der zukünftigen Entwicklungen in der Kolloid- und Grenzflächenforschung an die breite Öffentlichkeit zu transportieren. Entdecken Sie auf den folgenden Seiten, dass Wissenschaft faszinierend, kreativ und fesselnd ist! Sollten Sie bei auftretenden Fragen unsere Hilfe benötigen, unterstützen wir Sie jederzeit gern.

Katja Schulze
Presse- und Öffentlichkeitsarbeit
katja.schulze@mpikg.mpg.de



Press and Public Relations

Press and Public Relations at the Max Planck Institute of Colloids and Interfaces serve as the interface between the scientists' work and the public. We inform you about the research results, and want to create an independent, positive image and thus trust in scientific work. Simultaneously we try to bridge the gap between research institution and general public and hence get new impetus and ideas. We promote the perception of our research among the community, the press, government, corporate partners, prospective students, alumni and our own internal community. It is a matter of great importance that not only the scientific community but in fact anyone interested in modern science should have the opportunity to get an idea about the aims of our institute. Attention, interest and finally trust in science must be one of our most important concerns.

Therefore we inform journalists with profound news and background knowledge about current research. To pursue this task press releases are edited, brochures – such as this Report – are published and distributed on request and informal support is provided whenever necessary. Beside classical Press and Public Relations the complete conception, organisation and realisation of events is a second core theme.

One of our highlights every two years is the Open Day on the Potsdam-Golm Science Park, which is an interesting and fun-packed day, combining demonstrations of high-tech learning facilities with hands on activities for all age groups. The Open Day 2013 will be held together with the Max Planck Institutes of Gravitational Physics and Molecular Plant Physiology, the Fraunhofer Institutes for Applied Polymer Research IAP and for Biomedical Engineering IBMT, the Golm Innovation Center GO:IN and the Brandenburg Main State Archive. It takes place on September 14 from 11 a.m. till 5 p.m. There will be lab tours, popular talks and scientific demonstrations providing an excellent opportunity for everybody to experience scientific activity at first hand.

Furthermore the MPICI took part in a further important event: the "IdeasPark Essen 2012". Technology experience was being held at Messe Essen and Grugapark from August 11 to 23. An area of 60,000 square meters was given over to the fascination of technology. More than 120 partners from research, science, education and business attracted around 400,000 visitors. The emphasis was on interaction. Throughout the IdeasPark, visitors were invited to carry out their own experiments and make their own discoveries.



The visitors got to know various interesting biomaterials from the forest and the sea: always sharp sea urchin teeth, the unbreakable skeleton of the deep sea sponge *Euplectella* or wheat seeds, which are able to "swim" into the soil. Together with scientists from the Institute they discovered the principle of hierarchical structure. They learned how organisms use the available resources in a very efficient manner and that this can serve as a model for the development of new technical materials.

Beyond this tours through the institute as well as talks at schools are organized. But also the internet presence and the internal communication are additional important fields within Press and Public Relations.

We try to create awareness for the role of basic research in general, especially with regard to future developments in colloid and interface science. We also seek to show that the world of science and technology is fascinating, challenging, varied and rewarding. Within these pages you can find the latest news from the institute as well as a more in depth look at our research. If you have any further questions, please contact us. We are pleased to help you.

Katja Schulze
Press and Public Relations
katja.schulze@mpikg.mpg.de





- 
- Biological Materials
 - Biological and Bio-inspired Materials

BIOMATERIALS

Research in the Department of Biomaterials



The Department focuses on biomaterials research in a somewhat broader sense:

- by using materials science approaches for studying structure-function relationships in biological systems, with potential applications in biology or medicine;
- by studying the “engineering design” which arose during the evolution of natural materials and to extract useful principles for the development of new bio-inspired materials;

- by developing new materials for contact with biological tissues, leading to implantable biomaterials or with applications in tissue engineering.

Together we define this as Biological Materials Science which is inherently multidisciplinary between physics, chemistry and biology. All three areas mentioned above are addressed in the Department with a significantly stronger emphasis on the first two. To tackle such questions, the members of the Department have very diverse scientific backgrounds, including mathematics, physics, chemistry, materials science, physical chemistry, biochemistry, wood science, botany, zoology and molecular biology.

In the course of evolution, load-bearing biological materials have generally not evolved towards perfection and maximum strength, but instead developed high defect tolerance and adaptability [1]. Adaption occurs at various levels, see figure 1. While evolution leads to adaptation of entire species, each individual has mechanisms which confer some self-repair properties even at smaller scales to cope with a variety of environmental challenges. Healing and regeneration occur at the level of organs, but many biological materials are damage-tolerant at the supra-molecular level or have (passive) self-repair properties (see Fig. 1).

Research Topics

The Department addresses the adaptation of natural materials according to all three levels mentioned in Figure 1, both to advance the understanding of these biological systems, as well as to extract concepts for the development of adaptive, self-healing or multi-functional materials. The adaptation by evolution (cycle (a) in Fig. 1) can be studied by comparing the details of material structure (such as teeth, bones, or shells) in closely related species and comparing these to the variability in function due, for example, to differences in habitat. This perspective is taken in particular by *Mason Dean* in the context of fish skeletons and by *Michaela Eder*, studying plants which, for example, adapt to frequent fires (see their reports).

Bone remodeling is also a process by which damaged tissue is continuously replaced by newly synthesized material and, thus, an interesting case of adaptation (cycle (b) in Fig. 1). Bone remodeling generally depends on a dense network of mechanosensitive cells, called osteocytes. This network is such that all mineralized tissue in bone is not further away from the next osteocyte canalliculum than about one micron, making the network an extremely effective transport system [2]. While bone continuously repairs damage through remodeling, it needs a more complicated process to heal after a fracture occurred. The healing process is a matter of intensive research in the Department in collaboration with the Charité University Hospital in Berlin and other partners. The questions of healing, remodeling and mechanical adaptation of bone are addressed by the groups of *Wolfgang Wagermaier* and *Richard Weinkamer* (see their reports). In addition, scaffold-supported healing is studied in-vivo [3] as well as in-vitro [4], primarily to elucidate the interaction between growing tissue and the geometric constraints from the scaffold material (see report by *John Dunlop*). Other clin-

Peter Fratzl 13.09.1958

1980: Diploma (Ingénieur Diplômé de l'Ecole Polytechnique, Paris)

1983: PhD, Physics (University of Vienna)

Thesis: Investigation of an Al-Zn-Mg alloy using diffuse neutron scattering

1981-1985: Research Scientist

(Austrian Academy of Sciences, Vienna; Laboratoire Leon Brillouin, Saclay, France); Visiting Research Fellow

(Hahn Meitner Institute, Berlin; New York University)

1986-1998: Assistant and Associate Professor (Institute for Materials Physics of the University of Vienna, Austria)

1988 and 1989: Visiting Professor (Rutgers University, New Jersey, USA)

1991: Habilitation, Solid State Physics (University of Vienna)

Thesis: Precipitation in alloys – small-angle x-ray scattering and computer simulation

Since 1993: Research Associate (Ludwig Boltzmann Institute of Osteology, Vienna).

1993-1994: Visiting Research Fellow (Heriot-Watt University, Edinburgh)

1997: Visiting Professor, (Physics Department of the University of Munich)

1998-2003: Chair of Metal Physics (University Leoben, Austria)

Director (Erich Schmid Institute for Materials Science of the Austrian Academy of Sciences)

Since 2003: Director, Department of Biomaterials (Max Planck Institute of Colloid and Interfaces, Potsdam-Golm)

Since 2004: Honorary Professor of Physics at Humboldt University Berlin

Since 2009: Honorary Professor (Physics of Biomaterials) at the Potsdam University

Since 2010: Acting Director of the Experimental Department II at the Max Planck Institute for Microstructure Physics, Halle

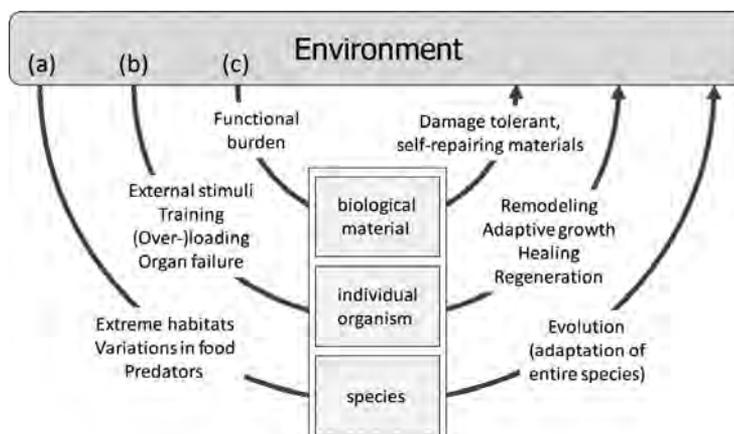


Fig. 1: Three levels of natural adaptation to environmental influences [1]. (a) Darwinian evolution acts on the species level to adapt to long-term challenges, such as habitat, food type or predators. (b) Remodeling, healing or regeneration operate at the organ level within an individual organism. (c) Biological materials, such as bone, extracellular tissue or protein fibers are damage tolerant and often have self-repair mechanisms that operate on the supra-molecular level.

ically oriented research on bone diseases, such as osteoporosis and osteogenesis imperfecta (brittle bone disease) is carried out in close collaboration with the Ludwig Boltzmann Institute of Osteology in Vienna, Austria.

While bone remodeling and healing are processes operating at the organ level (similarly to many kinds of wound healing in animals or plants), there are also intrinsic material properties which provide damage tolerance and self-repair (cycle (c) in **Fig. 1**). Examples are deformable interfaces connecting stiff protein or polysaccharide fibers or mineral platelets and capable of absorbing large deformations in tissues, such as tendons or plant cell walls **[5]**. In some cases, damage is fully recovered over a short or a longer period of time, thus providing some type of self-repair. This is a major topic in the research group of *Matthew J. Harrington* (see his report).

Natural materials are not only based on proteins or cellulose, but in many organisms also on chitin. Arthropods, such as spiders for example, use their chitin cuticle to house a wide range of sensors and tools which are highly exciting examples of unusual engineering solutions for a variety of technical problems. The group of *Yael Politi* is primarily focusing on this type of research (see her report). The interaction of water with all these biomolecules (proteins and polysaccharides alike) plays an important role for their mechanical behavior, including materials properties, such as stiffness and toughness, but also actuation and the generation of internal stresses. This topic is addressed by *Luca Bertinetti* and partially also in the group of *John Dunlop* (see their reports).

Biom mineralization is a further strong topic of the Department. Its director has just been chairing the Gordon Research Conference on Biom mineralization in 2012. *Damien Faivre*, who's research group is being essentially supported by an ERC Starting Grant from the European Research Council, works on elucidating how bacteria control the growth of magnetite nanoparticles through the interaction with specialized proteins (see his report). Together with partners at the Weizmann Institute (Prof. Lia Addadi), we were awarded a 5-year grant from the German Science Foundation (within the DIP-Program) to study the origin of the stability of amorphous bio-minerals **[6,7]**. *Wouter Habraken* is strongly active in this project (see his report) and *Yael Politi's* group is also involved in some of this research. Until spring 2012, Barbara Aichmayer was heading a group concentrating on biom mineralization of calcium-based minerals. She already left in summer 2012 and no report is included. Some of her publications are, however, mentioned here **[6,8,10,11]** and in other places of this report (see for example the section by *Admir Masic*).

Methodological Approaches

Generally, the experimental approach is based on multi-method imaging where different probes are used to image the same specimen. This provides information on different features of the materials such as micro-structure, chemical composition, or mechanical properties in a position-resolved manner with micron-range resolution. We are currently developing and using multi-method characterization approaches combining x-ray tomography; scanning electron microscopy and scanning x-ray diffraction to characterize micro- and nanostructure and many levels of structural hierarchy (see report by *Wolfgang Wagermaier*). We have established polarized and confocal Raman imaging to provide information on chemical composition and fiber orientation, which is now being combined in-situ with synchrotron x-ray scattering (see report by *Admir Masic*). We use nano-indentation as well as acoustic microscopy to estimate local mechanical properties. Currently, *Igor Zlotnikov* is establishing modulus mapping which pushes the lateral resolution of mechanical characterization into the nanometer range (see his report). The strength of this multi-method approach is that the different parameters measured on the same specimen can be correlated at the local level with micron (or even smaller)-scale spatial resolution. This facilitates the extraction of structure-property relationships even in extremely heterogeneous materials with hierarchical structure.

In a second type of approach, we study in situ changes in various materials (e.g. due to mechanical stress or to chemical or thermal processing) by time-resolved scattering or spectroscopy during mechanical deformation or thermal or hygroscopic treatment. This gives insight into the molecular and supramolecular mechanisms which are responsible for the noteworthy properties of these materials. In some cases, such measurements can be performed in the laboratory (e.g. with Raman or infrared spectroscopy or in the environmental scanning electron microscope), but in many cases synchrotron radiation is needed (e.g. for x-ray diffraction or small-angle scattering). A dedicated beamline end station for scanning small- and wide-angle scattering and fluorescence spectroscopy is operated at the synchrotron BESSY at the Helmholtz Zentrum Berlin **[8]**.

These efforts are complemented by a significant effort in mathematical modeling, which is always closely tied to the experimental work in the department. Typically, modeling and experimentation go hand in hand with the research projects (see for example the reports by *John W.C. Dunlop* and *Richard Weinkamer*).

References:

- [1]** Weinkamer, R., Dunlop, J.W.C., Bréchet, Y., Fratzl, P. All but diamonds: Biological materials are not forever, *Acta Mater* 61, 880 - 889 (2013).
- [2]** Kerschnitzki, M., Kollmannsberger, P., Burghammer, M., Duda, G.N., Weinkamer, R., Wagermaier, W., Fratzl, P. Architecture of the osteocyte network correlates with bone material quality, *Journal of Bone and Mineral Research* (2013) [Epub ahead of print] doi: 10.1002/jbmr.1927.
- [3]** Woodruff, W.A., Lange, C., Chen, F., Fratzl, P., Hutmacher, D.W., Nano- to macroscale remodeling of functional tissue-engineered bone, *Advanced Healthcare Materials* 2, 546 - 551 (2013).
- [4]** Bidan, C.M., Kommareddy, K.P., Rumppler, M., Kollmannsberger, P., Fratzl, P., Dunlop, J.W.C. Geometry as a factor for tissue growth: towards shape optimization of tissue engineering scaffolds, *Advanced Healthcare Materials* 2, 186 - 194 (2013).
- [5]** Dunlop, J.W.C., Weinkamer, R., Fratzl, P., Artful interfaces within biological materials, *Materials Today* 3, 70 - 78 (2011).
- [6]** Gal, A., Hirsch, A., Siegel, S., Li, C., Aichmayer, B., Politi, Y., Fratzl, P., Weiner S., Addadi, L., Plant cystoliths: a complex functional biocomposite of four distinct silica and amorphous calcium carbonate phases. *Chem. Eur. J.* 18, 10262 - 10270 (2012).
- [7]** Gur, D., Politi, Y., Sivan, B., Fratzl, P., Weiner, S., Addadi, L., Guanine-based photonic crystals in fish scales form from an amorphous precursor. *Angew. Chem. Int. Ed.* 52, 388 - 391 (2013).
- [8]** Paris, O., Aichmayer, B., Al-Sawalmih, A., Li, C., Siegel, S., Fratzl, P. Mapping lattice spacing and composition in biological materials by means of microbeam x-ray diffraction. *Advanced Engineering Materials* 13, 748 - 792 (2011).

[9] Kolednik, O., Predan, J., Fischer F.D., Fratzl, P., Bioinspired design criteria for damage-resistant materials with periodically varying boundary conditions.

Advanced Functional Materials **21**, 3634 - 3641 (2011).

[10] Schenk, A.S., Zlotnikov, I., Pokroy, B., Gierlinger, N., Masic, A., Zaslansky, P., Fitch, A.N., Paris, O., Metzger, T.H., Cölfen, H., Fratzl, P., Aichmayer, B., Hierarchical calcite crystals with occlusions of a simple polyelectrolyte mimic complex biomineral structures. Adv. Funct. Mater. **22**, 4668 - 4676 (2012).

[11] Gilow, C., Zolotoyabko, E., Paris, O., Fratzl, P., Aichmayer, B., Nanostructure of biogenic calcite crystals: a view by small-angle x-ray scattering. Cryst. Growth Des. **11**, 2054 - 2058 (2011).

Visiting Scholars

Several experienced scientists have been spending significant time in the Department. *Franz Dieter Fischer*, professor of mechanics at the Montanuniversität Leoben (Austria) recipient of the Alexander von Humboldt Award, came for many short visits, which helped advance the mathematical modeling of tissue growth in particular (see report by *J.W.C. Dunlop*) and was involved in theoretical research about the mechanical properties of biological hybrid materials [9]. *Hartmut Metzger* arrived in the beginning of 2010 from the European Synchrotron Radiation Facilities (ESRF), where he had been a staff scientist and group head responsible for several beamlines. He brought many years of experience in x-ray diffraction, in particular with grazing incidence and using coherent beams, to our Department. He is by now involved in a number of projects utilizing synchrotron radiation such as the study of biomimetic minerals [10] and other topics mentioned in the reports that follow. *Emil Zolotoyabko*, professor of materials science at the Technion (Israel Institute of Technology) spent several months of a sabbatical in the Department on continues to visit on a regular basis. He is also involved in a number of projects on studying biosilica (see report by *Igor Zlotnikov*) as well as other biomineralized tissues [11]. *Yves Bréchet*, professor of materials science at the Institut National Polytechnique de Grenoble (INPG) and at the Institut Universitaire de France (IUF) as well as "Haut Commissaire à l'Energie Atomique" received the Gay Lussac-Humboldt Award and is visiting our Department from 2012 onwards. Most recently, *Scott White*, professor at the University of Illinois at Urbana-Champaign received the Humboldt Research Award and is visiting the Department in 2013. His research is focused on developing self-healing and self-remodeling engineering materials. In addition to developing new collaborations, our visiting scholars play an important role in the mentoring of young scientists, and we are most grateful to them for this very important contribution.

The majority of the research in the Department of Biomaterials involves collaborations – within the Department, with other Departments in the Institute and with many outside partners around the world to whom we all extend our sincere gratitude for cultivating and fostering such positive and constructive partnerships.

Peter Fratzl
Director of the Department of Biomaterials

Biochemical Strategies in Load-Bearing Natural Materials



Matthew James Harrington

30.08.1980

2002: B.A., Biological Sciences
(University of Delaware, USA)

2008: PhD, Marine Science (University
of California Santa Barbara, USA)

Thesis: Molecular level structure-property relationships in the byssal threads of marine mussels

2008-2010: Alexander von Humboldt postdoctoral researcher, (MPI of Colloids and Interfaces, Potsdam)

Since 2010: Research Group Leader: Biochemical strategies in load-bearing natural materials

Proteins are the primary building blocks of countless biological materials ranging from spider silk and tendon collagen to hair and cornea. The organization and chemical structure of these building blocks holds important clues to the properties of the materials they compose. Using traditional biochemical and molecular biology techniques combined with those from materials science and chemistry, our group focuses on establishing fundamental relationships between the protein components of natural materials, their hierarchical organization, and the material properties and function. Once these design concepts have been “extracted”, they can be applied by polymer scientists to create biomimetic materials with enhanced properties.



Fig. 1: Marine materials such as the byssus and whelk egg capsule are adapted to be very tough. They are composed almost entirely of protein building blocks, and by understanding the biochemical structure and organization of these proteins, we gain important insights into structure-function relationships that define the materials.

Current research in the group is divided into two primary emphases: 1. Characterization of protein-based biological materials from marine organisms 2. Biochemical investigations of biomolecules with a specific focus on metal-binding proteins. These two foci are separate but complementary aspects of the group, both of which are aimed at understanding the biochemical and structural factors that provide interesting material properties such as underwater adhesion, increased toughness and self-repair.

Characterization of Marine Materials

One prominent aspect of our research is the characterization of structure-function relationships in protein-based materials produced by marine organisms, with a specific focus on those with high toughness or self-repair behaviors. Along these lines, two projects in the group that saw significant advances in the last two years were structural and spectroscopic analyses of mussel byssal threads and whelk egg capsules.

Role of Elastic Framework in Byssus Self-Healing

Mussel byssal threads are protein-based fibers used by mussels to create a strong attachment in wave-swept marine environments. Byssal threads possess notable mechanical properties, including a combination of high stiffness and extensibility that leads to high toughness and the ability to self-heal. *Stefanie Krauß* (former postdoc) has carried out a project to look at *in situ* structural changes in the structural order of the protein building blocks of mussel byssal threads during stretching and subsequent self-healing [1]. Our results indicate that the protein making up byssal threads are highly organized axially and laterally into an ordered elastic framework. When stretched, this order is largely lost; however, it recovers elastically almost instantaneously when unloaded. Structural recovery, however, does not lead to mechanical recovery, which requires much longer time scales. The major conclusion was that the structural order facilitates mechanical healing by bringing sacrificially ruptured cross-links back into spatial register so that they can re-form. The results of this study offer potential inspiration for the development of a new generation of self-healing polymers (currently most are isotropic). Current research in the group by *Clemens Schmitt* is focused on spectroscopically characterizing the sacrificial cross-links, which are believed to be coordination bonds between the byssal proteins and metal ions, such as Zn^{2+} and Cu^{2+} .

Marine Egg Capsules: Pseudoelastic Bio-Fibers

Whelks are marine prosobranch gastropods that lay their eggs in protective capsules. The protein-based material that makes up the whelk egg capsule (WEC) has been recently recognized for exhibiting a very remarkable mechanical behavior called pseudoelasticity. This means that when the material is deformed it dissipates large quantities of mechanical energy as hysteresis; however, like an elastic material, it returns instantaneously to its initial length and structure. It is capable of numerous loading cycles without exhibiting fatigue, and in doing so, can dissipate large amounts of mechanical energy from crashing waves or attacking predators.

In this study, performed in collaboration with researchers from the US, UK and Austria, the structural and chemical changes of the component protein building blocks were assessed at various levels of hierarchy using a combination of *in situ* wide-angle and small-angle X-ray scattering and Raman spectroscopy while simultaneously performing mechanical tensile experiments [2]. From these experiments, we gained important insights into the molecular level mechanisms of pseudoelasticity in the WEC, including the observa-

tion of a critical phase transition between an ordered α -helical protein structure and a disordered protein structure during the yield plateau. Based on these results, we created a simplified mathematical model to describe the equilibrium mechanical behavior of the WEC centered on a molecular phase transition. Further modeling efforts are underway with *Peter Fratzl* and *Dieter Fischer* to help explain the non-equilibrium behavior including strain-rate dependence and hysteresis. Additionally, we are collaborating with *Ali Miserez* (NTSU) in a comparative approach examining the structure and mechanical behaviors of WEC from different species.

Characterization of Biological Building Blocks

The other main focus in our group is the characterization of proteins that compose biological materials in order to develop a more biochemical understanding of how protein sequence, conformation and cross-linking affect material properties, such as underwater adhesion and self-repair. Along these lines, a major focus is the use of protein-metal coordination cross-links by organisms to tune mechanical properties.

Mussel Adhesive Proteins

The adhesive prowess of the mussel byssus under conditions where man-made adhesive simply fail is well known in the literature; however, surprisingly, there is only a cursory understanding of the mechanisms of adhesion at the molecular level. In collaboration with *Dong Soo Hwang* (UCSB), we combined mechanical measurements of adhesion by mussel proteins using a surface force apparatus (SFA) with spectroscopic characterization of the interaction at the adhesive interface using confocal Raman spectroscopy. It was demonstrated that adhesion on TiO_2 surfaces by mussel foot protein-1 (MFP-1) depends largely on the bidentate coordination of the Ti ion by the oxygen atoms on the DOPA catechol ring (**Fig. 2**). TiO_2 is a well known alloy used in biomedical applications and this strong attachment occurred in the presence of a salty buffered solution, demonstrating the potential of mussel inspired chemistry for biomedical applications, such as dental adhesives and coatings for biomedical implants.

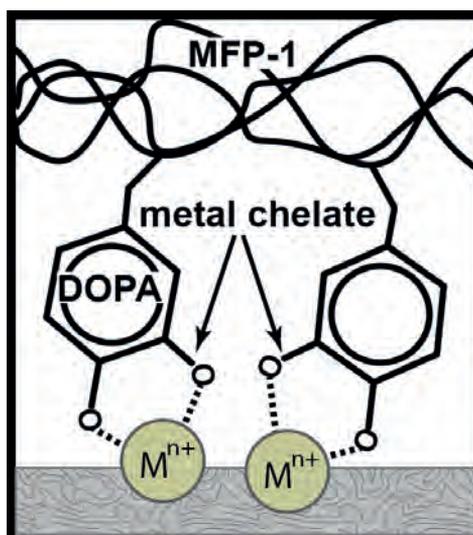


Fig. 2: Marine mussels make prodigious use of DOPA in roles such as adhesion, hardening, and self-repair. Experiments on DOPA containing proteins and polymers indicate that much of this behavior arises from the ability of DOPA to form stable coordination bonds with metal ions such as Fe, V, and Ti.

Mussel Inspired Biomimetic Polymers

In collaboration with *Niels Holten-Andersen* (MIT) continued efforts to create polymers that utilize the DOPA-metal coordination cross-link chemistry of the mussel byssus are underway. Initial efforts produced a PEG-DOPA based hydrogel that demonstrated tough and self-healing behaviors dependent on metal cross-links [4]. Currently, we are exploring the effect of metal ion and pH-dependence on the degree of cross-linking and mechanical performance. Apparently, these factors provide a convenient method for mechanical tunability of hydrogels.

*M. Harrington, E. Degtyar, G. Milliron, A. Reinecke, S. Schmidt, C. Schmitt and J. Steffen
matt.harrington@mpikg.mpg.de*

References:

- [1] Krauss, S., Metzger, H., Fratzl, P., and Harrington, M.J. Self-repair of a biological fiber guided by an ordered elastic framework. *Biomacromolecules*, Accepted (2013).
- [2] Harrington, M. J., Wasko, S.S., Masic, A., Gupta, H.S., Fischer, F.D., and Fratzl, P. Pseudoelastic behavior of a natural elastomeric proteinaceous material is achieved via reversible changes in backbone conformation. *Journal of the Royal Society Interface* **9**, 2911-2922 (2012).
- [3] Hwang, D.S., Harrington, M.J., Lu, Q., Masic, A., Zeng, H. and Waite, J.H. Mussel foot protein-1 (mcfp-1) interaction with titania surfaces. *Journal of Materials Chemistry* **22**, 15530-15533 (2012).
- [4] Holten-Andersen, N., Harrington, M.J., Birkedal, H., Lee, B.P., Messersmith, P.B., Lee, K.Y.C. and Waite, J.H. Mussel-inspired metal-ligand cross-links yield polymer gels with near covalent elastic moduli and self-healing properties. *Proceedings of the National Academy of Science, U.S.A.* **108**, 2651-2655 (2011).

Biological Chitin-Based Tools and Sensors



Yael Politi 10.9.1976

1999-2001: Bachelor of Science majoring in Biology (with Honours) (Tel Aviv University, Tel Aviv, Israel)

2002-2004: MSc. Thesis: Transient amorphous calcium carbonate in sea urchin skeleton. (Weizmann Institute of Science, Rehovot, Israel)

2005-2009: Doctoral Thesis: The formation of transient amorphous calcium carbonate in biomineralization and its transformation into calcite. (Weizmann Institute of Science, Rehovot, Israel)

2009-2012: Postdoctoral Scientist Department of Biomaterials, Max Planck Institute of Colloids and Interfaces.

2009: Alexander von Humboldt Fellow

Since 07/2012: Research Group Leader, Department of Biomaterials, Max Planck Institute of Colloids and Interfaces

After cellulose chitin is the second most abundant natural bio-macromolecule. For example, it forms the cell walls of fungi, plays major roles in the mollusc skeletal and mouth parts, and is the main building block of all arthropod cuticles. It is therefore possible to find biological chitin based materials with extremely wide range of physical, and in particular, mechanical properties. Due to its widespread abundance and biocompatibility chitin is also extensively used in diverse industrial processes and has found various technological and medical applications [1]. The study of chitin and chitin based materials therefore holds a promise for clever bio-inspired materials design.

The cuticle of arthropods is an example for such a family of materials. The large diversity seen in the arthropod phylum is also reflected in an ample diversity of cuticular materials with different physical properties that serve many different biological functions forming the external skeleton, skin, sense organs and more. The cuticle can be described as a fiber reinforced composite material, where -chitin crystallites tightly coated by a protein shell form the fibrous phase and the matrix is composed of a wide range of proteins [1].

The main goals of our newly formed group is to obtain basic understanding of the cuticular material on the one hand and to gain insight into the structure-function relations in specific functional organs such as cuticular tools (e.g. fangs, claws) and mechanosensors, on the other hand; We work in close collaboration with *Prof. Friedrich Barth*, from the University of Vienna (Vienna, Austria) *Prof. Vladimir Tsukruk* from Georgia Institute of Technology (Atlanta, USA) and *Prof. Leeor Kronik* from the Weizmann Institute of Science (Rehovot, Israel).

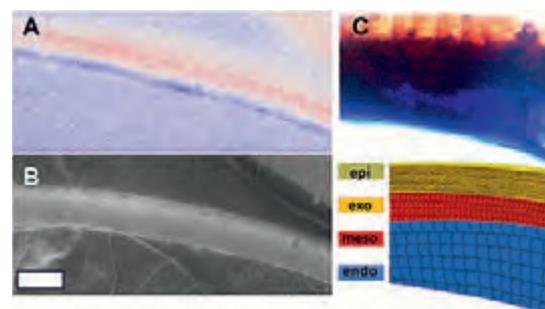
The current members of the group are *Dr. Clara Valverde Serrano*, *Dr. Maxim Erko*, *Dr. Osnat Younes-Metzler* and *Ms. Birgit Schonert*. In addition *Ms. Ana Licuco* and *Dr. Benny Bar-On* are expected to join the group during the coming semester.

Basic Research: Understanding of the Cuticular Material at the Molecular Level

We study the chitin-protein interaction, the cuticle interaction with water and the properties of the matrix in terms of composition, for example metal ions and halogen incorporation or mineralization (in crustaceans) and their effect on cuticle properties, and the chemical interaction between different cuticular components.

That water sorption has a strong effect on the cuticle is well documented. Maturation processes of the cuticle i.e. sclerotization involve drastic changes in cuticle hydration state, especially in the exocuticle. Cuticle dehydration often results in significant increase in the cuticle stiffness and brit-

tness. Nevertheless the exact manner in which water is adsorbed in the different cuticle layers (i.e. exo- meso- and endo-cuticle) is still unknown. Water sorption is studied by X-ray scattering, thermo-gravimetric analysis and differential scanning calorimetry and other techniques. Together with Dr. Luca Bertinetti we use a method based on Infrared Lock-In Thermography to spatially resolve and image water sorption in the main cuticular layers (Fig. 1).



*Fig. 1: water sorption in different cuticular layers. (A) Infrared lock-in thermography mapping of a cuticle section from the tibia (leg) of the spider *Cupiennius salei*. The colours in the image relate to the temperature of the sample resulting from the variable amount of water sorption at the sample surface and its energetics. Highest water sorption occurs at the endo-cuticle, however with low temperature increase (blue), whereas the exo-cuticle adsorbs less water, but with higher increase in temperature and is therefore seen blue. The meso-cuticle is white indicating intermediate level of water sorption/temperature change. (B) SEM image of the sample, scale bar = 1 μm. (C) Light microscope image of a tibia section stained with "Mallory stain" which is used to identify the cuticular layers. The epicuticle is un-stained, exo-cuticle is stained as amber, meso-cuticle: red and endo cuticle: blue. (D) a schematic representation of the cuticular layers in the tibia. Light green: epicuticle, Yellow: exo-cuticle, Red: meso-cuticle and blue: endocuticle.*

Incorporation of Metals and halogens incorporation in cuticular tools is widely used by many arthropods to enhance the cuticle mechanical properties. We have studied¹ this phenomenon in the spider's cheliceral fangs that are used to inject venom into prey. The fangs are rich in Zn, Ca and Cl with specific spatial distribution. Interestingly, the spiders' claws contain high levels of Mn ions. The manner in which these ions are incorporated is however still unclear. It is also unknown, what is the adaptive advantage of using a specific metal ion relative to another in the various tools. Amongst the various approaches we employ in this study, we take use of element-specific spectroscopy and microscopy techniques such as Zn, Ca and Mn K-edge XAS, and N K-edge EELS (in collaboration with *Dr. Eckhard Pippel*, MPI of Microstructure Physics, Halle) (Fig. 2) that allowed us to identify the Zn complexation by His residues in the fang matrix.

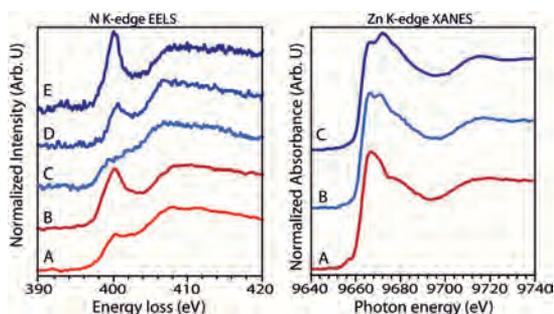


Fig. 2: Element-specific spectroscopy at the N and Zn K-edges showing the histidine-Zn complexation from the point of view of both the metal ion (Zn) and the amino acid (N in the imidazole ring). Left panel: Nitrogen K-edge Energy loss spectra of (A) the protein matrix in the spider fang where no Zn ions are detected. (B) The protein matrix in the spider fang in a Zn-rich region, the first peak, assigned to $1s \rightarrow \pi^*$ transition is enhanced by the interaction with Zn ions. (C) Spectrum of the protein insulin where most of the nitrogen atoms reside in the peptide bonds. (D) poly-histidine peptide, the two nitrogen atoms present in the imidazole ring, show increased $1s \rightarrow \pi^*$ signal, this interaction is increased with Zn complexation, as seen in (E) Poly-histidine peptide complex with Zn ions. Right panel: metal coordination from the Zn point of view by x-ray absorption spectroscopy: Zn K-edge spectrum of the (A) spider fang (B) insulin and (C) polyhistidine+Zn. The spectra series suggests that in addition to histidine, other molecules, e.g. water, may be involved in Zn coordination.

Structure Function Relations in the Cuticle

In fiber-reinforced material such as the arthropod cuticle, fiber orientation is a primary factor determining the anisotropy of the mechanical properties. In addition, lamella thickness and other structural motifs have large effect on the materials response to mechanical load. We aim at establishing direct correlation between organ morphology and chitin fiber arrangement, in terms of microstructure, fiber alignment and orientation and the spatial arrangement of different microstructural motifs within a functional organ/tool. For example, in the spider fang we have characterized various structural motifs and established gradient in mechanical properties that results from changes in degree of fiber alignment, in addition to the influence of metal ions [ref]. We use a similar approach to study the structure-function relation in the study of the spiders mechano-sensors (see below).

Mechano-Sensing in Spiders

The spider cuticle is covered by numerous cuticular-sensors that react with remarkable sensitivity and specificity to a wide range of mechanical stimuli (medium flow, substrate vibration and cuticle strain) [2]. Filtering of back-ground noise from relevant information occurs at the material/organ level which makes these structures appealing as models for the bio-inspired design of mechanoresponsive and adaptive nanostructured materials.

In order to exploit fundamental principles found in natural mechanoreceptors for bio-inspired materials, we focus on understanding the mechanism of mechanical signal detection, transmission and filtration for the spider slit biosensory system at the material level. We investigate the direct spatial correlation among cuticle morphology, hierarchical structural organization and micromechanical properties in spider slit-sensilla as well as hair like sensors (Fig. 3). We explore the time-dependent micromechanical properties of biological strain receptors embedded in the spider exoskeleton with high spatial resolution (down to a few nanometers) and relate the findings to the function of these organs as sensitive vibrational filters and efficient transmitters of external mechanical stimuli.

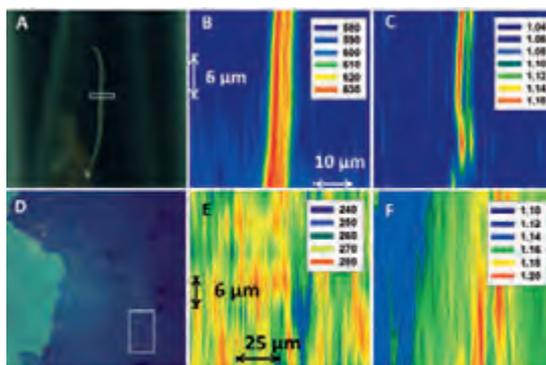


Fig. 3: XRD of two kinds of mechanosensors from the spider leg. Optical microscopy images from (A) a tactile hair and (F) the region around slit-sensilla organ. The white squares represent studied areas. (B, E) chitin scattering intensity of the corresponding regions (arb. Units). (C) and (H) show the degree of fiber orientation within a single hair and in the slit-sensilla region, respectively.

Y. Politi, C. Valverde Serrano, M. Erko, O. Younes-Metzler, B. Schonert.
politi@mpikg.mpg.de

References:

- [1] Y. Politi, M. Prieuwasser, E. Pippel, P. Zaslansky, J. Hartmann, S. Siegel, C. H. Li, F. G. Barth, and P. Fratzl, *Advanced Functional Materials* **22** (12), 2519 (2012).
[2] Peter Fratzl and Friedrich G. Barth, *Nature* **462** (7272), 442 (2009).

Advanced Raman Spectroscopic Imaging of Biological Tissues



Complex biological materials, such as bone, silk or wood, often exhibit outstanding mechanical properties, a feature that can be directly related to their functional adaptations and interactions at multiple hierarchical length scales. Raman spectroscopic imaging, a non-invasive and label-free approach to obtain both chemical (molecular interactions), and structural (orientation) information with sub-micrometer precision, is a powerful tool for the molecular level characterization of such materials.

The primary focus of our research is the *in situ* study of biological and biomimetic materials at various levels of hierarchy (from the molecular up to the macroscopic scale) taking advantage of advanced spectroscopic imaging techniques.[1-5] One of our research goals, for example, is to map collagen fibril orientation in a wide range of different tissue types by evaluating its molecular response to a polarized laser source (Fig. 1).[6]

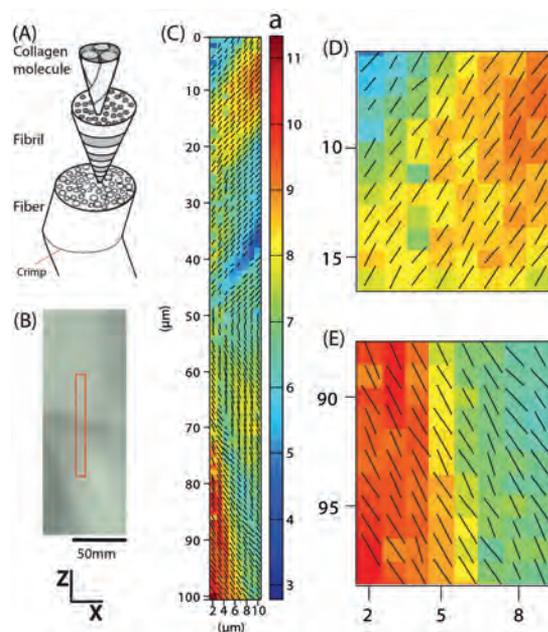


Fig. 1: Polarized Raman mapping of collagen fibril orientation in the crimp region of an un-stretched, fully hydrated rat tail tendon. The hierarchical structure of collagen (A), an optical microscopy image of the crimp region (B) and its corresponding collagen orientation map (C) with magnified regions of interest (D and E). For further details see ref. [6].

We are currently applying this methodology to map both the three-dimensional orientation of collagen in biological materials and the evolution of collagen organization in hard and soft tissues formed in the fracture gap (callus) during the process of bone healing in rats (with J. Dunlop, Biomaterials, and G. Duda, Charité Hospital Berlin).

The ultimate aim of our work is to link the structural organization and chemical composition to the physical properties of biological material.[3, 6-9] One such example is a collaboration with B. Aichmayer (Biomaterials) and A. Berman (Ben-Gurion University, Israel), where we used Raman spectroscopic imaging to study the chemical composition and microstructure of the ultra-tough and damage tolerant teeth from the freshwater crayfish, *Cherax quadricarinatus* (Fig. 2).

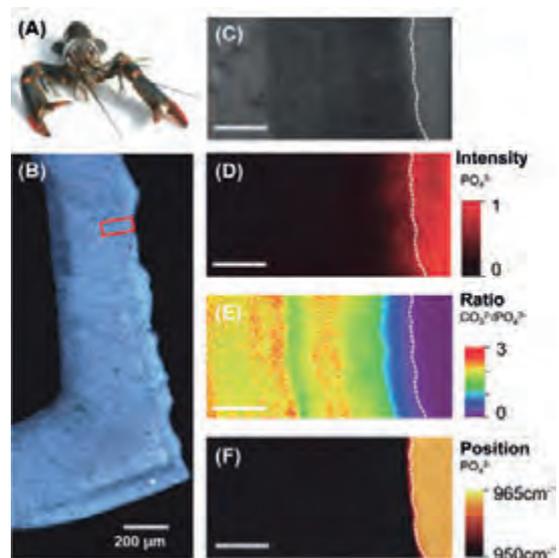


Fig. 2: Raman imaging of the crayfish (A) anterior molar. Light micrographs (B and C) of the analyzed area which covers the transition zone between the apatite and the amorphous mineral phase (indicated by the red rectangle in (B)). Raman imaging of the phosphate distribution (D), carbonate to phosphate intensity ratio (E), and the phosphate peak position (F). For details see ref. [9].

Our results reveal that the crayfish molar is a highly complex, periodically renewable organ, in which a unique architecture of amorphous and crystalline calcium carbonate and phosphate minerals constitutes a tool with mechanical properties comparable to those exhibited by mammalian teeth.

In addition to our work with high performance biological materials, and in collaboration with Federal Institute for Materials Research and Testing (BAM, I. Rabin), Helmholtz-Zentrum Berlin (HZB, U. Schade), and the University of Torino (R. Gobetto), we have also applied these techniques to the investigation of ancient historical manuscripts. For example, by combining polarized Raman, far infrared, and nuclear magnetic resonance spectroscopy techniques we have been able to directly investigate, in unprecedented detail, the changes in collagen structure during the deterioration of the Dead Sea Scrolls.[11]

A. Masic, M. Fechner, L. Galvis, B.E. Pinchasik, R. Schütz.
 admir.masic@mpikg.mpg.de

Admir Masic 16.06.1977
2001: M. Sc. Degree, Chemistry (University of Torino, Italy)
 Thesis title: Molecular motions of organometallic compounds included in cyclodextrins studied by means of solid state NMR
2005: PhD, Chemistry (University of Torino, Italy)
 Thesis title: Application of innovative techniques for the study of deterioration pathways within objects of cultural and artistic interest
2007: Postdoctoral scientist (University of Torino, Italy).
Since 2008: Researcher (Max Planck Institute of Colloids and Interfaces, Potsdam)

- References:**
 [1] Yashchenok, A., et al., *Small* **9** (3), 351 (2013).
 [2] Lee, K., et al., *Nature Communications* **3**, 725 (2012).
 [3] Harrington, M. J., et al., *Journal of the Royal Society Interface* **9** (76), 2911 (2012).
 [4] Bratashov, D. N., et al., *Journal of Raman Spectroscopy* **42** (10), 1901 (2011).
 [5] Schenk, A. S., et al., *Adv. Funct. Mater.* **22** (22), 4668 (2012).
 [6] Masic, A., et al., *Biomacromolecules* **12** (11), 3989 (2011).
 [7] Seto, J., et al., *PLoS ONE* **7** (10) (2012).
 [8] Ermeydan, M. A., et al., *Acs Applied Materials & Interfaces* **4** (11), 5782 (2012).
 [9] Bentov, S., et al., *Nature Communications* **3**, 839 (2012).
 [10] Bauer, F., et al., *Biomacromolecules* (2012).
 [11] Masic, A., et al., *Analytical and Bioanalytical Chemistry* **402** (4), 1551 (2012).

In-Situ Mechanical Characterization of Internal Interfaces in Biomaterials

Nature is successful in forming complex hierarchical composites with properties far superior to the properties of each constituent. The building blocks at all hierarchical levels are usually joined together by a gluing material to obtain a functional structure. Although internal interfaces between the building blocks comprise only a small volume fraction of the entire structure, mechanical properties of biomaterials are governed by their properties. In most cases, the building blocks are glued together by an organic softer phase. This interface can exhibit interpenetration of the two compounds, more than one order of magnitude change in elastic modulus, roughness, viscoelastic behavior and more. Thus, the main focus in this work is measuring the mechanical and compositional gradation across the interface between a single building block and the surrounding gluing medium, which is important for understanding the overall behaviour of the entire structure. This eventually, will have a significant impact on bio-inspired multi-scale composite material synthesis.

In order to measure gradual change of mechanical properties across an interface, we adapted a recently developed nanoscale modulus mapping technique and combined it with reverse finite element analysis [1]. The basis of the modulus mapping technique is the well-established nanoindentation instrumentation employing a Berkovich diamond tip. Thus, when measuring inside nanometric inclusions, the obtained modulus is strongly affected by the modulus of the matrix. Therefore, a detailed simulation by finite element approach is required to extrapolate the real value of the elastic moduli.

This methodology was first used to map the elastic modulus across a 35 nm thick organic layer within biosilica in a giant anchor spicule of the glass sponge *Monorhaphis chuni* [2]. *M. chuni*, is a deep sea glass sponge that belongs to the class of Hexactinellida and is among the earliest multicellular animals found as fossils. The most fascinating feature of the sponge is the giant basal spicule around which the animal is assembled. This spicule is used for anchoring the animal to the ocean's bottom and can reach up to 3 m in length and 8 mm in diameter. An organic filament, nearly 2 μm in diameter, provides the central vertical axis of the spicule with biosilica cylinders arranged in nearly concentric layers (2-10 μm wide) around it (Fig. 1a), separated by tiny organic layers (Fig. 1b).

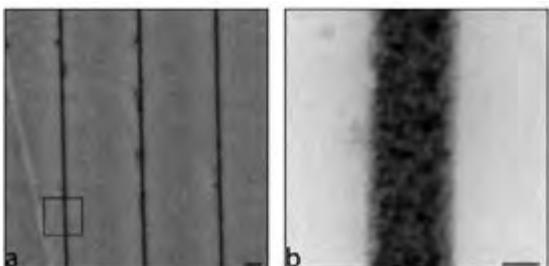


Fig. 1: (a) – SEM micrograph of the spicule cross-section (plane view) showing alternating biosilica-organic layers (scale bar is 1 μm); (b) – HAADF-STEM image of an individual organic layer (plane-view projection, scale bar is 20 nm) taken from the area indicated by a square box in (a).

After iterative simulations of the mapping procedure across the organic layer (Fig. 2a, b) we find the best fit to experimental results with modulus of 0.7 GPa in the organic layer as compared to 37 GPa in the bioglass. This indicates an impressive performance of the animal and a drastic increase of its fracture stress [3]. Furthermore, a modulus gradient extends 50 nm into the glass layer, probably due to spatial distribution of small organic inclusions (Fig. 2c).



Igor Zlotnikov 20.07.1980
1998-2003: B.Sc. in Materials Engineering, B.A. in Physics (Technion – Israel Institute of Technology, Haifa, Israel)
2003-2005: M.Sc. in Materials Engineering (Technion – Israel Institute of Technology, Haifa, Israel)
2005-2009: Ph.D. in Materials Engineering (Technion – Israel Institute of Technology, Haifa, Israel)
Since 08/2009: Postdoctoral Scientist, (Department of Biomaterials, Max Planck Institute of Colloids and Interfaces)
Since 7/2012: Independent Researcher (Department of Biomaterials, Max Planck Institute of Colloids and Interfaces, Golm, Germany)

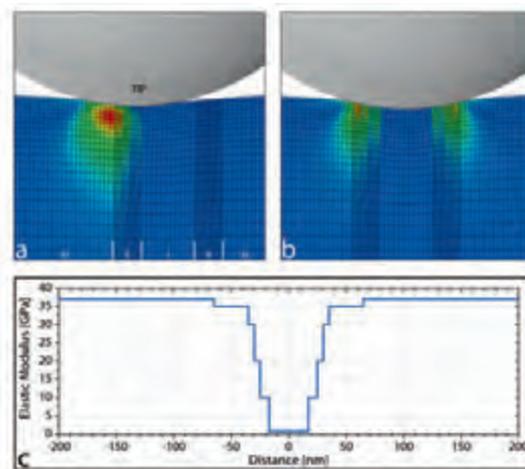


Fig. 2: (a) – a simulated Von Mises stress distribution map when the tip touches the left edge of the organic layer (I – organic layer, II – steep modulus gradient, III – biosilica); (b) – a simulated Von Mises stress distribution map when the tip touches both edges of the organic layer; (c) – resulted elastic modulus distribution across the organic layer.

With this new methodology it becomes possible to determine elastic moduli of nanometric inclusions even when embedded in a 50 times stiffer matrix. Currently, this technique is applied to investigate interface properties in other bio-structures such as the calcite/organic interface in the prismatic layer of the giant shell *Pinna nobilis* and to resolve the different ultrathin layers in the cell wall of the spruce tree *Picea abies*.

I. Zlotnikov, B. Bayerlein
 Igor.Zlotnikov@mpikg.mpg.de

References:

- [1] Zlotnikov I., Drezner H., Shilo D., Aichmayer B., Dauphin Y., Zolotoyabko E. and Fratzl P.: Mapping nanomechanical properties near internal interfaces in biological materials. *MRS Symp. Proceedings* **1345** (2011).
- [2] Woesz A., Weaver J. C., Kazanci M., Dauphin Y., Aizenberg J., Morse D. E. and Fratzl P.: Micromechanical properties of biological silica in skeletons of deep-sea sponges. *J. Mater. Res.* **21**, 2068-2078 (2006).
- [3] Fratzl P., Gupta H. S., Fischer F. D. and Kolednik O.: Hindered Crack Propagation in Materials with Periodically Varying Young's Modulus Lessons from Biological Materials. *Adv. Mater.* **19**, 2657-2661 (2007).

Mechanobiology



Richard Weinkamer 14.08.1967
1995: Diploma, Mathematics (University of Vienna)
 Thesis: The modular group: an investigation with methods of combinatorial group theory
1998: Research Stay (Rutgers University, New Jersey)
2000: PhD, Physics (University of Vienna)
 Thesis: Diffusion and diffusional phase transformations in binary alloys: Monte Carlo simulations of lattice models
2000-2003: Postdoc, (Erich Schmid Institute of Materials Science, Leoben)
Since 2003: Group Leader (Max Planck Institute of Colloids and Interfaces, Potsdam)
2012: Habilitation in Theoretical Physics (Humboldt University, Berlin) Thesis: Processes in living bone and the resulting structural changes – computational studies

Bone health is intimately linked to the processes of bone mineralization, remodeling and healing. The control of these processes occurs at the level of the cells, not only via biochemical signaling, but also via physical, in particular mechanical stimuli. Nowadays animal experiments cannot directly address cellular regulation, but are limited to the structural changes on the tissue level. Computer experiments can help bridge the gap between the cellular and the tissue level. In the computer model hypotheses about cellular regulation are implemented and the consequences for the tissue are calculated [1]. When modeling different bone processes, two aspects are important: (i) structural changes occur at very different length scales, from conformational changes of the collagen molecule to the bridging of a macroscopic bone fracture; (ii) the importance of mechanics demands not only an accurate description of the external loading, but also a characterization of the local mechanical properties of the tissues. Scanning acoustic microscopy is a promising technique to measure functional properties of biological materials in native wet conditions in a non-destructive way.

Collagen Structure, Mineralization and Remodeling

The initial stage of the mineralization process in bone is influenced by the molecular structure of collagen. This structure in turn depends on the presence of water and ions in its close environment. Together with the Theory Department we used Molecular Dynamics (MD) simulations to investigate how various collagen-like peptides change their structure, in particular their helicity, depending on ion environments containing Ca^{2+} or Na^+ . The simulations showed that the helicity

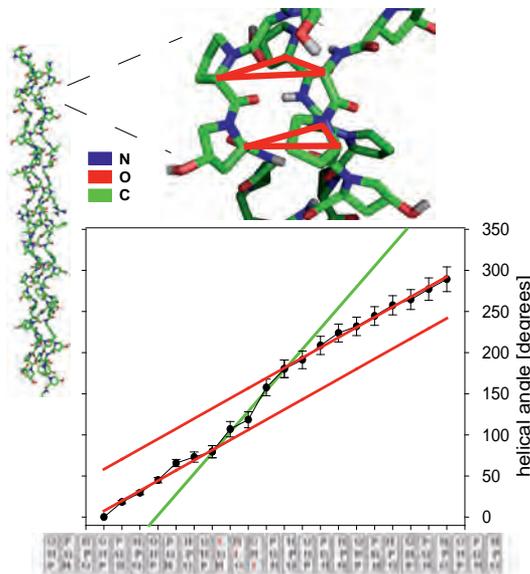


Fig. 1: Molecular model of a collagen-like peptide with 30 amino acids in an ionic environment containing Ca^{2+} . The helicity is calculated based on the triangles formed by the $C\alpha$ atoms on each chain of the triple helix (top, right). Comparing the amino acid sequence (bottom) and the helicity of the molecule, the latter is increased when leucine (L) interrupts the repetitive sequence of glycine (G), proline (P) and hydroxyproline (H).

changes with the ion concentration in regions, where the repetitive sequence of amino acids is not retained (Fig. 1).

The processes of bone mineralization and remodeling result in a patchwork structure of bone on the length scale of roughly $50 \mu m$, which can be imagined in the electron microscope using the backscattered mode (qBEI). In our mathematical description of this material heterogeneity, we corrected for the finite acquisition time during the qBEI-measurement [2]. The model can then predict the evolution of this heterogeneity in scenarios of bone diseases and medical treatment. For diagnostic purposes the discrimination between scenarios of a changed rate of bone remodeling and a disordered mineralization process is of particular importance. The spatial heterogeneity of the mineral content in bone can also be used to test current theories about the control of bone remodeling [3].

In vivo micro-computed tomography (micro-CT) opens a new possibility to monitor structural changes in the bone of living small animals. In collaboration with the ETH Zürich, we developed an evaluation method of micro-CT images to quantify the (de)mineralization kinetics in mice after deposition and before resorption of bone, respectively (Fig. 2). Measurements on mice, where the investigated vertebra was mechanically loaded, compared to the unloaded control group, indicate that loading accelerates the incorporation of mineral into the bone (Fig. 2) [4].

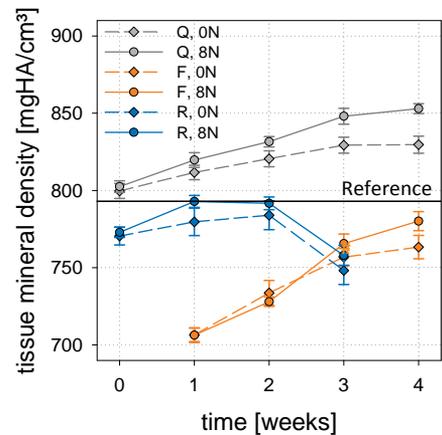


Fig. 2: Time evolution of the mean mineral content of formed (F), resorbed (R) and quiescent (Q) bone for trabecular bone loaded with 8N and unloaded control (0N). Bone was formed within the first week (therefore no data point at week 0) and resorbed within the last week (therefore no data point at week 4).

Micro-CT images of human trabecular bone of different age can also be used to learn about the control of trabecular bone remodeling. In the model the changes in the thickness of trabeculae during remodeling are described by a Markov chain. The calculated probabilities for bone deposition or resorption as a function of the thickness of the trabeculae show that the mechanical regulation of remodeling can be well described by a threshold above which bone deposition sets in [5].

In cortical bone, remodeling leads to the formation of cylindrical structures called osteons, which house a blood vessel in its central osteonal canal for nutrition supply. We quantified the order in the arrangement of osteons in the cor-

tices of horses and dogs, finding variations in the order not only between different bones of one animal, but also for different anatomical locations within the same bone. Model calculations showed that the measured order could be well understood under the assumption that osteonal canals are surrounded by an “exclusion zone”, which inhibits the formation of other canals within this zone [6], ensuring an efficient supply with nutrients.

Mechanical Heterogeneity of Bone

The heterogeneity of the mineral content as described in the last section together with the anisotropic structure of the material, results in a mechanical heterogeneity of bone. Scanning acoustic microscopy (SAM) allows measuring this heterogeneity with a lateral resolution of roughly 1 μm . The measured acoustic reflectivity from the bone surface depends on two local characteristics of the sample, the effective stiffness and the mass density. Via combination of an electron backscattered image (qBEI) containing the information about the local density and of two SAM-measurements with acoustic lenses of different resolution the effective stiffness of compact bone in a human femur was calculated. In the evaluation we separated the younger bone of an osteon formed by remodeling process from the surrounding older so-called interstitial bone (Fig. 3). The average value for the effective stiffness of the interstitial bone is more than 25% larger in the osteon, which can be largely explained by its higher mineral content. For both, osteons and interstitial bone, SAM maps show oscillations in the effective stiffness

with a wavelength of approximately 5 μm , which is the typical thickness of a bone lamella. This mechanical heterogeneity can be understood based on the anisotropic arrangement of the mineralized tissue. An evident clinical application of SAM is to complement structural images of bone biopsies with functional images of the mechanical properties to assess more directly bone quality.

Bone Regeneration and Healing

The regenerative property of bone allows healing of macroscopic defects as occurring, for example, after bone fracture. Via the transient presence of additional tissue called the callus, successful healing leads to a return to the pre-fractured state. One peculiarity of the process is that not only new bone is formed within the callus, but transiently also soft tissue like fibrous tissue and cartilage. Another peculiarity is that the reconnection of the broken bone ends does not occur “directly” via a bridging of the fracture by new bone formation. Bone healing rather occurs “indirectly” with the broken ends first reconnect outside of the fracture gap.

To address the above mentioned peculiarities of bone healing, we developed two complementary models. With the first we want to explain the spatio-temporal patterns of different tissues as observed experimentally using simple mechanobiological rules. The essence of these rules is a threshold of the mechanical stimulus, below which either cartilage or bone is formed, or bone resorption starts. The model considers the strong mechanical heterogeneity of the newly formed bone [7]. The simulated tissue patterns are compared with a succession of six images obtained from histological sections of a sheep experiment performed at the Julius Wolff Institute, Charité. Best agreement with the experiments is obtained when the volumetric strain is assumed as mechanical stimulus [8]. Intermediate stages of the healing process are strongly influenced by the stochastic influences on the control. In a separate study, the same mechanobiological rules could explain the asymmetric development of the bony callus on the inner (medial) and outer (lateral) side [9].

With the second more generic model we ask the question which factors in the local control determine, whether healing occurs directly or indirectly. The mechanical stimulus is assumed to be a combination of the local mechanical strain and the local stiffness of the material. Healing occurs when the stimulus is within a predefined window. For the case that the size of the window is strongly restricted, the simulations show that indirect healing is preferred.

R. Weinkamer, D. Fix, P. Kollmannsberger, C. Lukas, S. Pabisch, C. Pilz, F. Repp, N. Timofeeva, A. Vetter
richard.weinkamer@mpikg.mpg.de.

References:

- [1] R. Weinkamer, Habilitation Thesis, Humboldt University, Berlin (2011).
- [2] C. Lukas, P. Kollmannsberger, D. Ruffoni, P. Roschger, P. Fratzl, R. Weinkamer, The heterogeneous mineral content of bone — using stochastic arguments and simulations to overcome experimental limitations, *J. Stat. Phys.* **144**, 316-331 (2011).
- [3] M.A. Hartmann, J.W.C. Dunlop, Y.J.M. Bréchet, P. Fratzl, P. and R. Weinkamer, Trabecular bone remodeling simulated by a stochastic exchange of discrete bone packets from the surface, *J. Mech. Behav. Biomed.* **4**, 879-887 (2011).
- [4] C. Lukas; D. Ruffoni, F.L. Lambers, F.A. Schulte, G. Kuhn, P. Kollmannsberger, R. Weinkamer; R. Müller, Mineralization kinetics in murine trabecular bone quantified by time-lapsed in vivo micro-computed tomography, submitted.
- [5] M. Rusconi, A. Valleriani, J.W.C. Dunlop, J. Kurths, R. Weinkamer, Quantitative approach to the stochastics of bone remodeling, *EPL* **97**, 28009 (2012).
- [6] R. Shahar, C. Lukas, S. Papo, J.W.C. Dunlop and R. Weinkamer, Characterization of the spatial arrangement of secondary osteons in the diaphysis of equine and canine long bones, *Anat. Rec.* **294**, 1093-1102 (2011).
- [7] A. Vetter, Y. Liu, F. Witt, I. Manjubala, O. Sander, D.R. Epari, P. Fratzl, G.N. Duda, R. Weinkamer, The mechanical heterogeneity of the hard callus influences local tissue strains during bone healing: a Finite Element study based on sheep experiments, *J. Biomech.* **44**, 517-523 (2011).
- [8] A. Vetter, F. Witt, O. Sander, G.N. Duda and R. Weinkamer, The spatio-temporal arrangement of different tissues during bone healing as a result of simple mechanobiological rules, *Biomech. Model. Mechan.* **11**, 147-160 (2012).
- [9] F. Witt, A. Petersen, R. Seidel, A. Vetter, R. Weinkamer, G.N. Duda, Combined in vivo / in silico study of mechanobiological mechanisms during endochondral ossification in bone, *Ann. Biomed. Eng.* **39**, 2531-2541 (2011).

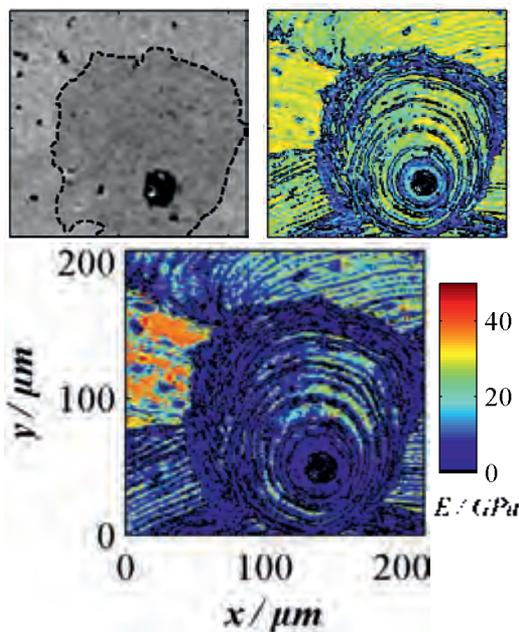


Fig. 3: Top, left: quantitative backscattered electron image (qBEI) of human cortical bone (measured by Paul Roschger, Ludwig Boltzmann Institute of Osteology, Vienna). The dashed line separates the osteon from the interstitial bone; top, right: scanning acoustic microscope (SAM) image obtained with an 820 MHz lens of the same sample region. Bottom: effective stiffness of osteons and interstitial bone as the combined result of qBEI and SAM-measurements.

Plant Material Adaptation



Plants are sessile. This means they are bound to a certain location in a given environment. To be successful under these circumstances, plants have developed sophisticated strategies which are typically reflected in the material forming the plant body. A plant is composed of different tissues which themselves consist of cells, each of them encased by a more or less rigid polymeric cell wall (**Fig. 1**).

Michaela Eder 1972

2003: Diploma in Wood Science and Technology (BOKU – University of Natural Resources and Applied Life Sciences, Vienna, Austria)

2007: Doctoral Thesis: Structure, properties and function of single wood fibres of Norway Spruce (*Picea abies* [L] Karst.) (BOKU, Vienna, Austria)

2007-2011: Postdoctoral Scientist Department of Biomaterials, Max Planck Institute of Colloids and Interfaces.

Since 09/2011: Research Group Leader, Department of Biomaterials, Max Planck Institute of Colloids and Interfaces

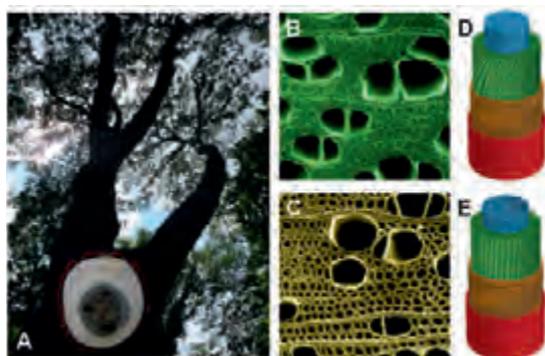


Fig. 1: Wood, an example for a plant forming material. The inserted cross section (A) shows alternating layers of earlywood and latewood (tissue) and excentric growth due to reaction wood formation. SEM images show reaction wood, here tension wood (B) and normal wood (C), cell wall cartoons depict proposed cell wall structure of (D) tension wood and (E) normal wood (black lines indicate the orientation of cellulose fibrils in the different cell wall layers).

Our research interests are plant material structure, (mechanical) properties, the function for the plant and how and/or whether the environment is reflected in the material. Selected plant systems are/will be studied in detail. In terms of applications, revealed material optimization strategies for certain functions could be used for the development of new materials. Furthermore a deeper understanding of plant based material is essential for sustainable and targeted use of the abundant resource plant material.

Plant Cell Wall Properties

Knowledge about cell wall structure is essential to understand plant material. A growing cell is surrounded by a primary cell wall which is both flexible enough to allow cell expansion and mechanically stable to resist internal and external forces. After cessation of growth, many cells form additional layers, the mechanically robust secondary cell walls. Cell walls in general can be seen as fibre-reinforced structures: stiff and strong cellulose fibrils are embedded in a more pliant hemicellulose-pectin matrix (primary cell walls) or in a hemicellulose-lignin matrix (secondary cell wall). The arrangement of the stiff cellulose fibrils determines cell wall mechanics and anisotropy to a large extent. Still, both the processes of cellulose synthesis and the arrangement of cellulose fibrils in growing cells is not fully understood yet. One outcome of the research activities on the model plant system *Arabidopsis thaliana* is the availability of numerous cell wall mutants. Structural and mechanical investigations of their dark grown hypocotyls are a promising approach to a deeper understanding of primary cell wall formation, structure and finally cell growth. However, detailed knowledge on the hypocotyl properties of wildtype plants, especially on how they change with hypocotyl growth (age) is essential.

We made structural and mechanical investigations on 4,5,6 and 7 day old dark grown hypocotyls (**Fig. 2**). The cellulose orientation in different regions along the hypocotyl was studied by a newly developed synchrotron X-ray method, the mechanical properties in the lower region of hypocotyls was determined by microtensile tests [1]. In the future these methods will be applied to study hypocotyls with targeted modification (in collaboration with *Staffan Persson*, MPIMP, Potsdam).

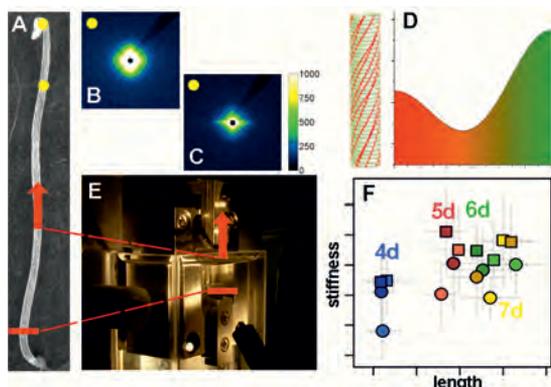


Fig. 2: Structural and mechanical studies on *Arabidopsis* hypocotyls (A), x-ray diffractograms of the apical hook (B) and ~ 5 mm below (C), diagram showing microfibril angle distribution (D). (E) lower part of a hypocotyl in the microtensile tester in liquid medium, (F) stiffness values of 4, 5, 6 and 7 day old hypocotyls, determined in the lower part of the hypocotyls.

To study the mechanically more robust secondary cell walls we apply a multitude of different methods, eg. [2,3]. An example for an interesting secondary cell wall system which we started to investigate in more detail is given below:

Plants and Fire - Storage and Protection of *Banksia* Seeds in Follicles

So-called serotinous plants are seen in some fire-prone environments. The term "serotiny" describes the trait to retain mature seeds on the plant instead of releasing them. The plant benefits from increased competitiveness after fire: a massive seed stock is released at once into the post-fire nutrient-rich soil. Prominent examples for this plant trait are species of the ancient Australian genus *Banksia*: seeds can be stored for more than 15 years in woody follicles (Fig. 3) on shrub- or tree-like plants with species-dependent triggers for opening, ranging from very high temperatures, to a combina-

tion of heat plus cyclic wetting and drying. To be a beneficial (adaptive) functional trait these follicles must meet at least two requirements (i) seed protection for long periods demanding (structural) stability against weathering, microorganisms and animals and (ii) the ability to open rapidly upon the appropriate environmental trigger or disturbance, most commonly fire.

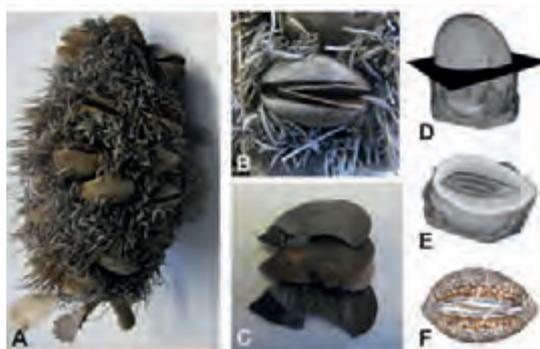


Fig. 3: *Banksia serrata*: (A) infructescence with closed and open follicles surrounded by remnant flowers; (B) open follicle with protruding separator; (C) two winged seeds and separator lying between; (D) CT scan of a closed follicle (E) cross section of CT scan showing internal follicle structure (F) unstained light micrograph of a cross section [4]

We expect sophisticated material properties of the follicles including dimensional and mechanical stability, durability and flame retardant properties. *Banksia* follicles of selected species will be studied in detail at different length scales (in collaboration with David Merritt, BGPA, Perth, Australia and Christoph Neinhuis, TU Dresden).

M. Eder, G. Bauer, M. Ermeydan, N. Horbelt, J. Huss, F. Saxe, V. Schöppler, S. Weichold, C. Weisskopf, G. Wiensköl
 Michaela.Eder@mpikg.mpg.de

References:

- [1] Saxe, F., Significance of cell wall ultrastructure for growth and mechanical properties of *Arabidopsis thaliana*, Doctoral thesis, University of Potsdam, 2012.
- [2] Eder, M., Arnould, O., Dunlop, J.W.C., Hornatowska, J., Salmén, L., Experimental mechanical characterization of wood cell walls, *Wood Sci Technol*, **47**, 163-182, (2013).
- [3] Gierlinger, N., Luss, S., König, C., Konnerth, J., Eder, M., Fratzl, P., Cellulose microfibril orientation of *Picea abies* and its variability on the micron-level determined by Raman imaging, *J Exp Bot*, **61**, 587-595 (2010).
- [4] Huss, J., Mikro- und ultrastrukturelle Charakterisierung von *Banksia serrata* Follikeln, Bachelorthesis, University of Freiburg, 2012.

Hierarchical Structure of Biological and Biomimetic Materials



Wolfgang Wagermaier 19.06.1974

2001: Diploma, Material Science (Montan-University, Leoben)

2003-2006: PhD, Material Science (MPI of Colloids and Interfaces, Potsdam and Montan-University, Leoben) Thesis: Synchrotron X-ray diffraction studies of nanoscale bone structure and deformation mechanisms

2007-2009: Postdoc, (GKSS Research Center, Center for Biomaterial Development, Teltow)

Since 2009: Group Leader (Max Planck Institute of Colloids and Interfaces, Potsdam)

References:

- [1] Wagermaier, W. and Fratzl, P.: Collagen. In: Matyjaszewski, K. and Möller, M. (eds.), *Polymer Science: A Comprehensive Reference*, Vol 9, pp. 35–55, (2012).
- [2] Kerschitzki, M., Wagermaier, W., Roschger, P., Seto, J., Shahar, R., Duda, G.N., Mundlos, S., Fratzl, P.: The organization of the osteocyte network mirrors the extracellular matrix orientation in bone. *J. Struct. Biol.*, **173**, (2), 303-311, (2011).
- [3] Kerschitzki, M., Wagermaier, W., Liu, Y., Roschger, P., Duda, G.N., Fratzl, P.: Poorly Ordered Bone as an Endogenous Scaffold for the Deposition of Highly Oriented Lamellar Tissue in Rapidly Growing Ovine Bone. *Cells Tissues Organs*, **194**, (2-4), 119-123, (2011).
- [4] Seidt, B.: Investigating material structure and mineralization processes during bone healing in Muridae osteotomy-models by X-ray scattering and electron microscopy. Diploma thesis, University of Kassel, (2012).
- [5] Cipitria, A., Lange, C., Schell, H., Wagermaier, W., Reichert, J. C., Hutmacher, D. W., Fratzl, P., Duda, G. N.: Porous scaffold architecture guides tissue formation. *Journal of Bone and Mineral Research*, **27**, (6), 1275-1288, (2012).

Many biological materials have excellent mechanical properties and they often show unique capabilities such as the ability to regenerate. Thereby the material is adapted to environmental conditions at all hierarchical levels by the activity of cells. In our group, we use specific combinations of materials science methods to answer biologically driven questions. We characterize biological materials at various levels, from the nano- to the centimeter range. In our research, bone serves as prototypical system for a hierarchically structured biological material. It can be considered as a composite material, consisting of collagen I molecules and mineral particles at the nanometer scale [1]. The research on bone is performed in cooperation with partners from the Julius Wolff Institute at the Charité in Berlin as well as the Ludwig Boltzmann Institute of Osteology in Vienna, Austria.

Furthermore, we investigate specific properties and basic formation mechanisms of synthetically produced complex materials and compare them with those of biological materials.

Our central experimental methods are X-ray scattering (SAXS, WAXS), X-ray fluorescence (XRF), polarized light microscopy (PLM), confocal laser scanning microscopy (CLSM), electron microscopy, micro-computed tomography (μ CT) and nanoindentation. For X-ray scattering experiments we use our lab sources as well as synchrotrons, in particular the MPI psport beamline at BESSY II (Helmholtz-Zentrum Berlin für Materialien und Energie, Berlin Adlershof).

Bone Formation and Healing

Bone formation takes usually place in two stages. First, a rather unorganized bone tissue (woven bone) is generated by bone-forming osteoblasts. Second, lamellar bone grows on top of the woven bone and partially replaces it. Hence, intramembranous bone formation requires an intermediate step in which bone with a lower degree of orientation serves as a substrate for osteoblasts [2]. This is followed by a cooperative action of osteoblasts resulting in the deposition of lamellar tissue. During bone formation some of the osteoblasts get embedded within the collagen matrix and differentiate thereby into osteocytes. They are then located in cavities called lacunae, and form cell processes within small tubes (canaliculi). These structures form a dense network through the entire bone matrix representing a fingerprint of bone formation, as the position of osteoblasts during the embedding can be deduced. In Fig. 1a, the osteocyte network of plexiform sheep bone shows a layer with a relatively small amount of woven bone surrounded by layers of lamellar bone. These structures can be very well visualized with CLSM [2], which enables the interpretation of the bone forming process.

A similar two-step process like in bone formation was also found during bone healing in a sheep callus [3]. To explore if this process during bone healing can be generalized we currently investigate also the material structure in small animal (rat and mouse) osteotomy models [4]. In a study on ovine bone with a critical size defect filled with a porous scaffold, we find that the scaffold architecture guides new tissue formation [5]. At first, the scaffold supports the formation of a structured

fibrous tissue across the defect. This fibrous network guides the mineralization process and consequently enables bone ingrowth into a critical-sized defect.

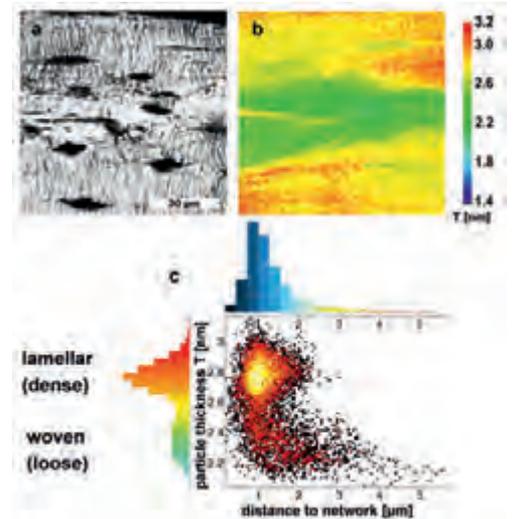


Fig. 1: Structure and properties of plexiform ovine bone. (a) CLSM image showing compact bone. Areas with a lower degree of orientation in the middle are surrounded by lamellar layers, represented by an oriented arrangement of osteocyte lacunae and canaliculi. (b) Mineral particle thickness (T -parameter in nm) from the same bone area as shown in (a); every pixel represents one measurement with small angle x-ray scattering with $1 \mu\text{m}$ resolution. (c) Correlation of mineral particle thickness (T -parameter) with the distance of these mineral particles to the cell network. The T -parameters shows a bimodal distribution in relation to the different bone areas.

The Role of Osteocytes in Bone

In bone, the physical properties of the extracellular matrix are closely correlated with cell functions. Osteocytes are known to orchestrate bone remodeling, but their precise role during mineral homeostasis and its potential impact on the quality of the bone material is not yet fully understood. To understand the interaction of the extracellular matrix with osteocytes we examined the network organization with respect to the properties of the surrounding material [6]. The osteocyte network was visualized by CLSM and characterized by topologically quantifying the distance of the bone matrix from the cell network (lacunae and canaliculi). By means of synchrotron SAXS with a $1 \mu\text{m}$ beam (ID13, ESRF, Grenoble, France) we determined the size and arrangement of mineral particles in the same bone sections. Fig. 1b shows the size (T -parameter in nm) of mineral particles in relation to the geometry of the osteocyte network. An important finding in this study was that these properties depend on the distance to the cell network (Fig. 1c). The most surprising insight was that the majority of the mineral particles reside within less than one micrometer from the nearest cell network channel. By this combination of research methods it could be shown that the osteocytes have potential access to a vast reservoir of minerals in the bone and therefore might contribute to the mineral homeostasis [6].

Mineralization in Healthy and Diseased Bone

New insights into the mineralization of bone could be achieved by applying a unique combination of quantitative X-ray scattering and fluorescence methods to fetal and postnatal mouse bone [7]. Our results revealed strong differences in size and orientation of the mineral particles between fetal and postnatal bone, with bulkier, randomly oriented particles at the fetal stage, and highly aligned, much longer particles after birth. Fig. 2 shows the amount of hydroxyapatite (HA-002-peak area) in fetal and postnatal samples measured by WAXS as a function of the calcium content determined by XRF. The correlation between HA and calcium is not linear and a linear regression of the fetal data (dashed line) reveals a calcium offset. This leads to the interesting observation that the tissue at all stages of development contains more calcium than is present in hydroxyapatite.

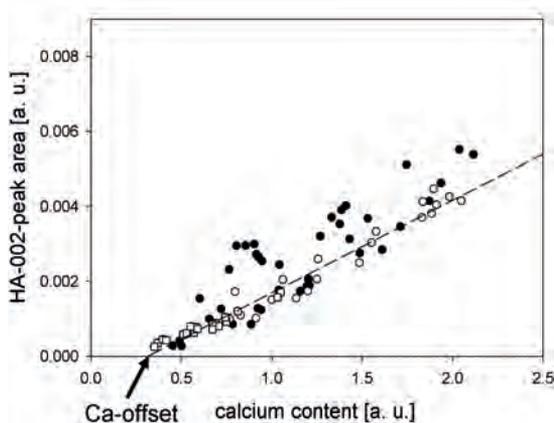


Fig. 2: Comparison of the WAXS (amount of hydroxyapatite, HA-002-peak area) and XRF (calcium content) data for two representative fetal samples, F16.5 (open squares, open circles) and one representative postnatal sample, P1 (closed circles). The plot shows the amount of hydroxyapatite (HA-002-peak area) as a function of the calcium content.

Currently we are investigating medullary bone which serves as model system for rapid bone turnover rates as it is a calcium source for daily egg shell formation in hens [8]. One of the main discoveries there is that there are three different bone types. Additionally to the two known bone types (cortical and medullary bone) a third type (termed 'nebular bone') has been discovered, which may represent an intermediate phase during mineralization. Understanding the structure of medullary bone at different points in time during egg shell formation might be a key to gain further insights into mineralization mechanisms in bone.

Osteogenesis Imperfecta (OI) is a genetic mutation resulting directly in a disturbed collagen formation and indirectly in a disordered bone with increased bone fragility, low bone mass, impaired bone material properties and unusually high bone matrix mineralization. In human bone of children, we compared the mineral crystal size in OI with a control group and found that the increase in mineral density in OI is not due to an increase in particle size, but due to an increase in the number of particles [9].

Microlens Arrays with Uniform Size and Focal Length

Biomaterialized tissues, such as sea shells and bones, grow in a genetically programmed way to obtain specific compositions and shapes, which define their unique functionalities. The growth of biominerals usually takes place in aqueous media at ambient conditions. While such natural systems and processes are usually very complex, tailor-made model systems can be used to explore basic processes. We developed a simple synthesis of unique micro-optical devices: microlens arrays [10].

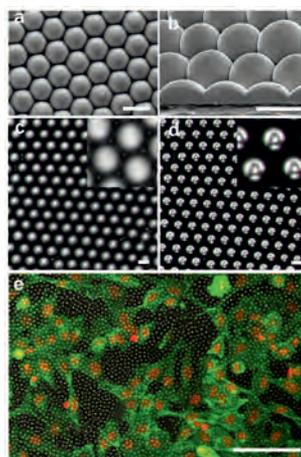


Fig. 3: Morphology and optical properties of the microlens arrays. (a) SEM image of the homogeneous and well-ordered CaCO_3 microlens array from top view. (b) SEM image of cross-sectioned microlens array from tilted view. The microlens array was etched by focused ion beam milling. (c, d) Optical microscope images of CaCO_3 microlens array and inversely projected 'A' array. The magnified images are shown in the insets. (e) Overview of NIH3T3 fibroblast cell growth on the microlens array. The actin filaments within the cells are stained in green and the nuclei in red with fluorescent dyes (overlay of fluorescent and phase contrast images). Scale bars: a-d: $5\mu\text{m}$, e: $20\mu\text{m}$

To produce these optically functional CaCO_3 structures, we used saturated calcium solution and CO_2 in air for the mineral precipitation. The formation process is regulated by an organic surfactant whose amphiphilic molecules play a crucial role at the early stage of self-assembly. Within one to two hours micrometer-sized CaCO_3 structures with hemispherical shape and uniform size are formed as a thin film on the surface of the solution (Fig. 3a and b). By means of light microscopy multiple images of a micron-sized 'A' could be projected through the array of microlenses, proving that the hemispherical CaCO_3 structures work as micron-sized convex lenses (Fig. 3c and d). In this project the biocompatibility of the CaCO_3 microlens arrays was demonstrated by seeding fibroblasts on the array (Fig. 3e). The study was performed at the Max Planck Institute of Colloids and Interfaces in Potsdam and is a joined work with KAIST in South Korea.

W. Wagermaier, G. Benecke, R. Hoerth, M. Kerschitzki, C. Lange, K. Lee, C. Li, B. Seidt, I. Schmidt, S. Siegel, T. Zander and I. Zenke, wolfgang.wagermaier@mpikg.mpg.de.

[6] Kerschitzki, M., Kollmannsberger, P., Duda, G.N., Weinkamer, R., Wagermaier, W., Fratzl, P.: Architecture of Osteocyte Communication Channels Correlates with Bone Material Quality. *Journal of Bone and Mineral Research*, accepted 2013, DOI: 10.1002/jbmr.1927.

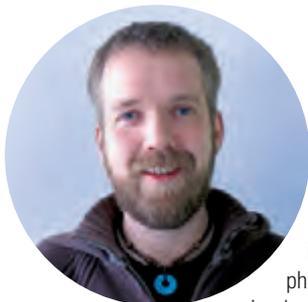
[7] Lange, C., Li, C., Manjubala, I., Wagermaier, W., Kuhnisch, J., Kolanczyk, M., Mundlos, S., Knaus, P., Fratzl, P., Fetal and postnatal mouse bone tissue contains more calcium than is present in hydroxyapatite. *Journal of Structural Biology*, 176, (2), 159-167, (2011).

[8] Zander, T.: X-ray scattering and electron microscopy studies of mineralization processes in medullary bone. Master thesis, TU Berlin, (2012).

[9] Schmidt, I.: Charakterisierung der Mineralpartikelgrößen und Mineralpartikelorientierung in Knochen von Patienten mit Osteogenesis imperfecta Typ I mittels Röntgenstreuungsmethoden. Diploma thesis, TU Berlin, (2012).

[10] Lee, K., Wagermaier, W., Masic, A., Kommareddy, K. P., Bennet, M., Manjubala, I., Lee, S. W., Park, S. B., Colfen, H., Fratzl, P.: Self-assembly of amorphous calcium carbonate microlens arrays. *Nature Communications*, 3, Art.Nr. 725, (2012).

Synthesis and Thermodynamic Stability of Amorphous Minerals



Amorphous Calcium Carbonate/ Calcium Phosphate Mixtures

Many of the most complex mineral structures found in nature are not from geological origin, but are the result of biological processes. Examples are vertebrate bones or invertebrate exoskeletons, where a mineral phase (calcium phosphate/calcium carbonate) is in close contact with an organic matrix composed of either collagen or chitin. Recent developments show indications that the mineralization of, what is initially a fully organic matrix, is governed by the attachment of spherical, sub-micron to nm-sized mineral particles that are amorphous and possibly excreted by neighboring matrix-forming cells. In most cases, this amorphous phase crystallizes in the final mineral structure, however, in some cases the amorphous nature is retained. The high stability of such amorphous biominerals against crystallization is remarkable and requires further understanding. From *in vitro* experiments we know that highly charged polymers [1], phosphorylated proteins, small organic molecules or inorganic impurities are able to delay the nucleation of a crystalline phase or even stabilize an amorphous calcium carbonate (ACC) or calcium phosphate (ACP) (Fig. 1). However, the more complex the stabilizing agent gets, the less we know about the actual mechanism. Furthermore, the influence of these agents on the local physical conditions of the reaction medium (pH, ionic strength, depletion of ions) is often underestimated, making it a tedious job to extract trustworthy mechanistic data.

To deepen the present understanding on the stability of some biomimetic amorphous minerals, in our research we are focusing on 1 special characteristic of many stable amorphous calcium carbonates, which is the presence of (large amounts of) inorganic phosphate. In line with the proposed influence of Mg^{2+} on calcium carbonate mineralization, next to a possible mismatch in charge (3+ instead of 2+) the large tetrahedral phosphate groups impose a structural mismatch with the planar CO_3^{2-} in the final crystalline calcium carbonate. The procedure we apply is to: 1) prepare amorphous calcium carbonate/calcium phosphate mixtures with various biologically relevant compositions 2) investigate the efficiency of mixing between carbonate/phosphate groups and 3) investigate the stability of the prepared amorphous material. Here, results from step 2) and 3) are used to optimize the synthesis method, thereby providing us detailed information on the conditions necessary to obtain a perfectly mixed ACC/ACP. Furthermore, by varying the ratio between ACC and ACP we can relate the stability of a certain mixture to its chemical composition. Finally, we can compare the specific ACC/ACP mixtures with their biological analogues, telling us more about the origin of their stability. In all steps of the research there is a close cooperation with the Department of Structural Biological of the Weizmann Institute (*Assaf Gal, Lia Addadi*).

Synthesis of Amorphous Minerals

Various synthesis methods for amorphous calcium carbonate and amorphous calcium phosphate have been described. Most of them rely on the formation of an instant high supersaturation with respect to the crystalline phase, thereby provoking the formation of the metastable, amorphous precursor using a simple two-pot synthesis. The extended lifetime of these materials enables the collection of a rather stable dried amorphous phase after carefully extracting the sample from the reaction solution. Using such a preparation method, initial investigation shows that an amorphous phase with chemical and physical properties in Raman-spectroscopy, X-ray diffraction and morphology (SEM), which are intermediate between ACC and ACP, is easily obtained. However, this method doesn't allow us to control the physical conditions in the reaction medium in a great extent and furthermore raises questions whether the sample collection doesn't change the structure or chemistry of the ACC/ACP mixture.

Therefore, to control and monitor crucial parameters during the formation of the ACC/ACP phase like the pH and concentration of Ca^{2+} , a titration setup will be applied [1,2]. Furthermore, in addition to analysis performed on extracted samples, analysis of the mineral phase inside the reaction medium will be performed as earlier described for the nucleation of calcium phosphates [2].

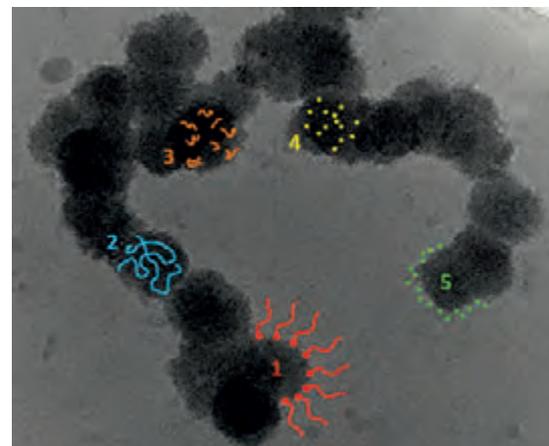


Fig. 1: Different mechanism for stabilization, 1) membrane 2) incorporated polymer/protein, 3) small incorporated molecule, 4) inorganic impurity, 5) surface counter-ion/impurity

W.J.E.M. Habraken
wouter.habraken@mpikg.mpg.de.

Wouter Habraken 04.12.1979

1998-2003: Master of Science at the Department of Chemical Engineering and Chemistry at the Eindhoven University of Technology (Eindhoven, The Netherlands).

2003-2008: Doctoral Thesis: "Development of Biodegradable Calcium Phosphate Cement for Bone Tissue Engineering" at the Radboud University Nijmegen Medical Center (Nijmegen, The Netherlands) Supervised by John .A. Jansen in cooperation with Antonios G. Mikos (Rice University, USA).

2008-2010: Postdoctoral Scientist at the Laboratory of Materials and Interface Chemistry and Soft Matter Cryo-TEM Research Unit (Nico A.J.M. Sommerdijk, Eindhoven University of Technology, Eindhoven, The Netherlands)

2010-2012: Postdoctoral Scientist at the Bio-Inspired Hybrid Materials and Synchrotron Research group (Barbara Aichmayer, Department of Biomaterials, Max Planck Institute of Colloids and Interfaces, Goltm, Germany)

Since 7/2012: Independent Researcher (Department of Biomaterials, Max Planck Institute of Colloids and Interfaces, Goltm, Germany)

References:

[1] Dmitrovic, V.; Habraken, G.J.; Hendrix, M.M.; Habraken, W.J.; Heise, A.; de With, G.; Sommerdijk, N.A. Random Poly(Amino Acid)s Synthesized by Ring Opening Polymerization as Additives in the Biomimetic Mineralization of $CaCO_3$. *Polymers* **4** 1195-1210 (2012).

[2] Habraken, W.J.E.M.; Tao, J.; Brylka, L.J.; Friedrich, H.; Bertinetti, L.; Schenk, A.S.; Verch, A.; Dmitrovic, V.; Bomans, P.H.H.; Frederik, P.M.; Laven, J.; Schoot, P. v. d.; Aichmayer, B.; de With, G.; DeYoreo, J.J.; Sommerdijk, N.A.J.M.

Ion association complexes unite classical and non-classical theories for the biomimetic nucleation of calcium phosphate, *Nature Comm.*, accepted (2012).

Water Interactions in Complex Biological Materials

Nature shows many examples of nanocomposite tissues constituted of soft materials that are reinforced by complex architectures of stiff components. Besides being tailored at the higher hierarchical levels to bear and distribute loads, these tissues are carefully designed to optimize the interactions of their molecular/macromolecular components with water to obtain desired properties/behaviors on which biological organisms rely to accomplish their vital functions. In many tissues, in fact, the chemistry of the constituents drives water absorption that, thanks to the peculiar arrangement of the macromolecular components or to their structure, results in anisotropic volume changes (swelling). This swelling and deswelling has been shown to generate complex (ametabolic) movements that are exploited in nature for different aims: swimming of the wheat awns[1], opening of pine and spruce cones[2] or plant seeds dispersal units during rain in arid regions.[3] In a similar way, swelling is responsible for growth stresses in trees to compensate for the load of branches or of side winds.[4] Biological materials act then as structure mediated, chemo-mechanical energy converter, as they are able to exploit molecular forces to generate mechanical energy.

Of particular interest for me is:

- to understand and describe molecular interactions in such complex materials,
- to set thermodynamic models able to describe the structure mediated chemomechanical energy conversion,
- to image, at the microscopic level, water sorption and water/tissues interactions in heterogeneous biological materials.

Molecular Interactions

Typically, biological materials are very complex, but they can be described as a collection of primary building blocks regularly arranged at the various hierarchical levels. Their characteristic size lies in the nanometric range and they are usually separated by few nm. Because of these reasons, a variety of interactions occur at the molecular level between the constituents of the tissues or between these latter and the solvent molecules. Typical examples are hydration forces, associated to the particular structure of water when confined to very small spaces (typically sub-nanometric) between two surfaces, Van der Waals interactions, entropic forces, H-Bonds etc... One goal of my research is to describe, starting from a chemical and structural description of the biological nanocomposites and considering the hierarchical arrangement, which of those interactions play a critical role in the hydration processes and how these forces are varying as a function of the amount of solvent taken up. Mainly my work focuses on plants tissues: in collaboration with prof. Thomas Zemb (ICSM - Marcoule), a model describing the equation of state for wood has been set, and, in collaboration with former groups (I. Burgert) and the group of John Dunlop, a chemical description of the opening of the seed dispersal units of the ice plant has been proposed.

Additionally, I study the hydration of collagen and other protein based fibers[5,6] (in collaboration with Dr. Admir Masic) and the interactions between mineral surfaces (biomimetic calcium phosphates) and water.[7]

Chemomechanical Energy Conversion

Once the molecular forces driving water sorption are described, the continuum mechanics can be used to express the changes of mechanical energy with the dimensional changes the materials undergoes when taking up solvent. In this way, using the gas/liquid or liquid/liquid phase equilibrium thermodynamics, an ab initio model predicting the equilibrium stresses/strains the structure can produce, under desired geometrical/mechanical constraints and for given changes in the chemical potential of the solvent, can be set.

At the same time, the predictions of the model are compared with *in situ* experimental data.

Water Sorption Imaging

Finally, as the natural tissues are often heterogeneous at the micro/nanometric scale, I lately started to develop, in collaboration with Dr. Breitenstein of the Max Planck Institute of Microstructure Physics in Halle, a technique based on Infrared Lock-In Thermography to spatially resolve and image water sorption sites, water sorption kinetics and possibly water/matrix binding energies in the aforementioned tissues (Fig. 1).

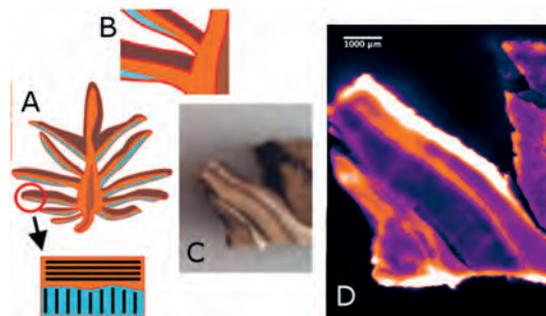


Fig. 1: Water sorption imaging: A) Sketch of a pine cone (After Ref. 2); the bottom (blue) blue layer is swelling more than the upper one. Cellulose fibres are represented in black, B) detail of the scales, C) Optical image of a typical bilayer structure, D) Corresponding water map showing the different water sorption behaviour of the bilayer structure (darker areas indicates higher sorption ability).

L. Bertinetti and P. Fratzl
bertinetti@mpikg.mpg.de.



Luca Bertinetti 03.09.1975

1994-2001: Master of Science (110/110 cum Laude) majoring in Materials Science (University of Torino, Italy)
2002-2005: Doctoral Thesis (Chemistry): Nanomaterials for biomedical applications: synthesis and surface characterization. (University of Torino, Italy)
2006-2009: Research Technician in charge of the Electron Microscopy research line of the Structural and Functional Materials Group of the IPM Department of the Torino University, Italy
Since 1/2010: Postdoctoral Scientist Department of Biomaterials, Max Planck Institute of Colloids and Interfaces.

References:

- [1] Elbaum, R., Zaltzman, L., Burgert, I. & Fratzl, P. The role of wheat awns in the seed dispersal unit. *Science* **316**, 884–886 (2007).
- [2] Dunlop, J. W. C., Weinkamer, R. & Fratzl, P. Artful interfaces within biological materials. *Materials Today* **14**, 70–78 (2011).
- [3] Harrington, M. J. et al. Origami-like unfolding of hydro-actuated ice plant seed capsules. *Nat Commun* **2**, 337 (2011).
- [4] Fratzl, P. & Barth, F. G. Biomaterial systems for mechanosensing and actuation. *Nature* **462**, 442–448 (2009).
- [5] Masic, A. et al. Observations of Multiscale, Stress-Induced Changes of Collagen Orientation in Tendon by Polarized Raman Spectroscopy. *Biomacromolecules* (2011).
- [6] Bauer, F., Bertinetti, L., Masic, A. & Scheibel, T. Dependence of mechanical properties of lacewing egg stalks on relative humidity. *Biomacromolecules* (2012).
- [7] Bolis, V. et al. Coordination chemistry of Ca sites at the surface of nano-sized hydroxyapatite: interaction with H₂O and CO. *Philos Transact A Math Phys Eng Sci* **370**, 1313–1336 (2012).

Magnetite Formation and Organization



Systematic studies of biologically formed materials have showed that they have remarkable properties. Nature thus not only provides us with inspiration for designing new materials but also teaches us how to use soft molecules such as proteins to tune interparticle and external forces to structure and assemble simple building blocks into functional entities.

Magnetotactic bacteria and their chain of magnetosomes (Fig. 1) represent a striking example of such an accomplishment where a very simple living organism precisely controls the properties of inorganics via organics and at the nanometer-scale to form a single magnetic dipole that passively orients the cell in the Earth magnetic field lines [1, 2]. In my group, we have thus developed a bio-inspired research based on magnetotactic bacteria. This research combines the recent developments of nanoscale engineering in the chemical science, the latest advances in molecular biology together with modern progresses in physical analysis. My research thus focuses at the interface between chemistry, materials science, physics, and biology to understand how biological systems synthesize, organize and use minerals, and to apply the design principles to sustainably form hierarchical materials with controlled properties that can be used e.g. as magnetically directed nanodevices towards applications in sensing, actuating, and transport.

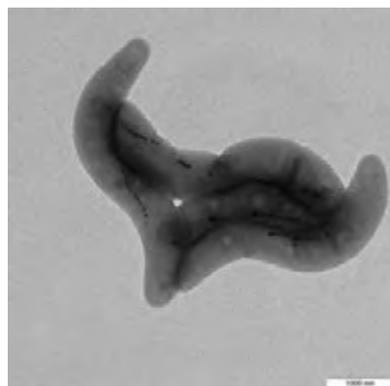


Fig. 1: a typical TEM image from magnetotactic bacteria (strain AMB-1). The magnetosomes are the electron-dense particles that are aligned and form chain in the cells. Image by A. Körnig and M. Widdrat.

Biological Materials

Magnetosomes: Hierarchy at the Structural Level

The biomineralization of the mineral magnetite inside the magnetosome organelle together with the chain formation in magnetotactic bacteria are two processes that are highly controlled at the cellular level in order to form cellular magnetic dipoles. The smallest building block in this hierarchical structure is the magnetosome crystal. However, only controversial results about its micro-structure were obtained so far, partly because of the very limited amount of materials available. Thereby, the influence of the ultrastructure in the for-

mation of the magnetic dipole i.e. on the function of the assembly is also to be specified.

We have thus investigated the structure of the magnetosomes using high-resolution synchrotron X-ray diffraction at the microspot beamline of the BESSY II synchrotron of the Helmholtz-Zentrum Berlin [3]. Significant differences in lattice parameter were identified between intracellular magnetosomes from cultured magnetotactic bacteria and isolated ones (Fig. 2). Through comparison with synthetic nanoparticles (abiotic control materials) of similar size, we showed that this difference could be associated with different oxidation states and that the biogenic magnetite was stoichiometric, i.e. structurally pure. However, as soon as the magnetosomes were isolated from the cells, oxidation took place.

We thus proposed that the hierarchical structuring of the magnetosome chain starts with the formation of structurally pure magnetite nanoparticles. In addition, this property can be directly connected with the magnetic property of the magnetosome chains where it is of advantage for the cell to form structurally pure magnetite crystals for optimal magnetic response.

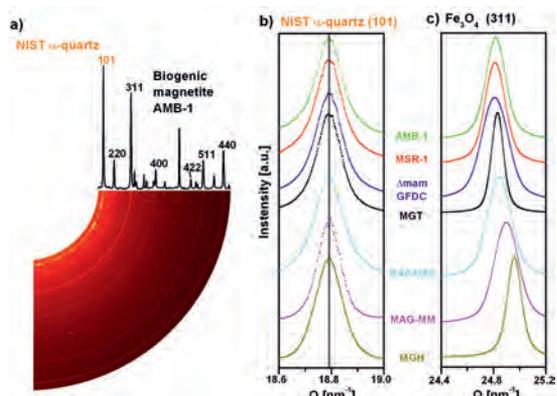


Fig. 2: a) Exemplary 90° sector of AMB-1 diffraction pattern to visualize the azimuthal integration. Analyzed magnetite peaks and calibration peak (NIST α -quartz) indexed b) α -quartz (101) calibration peaks of different biogenic and abiotic magnetite/maghemite samples. All peaks calibrated to $Q = 18.7910 \text{ nm}^{-1}$ c) most intensive (311) reflex of all analyzed samples. Remarkable peak shift between biogenic magnetite in cell solution samples (AMB-1, MSR-1 and Δ mamGFDC) compared to isolated magnetosomal magnetite with and without membrane (MAG-MM and MGT) or even more pronounced with maghemite (MGH).

Magnetosomes Chains: Hierarchy at the Chain Level

Magnetotactic bacteria benefit from their ability to form cellular magnetic dipoles by assembling stable single-domain ferromagnetic particles in chains as a means to navigate along Earth's magnetic field lines on their way to favourable habitats. After studying the smallest building-blocks, i.e. the magnetosomes and their ultrastructure, we studied their assembly by a combined experimental and theoretical approach [4, 5]. A number of genetic factors involved in the controlled assembly of these magnetosome chains have been identified in recent years, but we have addressed how the specific biological regulation is coordinated with general physical processes.

The simulations indicate that physical processes of magnetosome diffusion, guided by their magnetic interactions, are not sufficient for the chain formation observed experimentally. In turn, they suggest that biologically encoded active movements of magnetosomes may be required. Not surprisingly, the chain pattern is most resembling experimental results when both magnetic interactions and active movement are coordinated (**Fig. 3**).

In addition, we estimate that the force such active transport has to generate is compatible with forces generated by the polymerization or depolymerization of cytoskeletal filaments. The simulations suggest that the pleiotropic phenotypes of mamK deletion strains may be due to a defect in active motility of magnetosomes and that crystal formation in magnetosome vesicles is coupled to the activation of their active motility in *M. gryphiswaldense*, but not in *M. magneticum*.

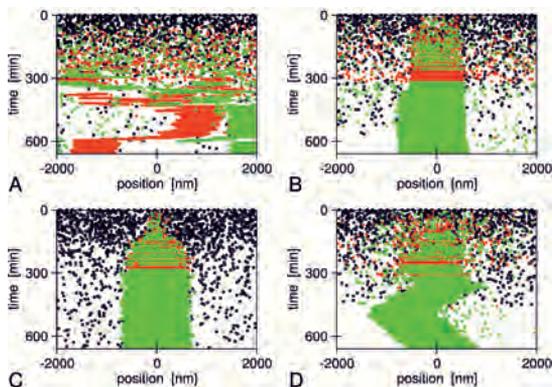


Fig. 3: Example time traces of magnetosome formation in our simulations. (A) Magnetic interactions and diffusion only, (B) binding zone in the cell center ($L_b = 1000$ nm), (C) and (D) active transport to the cell center with an active force $F_{act} = 1$ pN (C) and 0.01 pN (D). In all panels, black dots indicate empty magnetosome vesicles, green and red points indicate magnetosomes containing a crystal with plus or minus orientation of its magnetic moment. In all panels, the magnetosome mobility is given by $D = 10^5$ nm²/s. (Fig. from Klumpp and Faivre, 2012)

Biomimetic Materials

Synthetic Magnetite Nanoparticles:

Studying the Nucleation and Growth of Nanoparticles

The formation of crystalline materials from solution is typically described by the nucleation and growth theory, where atoms or molecules assemble directly in and from solution. For various systems however, the formation of the thermodynamically stable mineral is preceded by intermediate phase(s). More complex pathways have recently been proposed, such as aggregational processes of nanoparticle precursors or pre-nucleation clusters, which seem to contradict the classical theory.

Multiple synthetic routes for the production of magnetite nanoparticles have been reported in the literature. Indeed, the ferrimagnetic properties of such particles are increasingly exploited in bio- and nanotechnological applications. However, the formation mechanism has remained unclear. We have developed a set-up for the controlled growth of magnetite particle *in vitro* [6]. We can reach average particle dimension

of 50 nm (**Fig. 4**), and thereby control the magnetic properties of the particles, changing from superparamagnetic for particles smaller than 25 nm to stable single domain for particles larger than 25 nm. We are thus able to synthetically reach particle size so far only attainable by biological synthesis.

We further have studied the mechanism of such formation by cryogenic transmission electron microscopy [7]. We found out that the nucleation and the growth of magnetite proceeds through rapid agglomeration of nanometric primary particles and that no intermediate amorphous bulk precursor phase is involved. We also demonstrate that these observations can be described within the framework of classical nucleation theory.

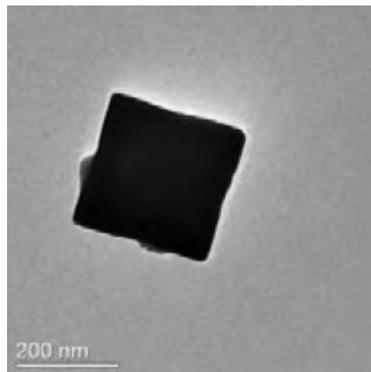


Fig. 4: TEM image of a large synthetic magnetite nanoparticle.

Biomimetic Chains:

Towards Hierarchy in a Semi-Synthetic System

Hierarchical structuring of single particles can lead to the formation of multifunctional materials. We are thus interested in the biomimetic arrangement of the magnetic particles we form *in vitro*. MamK is a filamentous Actin-like magnetosomal protein sharing significant homology with bacterial cytoskeletal proteins such as MreB and ParM. With little or no information on the structural and behavioural characteristics of MamK outside the cell, the mamK gene from *Magnetospirillum gryphiswaldense* was cloned and expressed to better understand the differences in the cytoskeletal properties with its bacterial homologues [8].

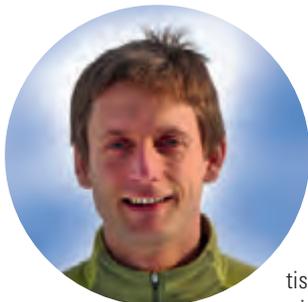
Despite the low sequence identity shared between MamK and MreB (22%) and actin (18%), the behavior of MamK monitored by light scattering broadly mirrored that of its bacterial cousin MreB. The broad size variability of MamK filaments revealed by light scattering studies was supported by transmission electron microscopy imaging. Filament morphology however, indicated that MamK conformed to linearly orientated filaments that appeared to be distinctly dissimilar compared to MreB suggesting functional differences between these homologues.

D. Faivre, J. Andert, J. Baumgartner, M. Bennet, M. A. Carillo, A. Fischer, K. Halbmaier, A. Körnig, P. Lesevic, A. Olszewska, T. Perez Gonzalez, M. Schmitz, P. Vach, M. Widdrat
faivre@mpikg.mpg.de.

References:

- [1] Perez-Gonzalez T., Bennet M., Wood D. and Faivre D., Magnetosomes, in Biological self-assembly and its applications (ed. B. H. A. Rehm), 241-272, Horizon Scientific Press, Hethersett (2012).
- [2] Körnig A., and Faivre D., Nanoparticles in magnetotactic bacteria, in Nature's Nanostructures (ed. A.S. Barnard and H. Guo), 249-271, Pan Stanford Publishing, Singapore (2012).
- [3] Fischer A., Schmitz M., Aichmayer B., Fratzl P., and Faivre D., Structural purity of magnetite nanoparticles in magnetotactic bacteria, Journal of the Royal Society Interface **8**, 1011-1018 (2011).
- [4] Charilaou M., Sahu K. K., Faivre D., Fischer A., Garcia-Rubio I., and Gehring A., Evolution of magnetic anisotropy and thermal stability during nanocrystal-chain growth, Applied Physics Letters **99**, 182504 (2012).
- [5] Klumpp S., and Faivre D., Interplay of magnetic interactions and active movements in the formation of magnetosome chains, PLoS ONE **7** (3), e33562 (2012).
- [6] Baumgartner, J., Bertinetti, L., Widdrat, M., Hirt, A. M. & Faivre, D. Formation of Magnetite Nanoparticles at Low Temperature: From Superparamagnetic to Stable Single Domain Particles. PLoS One **8**, e57070 (2013).
- [7] Baumgartner, J. et al. Nucleation and growth of magnetite from solution. Nat. Mater. **12**, 310-314 (2013).
- [8] Sonkaria S., Fuentes G., Verma C., Narang R., Khare V., Fischer A., and Faivre D., Insight into the assembly properties and functional organisation of the magnetotactic bacterial actin-like homolog MamK, PLoS ONE **7** (5), e34189 (2012).

Biomimetic Actuation and Tissue Growth



John Dunlop 06.04.1978

1996-2001:

Bachelor of Science (1st Class Honours) majoring in Chemistry Bachelor of Engineering (1st Class Honours) majoring in Materials Engineering University of Western

Australia (Perth, Australia)

2002-2005: Doctoral Thesis: Internal variable modelling of creep and recrystallisation in zirconium alloys

Institut National Polytechnique de Grenoble, Laboratoire

Thermodynamique et de Physico-chimie des Matériaux. Grenoble (France)

Since 02/2006:

Postdoctoral Scientist

Department of Biomaterials, Max Planck Institute of Colloid and Interfaces, Potsdam (Germany)

2007: Alexander von Humboldt Fellow

Since 11/2008: Research Group Leader Department of Biomaterials, Max Planck Institute of Colloids and Interfaces

Biological materials, in addition to having remarkable physical property combinations such as high toughness and stiffness, can also change shape and volume. These shape and volume changes allow organisms to form new tissue during growth and morphogenesis, as well as to repair and remodel old tissues. In addition shape or volume changes in an existing tissue can lead to useful motion or force generation (actuation) that may even still function in the dead organism. Both growth and actuation of tissues are mediated, in addition to biochemical factors, by the physical constraints of the surrounding environment and the architecture of the underlying tissue.

This research group combines experimental and theoretical methods to understand how tissue architecture and external physical constraints interact to control firstly tissue growth and secondly tissue actuation.

The work on tissue growth was done in collaboration with: *M. Rumpfer*, Ludwig Boltzmann Institute for Osteology, Vienna, *F. D. Fischer*, and *E. Gamsjäger*, Uni. Leoben, *C. Werner* and co-workers at the Max Bergmann Institute, Dresden, and *A. Petersen* and co-workers at the Julius Wolff Institute, Berlin. The work on actuation was done in collaboration with *I. Burgert*, now at the ETH - Zurich, *R. Elbaum* and *Y. Abraham*, Hebrew Uni. Jerusalem, *Y. Bréchet*, INP-Grenoble, *T. Antretter* and *G. Zickler*, Uni. Leoben, *L. Ionov* and co-workers at the Leibniz Institute of Polymer Research, Dresden.

Using Geometry to Direct Tissue Growth

Previous research in the group has shown that the shape of the surrounding environment can have a surprising influence on the rate of tissue formation [1]. 3D-printing techniques allow the production of pores with controlled surface geometries which can then be tested in tissue culture. The experimentally measured growth rates were shown to be proportional to the local surface curvature, meaning that despite the cells small size, collectively cells can measure geometries at length scales much larger than themselves. These observations can be readily implemented in a simple 2D computer model for curvature driven growth [2,3], and give excellent predictions for the position of the tissue interface as a function of time (Fig. 1). Furthermore this model was also used to determine optimal pore shapes for tissue engineering applications [3].

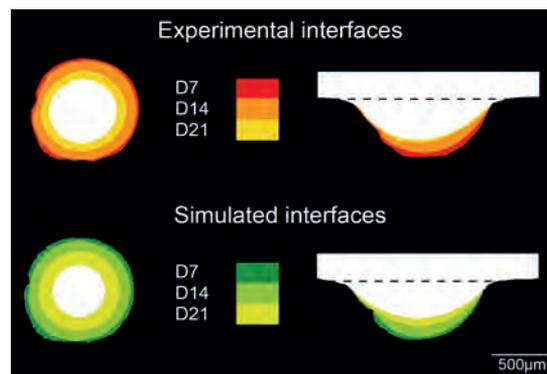


Fig. 1: Comparison between experimentally measured interfaces and predicted interfaces as a function of time in circular pores and semi-circular channels [2].

Despite the success of this simple geometric model in describing growth, it is difficult to directly link to it the mechanisms responsible for growth at the cellular scale. It seems likely that mechanical stresses developed by the cells themselves are responsible for the tissue patterning observed [1]. Inspired by the observation of high contractile stresses in the tissue surface, we have also been developing, together with *E. Gamsjäger* and *F. D. Fischer* (Uni. Leoben), a more complex model for tissue growth. This model takes into account both the stresses induced by confined growth as well as the stress induced by a contractile layer of cells on the surface [4], and is successful in describing the asymmetric response of cells to the sign of curvature.

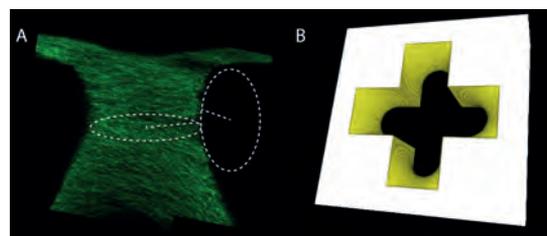


Fig. 2: A) An oblique view of the 3D actin architecture of tissue formed in the corner of a pore. The circles highlight the double curvature produced during growth. B) Result of the 3D curvature driven growth simulation in a cross-shaped pore.

The 3D nature of the tissue formed in the scaffolds has up till now been neglected, as the pores studied up till now have straight sides (they are prismatic), meaning one of the principle curvatures of the starting interface is always zero. 3D imaging methods, as illustrated in (Fig. 2A), show that due to growth the tissue develops a double curvature, with positive and negative mean curvatures, which may in turn influence

the overall curvature driven growth. As such the 2D geometric model has been extended to 3D (Fig. 2B). In this model, much akin to the Laplace law, the mean surface curvature is taken as the driving force for growth.

Using Geometry to Direct Actuation

Plants move their organs during their lifetime via active biological processes such as differential growth, or active changes in osmotic pressure exemplified by the fast closing of the Venus-fly trap. In addition to this some organs may also move after death due to the swelling of tissues upon hydration/dehydration. Such hygroscopic actuation is controlled solely by the clever arrangement of swellable and non-swellable tissues, and in principle can be readily copied by the Engineer. Many examples of such pre-programmed shape changes can be found in structures related to seed-propagation, such as in the awns of many seeds, or in the opening mechanisms of a variety of seed capsules (See also the work being done on *Banksia* in the Plant Adaptation group of *M. Eder*). The twisting/untwisting movement of the awns of *Erodium gruinum* for example [5] propel the seeds along and into the ground. This is controlled by the complex arrangement of tilted spirals cellulose microfibrils inside the cell walls. Similarly the awns of wheat also move upon humidity changes, with the rapid response to humidity changes thought to be accelerated by swelling induced pore opening [6]. The opening of the ice-plant seed capsule was studied by *M. Harrington* and *I. Burgert* [7], and was shown to be controlled by hygroscopic keels consisting of diamond-honeycombs filled with a swellable cellulose-like gel (Fig. 3A). Such a honeycomb like structure converts the isotropic swelling into a strongly anisotropic response, which may be interesting in the design of artificial actuators.

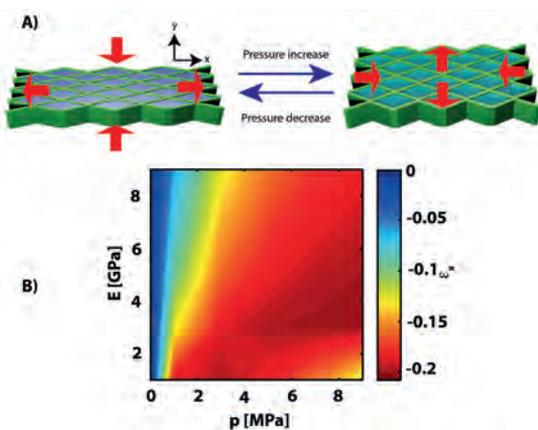


Fig. 3: A) Schematic of swelling of a diamond-honeycomb upon pressure changes in the cells, akin to what is observed in the ice-plant [7]. B) Simulated actuation strains in a diamond honeycomb as a function of pressure and cell-wall modulus.

Surprisingly despite the simplicity of such a pressurised honeycomb, very little work has been done on modelling its mechanical properties. By combining Finite Element (FE) methods with micromechanical modelling it is possible to develop maps of actuation response as a function of actuation pressure, material properties and architecture (Fig. 3B). Further work is underway together with *J. Weaver* (Wyss Institute, Boston) to produce working mechanical prototypes of these systems using the latest generation multi-material 3D printer. Initial testing has begun on linear structures with extrude-able cross-sections simulated previously [8].



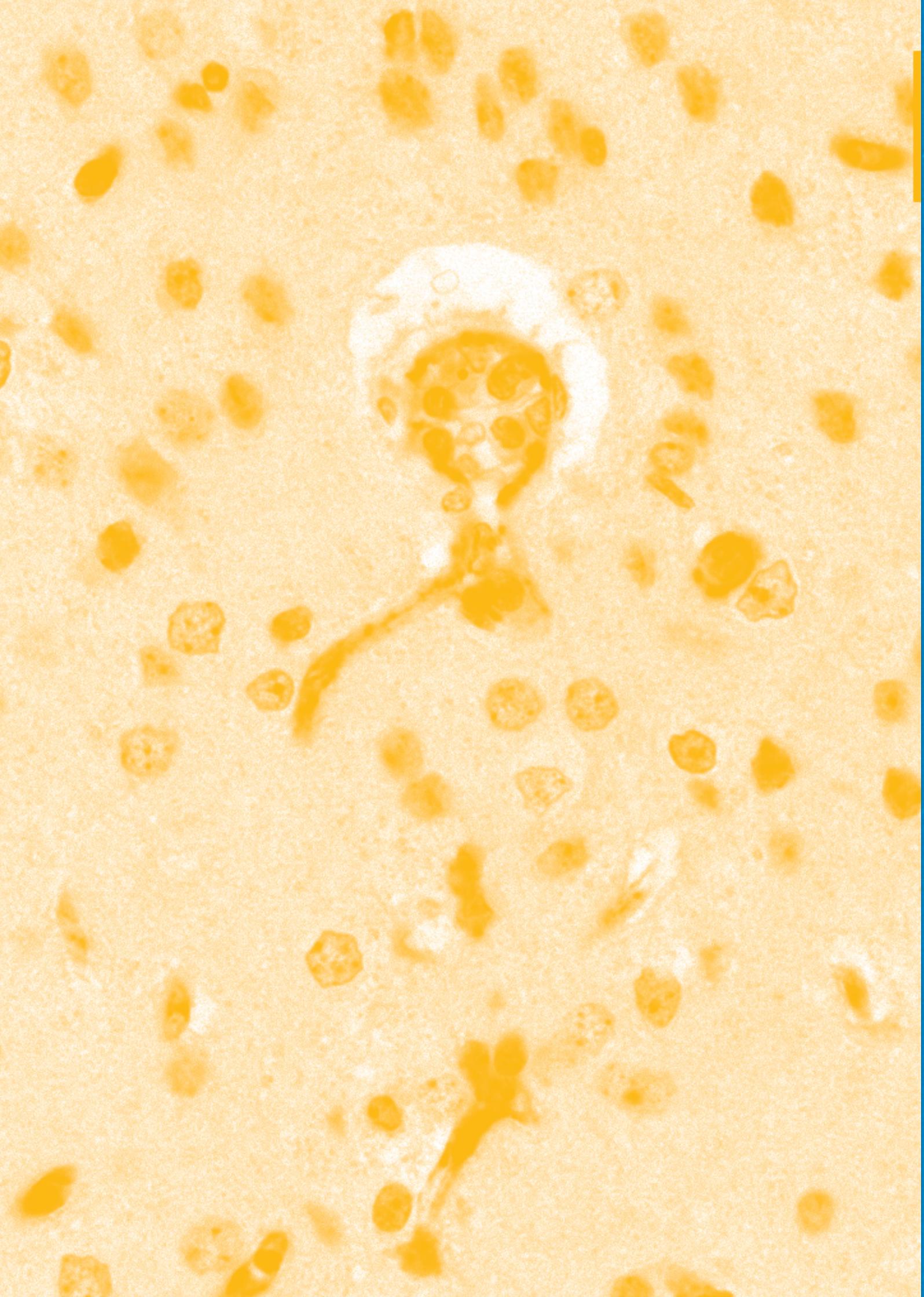
Fig. 4: Simulated rolling and folding of three actuating bilayers with different aspect ratios attached to a partially adherent substrate [9].

Despite their apparent simplicity, bilayer structures can produce quite complex motion [9,10], depending on their shape. In a collaboration with the experimental group of *L. Ionov* (Leibniz Institute, Dresden) we have been using FE simulations to understand the role of external shape on how active polymeric bilayers attached to a substrate unpeel and fold. (Fig. 4) illustrates some examples of simulations carried out on layers with different aspect ratios. This illustrates the competition in all-side rolling observed in low aspect ratio systems compared to the one side rolling seen in more elongated structures. One surprising output of the model was the prediction of wrinkling in early stages of rolling that was subsequently confirmed in the experiments. More recent experiments by the Dresden group on star-like shapes led to the development of a set of simple design rules for folding [10], supported by our mechanical simulations. Further work needs to be done to address the problems of kinetics, or the rate of shape change and to include these effects in our models.

J. Dunlop, *C. Bidan*, *A. Bornmüller*, *L. Galvis*, *V. Gering*, *L. Guiducci*, *P. Kollmannsberger*, *K. Kommarreddy*, *P. Leibner*, *J. Panichpakdee*, *S. Turcaud*, *F. Wang*.
dunlop@mpikg.mpg.de

References:

- [1] Kollmannsberger, P., Bidan, C. M., Dunlop, J. W. C., Fratzl, P. The physics of tissue patterning and extracellular matrix organisation: How cells join forces, *Soft Matter*, **7**, 9549-9560, (2011).
- [2] Bidan C.M., Kommareddy K.P., Rumppler M., Kollmannsberger P., Bréchet Y., Fratzl P., Dunlop J.W.C., How Linear Tension Converts to Curvature: Geometric Control of Bone Tissue Growth, *PLoS ONE*, **7**(5): e36336, (2012).
- [3] Bidan C.M., Kommareddy K.P., Rumppler M., Kollmannsberger P., Fratzl P., Dunlop J.W.C. Geometry as a factor for tissue growth: Towards shape optimization of tissue engineering scaffolds, *Adv. Healthcare Mater.*, **2**, 186-194, (2013).
- [4] Gamsjäger, E., Bidan, C. M., Fischer, F.D., Fratzl P., Dunlop, J.W.C., Modelling the role of surface stress on the kinetics of tissue growth in confined geometries, *Acta Biomater.*, DOI: **10.1016/j.actbio**. 2012.10.020, (2012)
- [5] Abraham, Y., Tamburu, C., Klein, E., Dunlop, J. W. C., Fratzl, P., Raviv, U., Elbaum, R., Hygroscopic coiling movement from a single layer is created by a tilted cellulose arrangement in stork's bill awns, *J. Roy. Soc. Int.*, **9** 640-647, (2012).
- [6] Zickler, G. A., Ruffoni, D., Dunlop, J. W. C., Elbaum, R., Weinkamer, R., Fratzl, P., Antretter, T., Finite element modeling of the cyclic wetting mechanism in the active part of wheat awns, *Biointerphases*, **7**, 42, (2012).
- [7] Harrington, M. J., Razghandi, K., Ditsch, F., Guiducci, L., Rueggeberg, M., Dunlop J. W. C., Fratzl, P., Neinhuis, C., and Burgert, I., Origami-like unfolding of hydro-actuated ice plant seed capsules, *Nature Comm.*, **2011**, **2**, 337, (2011).
- [8] Turcaud, S., Guiducci, L., Fratzl, P., Bréchet, Y. J. M., Dunlop, J. W. C., An excursion into the design space of biomimetic architected biphasic actuators, *Int. J Mater Res.* **102**, 607-612 (2011).
- [9] Stoychev, G., Zakharchenko, S., Turcaud, S., Dunlop, J. W. C., Ionov, L., Shape programmed folding of stimuli-responsive polymer bilayers, *ACS Nano*, **6**, 3925-2934, (2012).
- [10] Stoychev, G., Turcaud, S., Dunlop, J.W.C., Ionov, L., Hierarchical multi-step folding of polymer bilayers, *Adv. Func. Mater.*, DOI: **10.1002/adfm**. 201203245, (2012).



- Carbohydrate Synthesis
- Host Microbe Interactions
- (GPIs) and Glycoproteins
- Biomolecular Systems
- Precision Polymers and Polymeric Biomimetics
- Glycoimmunology
- Structural Glycobiology
- Glycoproteomics

BIOMOLECULAR SYSTEMS



Research in the Department of Biomolecular Systems



Peter H. Seeberger 14.11.1966
1989: Vordiplom
(Univ. Erlangen-Nürnberg)
1995: PhD, Biochemistry
(University of Colorado, Boulder)
1995-1997: Research Fellow
(Memorial Sloan-Kettering
Cancer Center)
1998-2003: Assistant and Associate
Professor (Massachusetts Institute of
Technology, MIT, Cambridge, USA)
2003-2009: Professor
(Swiss Federal Institute of Technology
(ETH) Zurich, Switzerland)
Since 2003: Affiliate Professor
(The Burnham Institute for Medical
Research, La Jolla, USA)
Since 2009: Director, Department of
Biomolecular Systems (Max Planck
Institute of Colloids and Interfaces)

The Department for Biomolecular Systems conducts research at the **interface of chemistry, engineering, biology, immunology and medicine**. The approach is trans-disciplinary and interactive between the groups in the department that cover different areas of expertise. The core focus is the development of **synthetic methods** for the chemical synthesis of defined oligosaccharides. The compounds are the basis for **chemical tools** that aided **biochemical investigations** into the fundamental roles complex carbohydrates play in biological processes that underlie disease. The findings helped create diagnostic carbohydrate arrays to begin to understand **immunological aspects** of infectious disease epidemiology. **Vaccine development** of several glycoconjugate vaccine candidates is rapidly advancing towards clinical trials. In the past four years the Department has developed by the addition of several new groups following the move from ETH Zurich in 2009. Glycan sequencing and glycomics (Dr. Kolarich) helps to identify glycans of biological importance particularly on interfaces of the human body – skin and intestine. The role of glycans is assessed (Dr. Lepenies, glycoimmunology) using particularly animal models of infectious diseases (glycobiology and vaccinology (Dr. Anish). We are actively pursuing different questions in the glycosciences including the structure, function and biological role of sugars found on the surface of mammalian and bacterial cells particularly in the areas of immunology, biochemistry and human disease.

Materials aspects related to carbohydrates are continuing to be pursued in the department. The Emmy-Noether group of Dr. Hartmann is producing well-defined polymers and collaborates closely with the glycoimmunologists to assess the *in vivo* activity of complex synthetic molecules. Our increased interest in establishing structure-function correlations of glycans is expressed by the addition of the Emmy-Noether group of Dr. C. Rademacher in 2012. This group is concerned with questions relating to structural immunology and as such forms a bridge between the synthetic chemists, glycobiologists and glycoimmunologists. The increasing importance of continuous-flow synthesis has been addressed by adding a new member of the Department, Prof. Dr. T. McQuade an expert in this area who joined us in May 2012.

The department is engaged in collaborations with the Colloid Department concerning the synthesis of colloidal polymers and supported catalysts. Many other applications of the flow paradigm from organic to nanoparticle synthesis and polymer chemistry are currently progressing rapidly.

Automated Synthesis of Carbohydrates

Since our arrival at the institute, we have expanded the scope of our core technology – the automated oligosaccharide synthesizer. After streamlining the process and inventing new linkers as well as a set of “approved” building blocks, the first demonstrator model of a new synthesizer has been completed. This new synthesizer is entering service in early 2013. Thus, the Department is closing in on the ultimate goal of creating a commercially available instrument that uses a defined set of monosaccharide building blocks to assemble most oligosaccharides reliably.

Automated synthesis has allowed us to set a new world record by assembling a 30-mer oligosaccharide. After more than ten years of work, the automated synthesis of glycosaminoglycans has become possible. Currently, different members of this class of biologically extremely important oligosaccharides such as chondroitin sulfate heparin open completely new areas for biology but also material sciences.

Synthetic Tools for Glycobiology

Access to synthetic oligosaccharides has given rise to tools such as glycan microarrays, glycan nanoparticles, glycan dendrimers and glycans on polymers and fibers as well as inorganic materials such as quantum dots and zeolites. These tools are now commonly used by the glycobiologists in the department to elucidate fundamental processes such as the entry mechanism of parasites into host cells.

Synthetic Carbohydrate Vaccines

We have established a comprehensive program targeting the development of fully synthetic carbohydrate vaccines. Our commitment is evidenced by the addition of an additional group leader (Dr. C. Pereira) who is in charge of vaccine chemistry. This team is currently producing a host of antigens found on the surface of pathogenic bacteria. Conjugation and analysis of the antigens is now routinely performed as are immunological and functional studies in several disease models in experimental animals. Our integrated in-house approach has accelerated the development of important immunological tools as well as vaccine development.

Carbohydrate-based Nanotechnology

The attachment of carbohydrates to the surface to nanoparticles has been expanded across many platforms. Glycosylated-fullerenols have surprising activity against neurological damage in a stroke model in rats. Further preclinical studies are currently underway. The past two years have seen new projects focused at *in vivo* imaging using a new tridentate ligand system we have developed for carbohydrate labeling. With this approach we have monitored the distribution of specific oligosaccharides in animal models of disease.

Glycoimmunology

Carbohydrate recognition by C-type lectin receptors influences key functions of dendritic cells such as antigen presentation, cytokine release, and the expression of co-stimulatory molecules. Since all of these processes impact T cell priming and differentiation, CLR targeting is a means to orchestrate an initiated immune response. Recently, in collaboration with the MPI-DKTS in Magdeburg we investigated the impact of hemagglutinin (HA) *N*-glycosylation on influenza virus immunogenicity. Virus deglycosylation dramatically decreased cytokine production by spleen cells and reduced HA-specific antibody responses upon immunization of mice indicating a crucial role of HA *N*-glycosylation for immunogenicity.

To identify immune stimulatory and immune modulatory CLR ligands, a screening platform has been developed, followed by *in vitro* and *in vivo* assays. The extracellular domains of different CLRs were expressed as fusion proteins and used in conjunction with the glycan array technology for high-throughput screening of lectin/carbohydrate interactions. Novel binding partners of CLRs were identified and interactions with known ligands confirmed. Carbohydrate-protein interactions were further characterized by surface plasmon resonance (SPR) measurements. This platform brings together CLR ligand identification and their immunologic evaluation. Hence, it is a highly useful tool for the functional analysis of CLR ligands.

Carbohydrate-carbohydrate interactions

As part of the Collaborative Research Centre (SFB) 765 ("Multivalency as chemical organization and action principle"), we focus on the characterization of carbohydrate-carbohydrate interactions. Interactions between carbohydrates are even weaker than carbohydrate/lectin interactions, thus are often hardly measurable. In this context we focus on biophysical and biological analyses of interactions between the tumor-specific carbohydrate antigens GM3 and Gg3 as well as GB4 and GalGB4. Currently, we investigate whether these multivalent carbohydrate interactions are suitable for cell-specific targeting and imaging.

Continuous Flow Microreactors as Tools for Organic Chemists

After pioneering the use of continuous flow microreactors for use by synthetic organic chemists more than ten years ago, the department is now utilizing continuous flow to address different chemical problems. In 2012 the most high profile project was the continuous synthesis of the anti-malarial compound artemisinin using photochemistry. His project has resulted in the formation of a spin-off company "ArtemiFlow" that is scaling the synthesis to ton scale and is working with international organizations to bring the scientific advance to bear on the production of the drug.

With the addition of Prof. Tyler McQuade to the department an additional focus is placed on the production of generic drugs using the benefits of flow synthesis. In addition, different chemistries ranging from gold-catalyzed glycosylations to transition mediated photochemistry to polymerizations are pursued.

Peter H. Seeberger

Director of the Department of Biomelecular Systems

Selected References:

- [1] Yang, Y.; Martin, C.E.; Seeberger, P.H.: Total Synthesis of the Core Tetrasaccharide of *Neisseria meningitidis* Lipopolysaccharide Based on Versatile Heptose Building Blocks Obtained by *de novo* Synthesis; *Chem. Sci.* 2012, **3**, 896 – 899.
- [2] Levesque, F.; Seeberger, P.H.: Continuous flow synthesis of the antimalarial drug artemisinin; *Angew. Chem. Int. Ed.* 2012, **51**, 1706-1709.
- [3] Bou-Hamdan, F.; Seeberger, P.H.: Visible-Light-Mediated Photochemistry: Accelerating Ru(bpy)₃²⁺-catalyzed Reactions in Continuous Flow; *Chem. Sci.* 2012, **3**, 1612-1616.
- [4] Castagner, B.; Kröck, L.; Esposito, D.; Wang, C.-C.; Bindschädler, P.; Seeberger, P.H.: Streamlined Access to Conjugation-Ready Glycans by Automated Synthesis; *Chem. Sci.* 2012, **3**, 1617-1622.
- [5] O'Brien, A.G.; Horváth, Z.; Lévesque, F.; Lee, J.; Seidel-Morgenstern, A.; Seeberger, P.H.: Continuous synthesis and purification by direct coupling of a flow reactor with simulated moving bed chromatography; *Angew. Chem. Int. Ed.* 2012, **51**, 7028-7030.
- [6] Laurino, P.; Hernandez, H.F.; Bräuer, J.; Grützmacher, H.; Tauer, K.; Seeberger, P.H.: Snowballing Radical Generation Leads to Ultrahigh Molecular Weight Polymers; *Macromol. Rapid Commun.* 2012, **33**, 1770-1774.
- [7] Tsai, Y.-H.; Liu, X.; Seeberger, P.H.: Chemical Biology of Glycosylphosphatidylinositol Anchors; *Angew. Chem. Int. Ed.* 2012, **51**, 11438-11456.
- [8] Santer, M.; Wehle, M.; Vilotijevic, I.; Lipowsky, R.; Seeberger, P.H.; Varón-Silva, D.: „How Flexible is the Glycosylphosphatidylinositol (GPI) Anchor Glycan Backbone? Challenges in Simulation Studies of Oligosaccharides“; *J. Am. Chem. Soc.* 2012, **134**, 18964-18972.
- [9] Stefaniu, C.; Vilotijevic, I.; Varón-Silva, D.; Santer, M.; Brezesinski, G.; Seeberger, P.H.: Subgel Phase Structure in Monolayers of Glycosylphosphatidylinositol Glycolipids; *Angew. Chem. Int. Ed.* 2012, **51**, 12874-12878.

Automated Solid Phase Oligosaccharide Synthesis



Mattan Hurevich 02.09.1976

1998-2003: B.Sc. and M.Sc in organic chemistry (The Hebrew University of Jerusalem, Israel).

2003-2009: Doctoral Thesis title: "Development of tools for rational design of proteinomimetic and peptidomimetic drug leads" (The Hebrew University of Jerusalem, Israel).

2009-2010: Postdoctoral Scientist, Department of Biomolecular systems, Max Planck Institute of Colloids and Interfaces.

since 2010: Postdoctoral Minerva Fellow and Project Manager. Department of Biomolecular systems, Max Planck Institute of Colloids and Interfaces.

Sequencing and synthesis of peptides and oligonucleotides have been successfully automated. Given the structural diversity and complexity of carbohydrates access to glycans has been very time consuming to date. In order to delineate the structure–function relationship of carbohydrates usable quantities of defined, pure glycans is required.

The ultimate goal of our group is the development of an generally solid phase automated synthesis method for glycan synthesis. In this context we analyzed the bacterial glycospace using bioinformatics tools. Interestingly, this analysis revealed that relatively few monosaccharide building blocks are required to access most bacterial oligosaccharide structures [1]. Following on fundamental work regarding all aspects of automated oligosaccharide synthesis [2] we developed an efficient and reliable production of structurally defined oligosaccharides based on a standardized, automated synthesis procedure that will provide an essential foundation for the field of glycobiology [3]. To be of use in glycobiology studies, these oligosaccharides are usually immobilized or conjugated through a functional linker (Fig. 1).

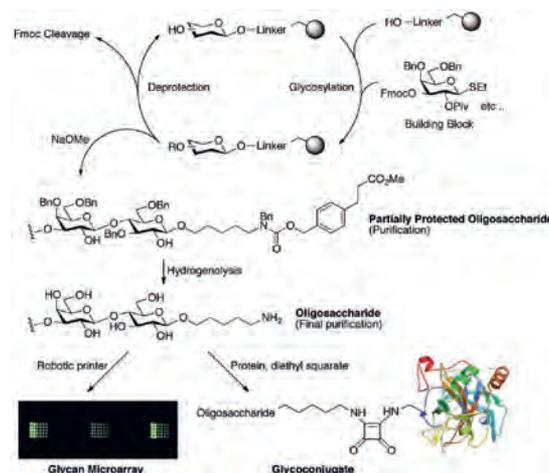


Fig. 1. Overview of the fully-automated solid-phase oligosaccharide synthesis work flow [3].

Sialylated glycans are particularly important for interactions of complex glycans with proteins relevant for viral infections. For the first time we have been able to extend the automated solid phase synthesis paradigm to the incorporation of sialic acid residues into oligosaccharides of biological relevance [4].

Presentation of Carbohydrates on DNA Duplexes

Multivalent interactions occur throughout biology in which two biological entities interact with each other through simultaneous, specific association of two or more ligands and receptors. Many different polymeric backbones, including peptides, have been used for the presentation of carbohydrate antigens as vaccine candidates. However, most of these approaches result in constructs that require long synthetic routes and spatially undefined structures.

A new method [5] for the spatially defined alignment of carbohydrates on a duplex DNA scaffold is presented (Fig. 2). The use of a NHS-ester phosphoramidite along with carbohydrates containing an alkylamine linker allows for on-column labeling during solid-phase oligonucleotide synthesis. This modification method during solid-phase synthesis only requires the use of minimal amounts of complex carbohydrates. The covalently attached carbohydrates are presented in the major groove of the B-form duplex DNA as potential substrates for type II C-type lectin receptors mMGL1 and mMGL2. CD spectroscopy and thermal melting revealed only minimal disturbance of the overall helical structure.



Fig. 2. Conjugation of carbohydrates synthesized by automation or in solution is achieved during the DNA synthetic cycle to produce DNA-carbohydrate conjugates.

Automated Solid Phase Synthesis of Alginates.

For the first time the automated platform was utilized by other groups in 2012. In collaboration with a group at Leiden University, mannuronic acid alginate oligomers, featuring up to twelve 1,2-cis-mannosidic linkages were constructed using the second-generation automated oligosaccharide synthesizer. The stereoselective formation of the β -mannosidic linkages was secured through the use of novel mannuronic acid building blocks. The use of the synthesizer allowed us to rapidly access target structures, without intermediate purifications and in quantities that are not only sufficient to cater for biological experiments but also to facilitate verification of the structural integrity of the compounds [6].

Automated Solid-Phase Synthesis of Glycosaminoglycans

Glycosaminoglycans (GAGs) are important sulfated carbohydrates prevalent in the extracellular matrix. The synthesis of structurally defined GAGs requires laborious procedures, and incorporating defined sulfation patterns is challenging. Novel orthogonal linkers are key to this very challenging project and a new acylsulfonamide safety-catch linker was developed [7].

Automated Synthesis of Sialylated Oligosaccharides.

Sialic acid-containing glycans play a major role in cell-surface interactions with external partners such as cells and viruses.

Straightforward access to sialosides is required in order to study their biological functions on a molecular level. An automated oligosaccharide synthesis was used to facilitate the preparation of this class of biomolecules [4]. Our strategy relies on novel sialyl α -(2 \rightarrow 3) and α -(2 \rightarrow 6) galactosyl imidates, which, used in combination with the automated platform, provided rapid access to a small library of conjugation-ready sialosides of biological relevance.



Fig 3. Fully Automated synthesis of sialosides starting from common disaccharide building blocks [4].

Hurevich M. Calin, O. Esposito, D. Eller, S. Hahm H.S. Kandasamy, J. Schlegel, M.K. Weishaupt, M. mattan.hurevich@mpikg.mpg.de

References:

- [1] Adibekian, A.; Stallforth, P.; Hecht, L.-M.; Werz, D.B.; Gagneux, P.; Seeberger, P.H.; Comparative bioinformatics analysis of the mammalian and bacterial glycomes; *Chem. Sci.* **2**, 337-344 (2011).
- [2] Castagner, B.; Esposito, D.; Seeberger, P.H.; Automated Solid Phase Oligosaccharide Synthesis; In: *Essential Reviews in Experimental Biology*, 2011, Volume 4, Eds. Brooks, S.A.; Rudd, P.M.; Appelmek, B.J.; Chapter **12**; 237-270.
- [3] Kröck, L., Esposito, D., Castagner, B., Wang, C. C., Bindschädler, P. and Seeberger, P. H.: Streamlined Access to Conjugation-Ready Glycans by Automated Synthesis. *Chem. Sci.* **3**, 1617-1622 (2012).
- [4] Esposito, D.; Hurevich, M.; Castagner, B.; Wang, C.-C.; Seeberger, P.H.; Automated Synthesis of Sialylated Oligosaccharides; *Beilstein J. Org. Chem.* **8**, 1601-1609 (2012).
- [5] Schlegel, M.K., Hütter, J., Eriksson, M., Lepenies, B. and Seeberger, P.H. ChemBioChem Defined Presentation of Carbohydrates on a Duplex DNA Scaffold. **12**, 2791-2800 (2011).
- [6] Walvoort, M.T.C.; van den Elst, H.; Plante, O.J.; Kröck, L.; Seeberger, P.H.; Overkleef, H.S.; van der Marel, G.A.; Codée, J.D.C.; Automated solid-phase synthesis of β -mannuronic acid alginates; *Angew. Chem. Int. Ed.*, **51**, 4393-4396 (2012).
- [7] Yin, J.; Eller, S.; Collot, M.; Seeberger, P.H.; Acylsulfonamide safety-catch linker: promise and limitations for solid-phase oligosaccharide synthesis; *Beilstein J. Org. Chem.* **8**, 2067-2071 .

Synthetic Carbohydrate Antigens



Claney L. Pereira 17.05.1978

1996-1999: St. Aloysius College, Mangalore, India B.S., (Chemistry, Botany and Zoology)

1999-2001: Mangalore University, Mangalore, India M.S., Chemistry

2005-2010: Emory University, Atlanta, USA Advisor: Prof. Frank E. McDonald Ph. D., Organic Chemistry

2010-2012: Post-Doctoral Researcher Max-Planck-Institute of Colloids and Interfaces, Berlin, Germany

Advisor: Prof. Peter H. Seeberger

Since 11/2012: Group Leader Biomolecular Systems, Max-Planck-Institute of Colloids and Interfaces, Berlin, Germany

References:

[1] a) Pereira, C. L., Anish, C., Seeberger, P. H. "Development of Synthetic Carbohydrate-Conjugate Vaccine Candidates against *Streptococcus pneumoniae*" (Manuscripts under preparation).

[2] a) Anish, C., Martin, C. E., Rathwell, D., Matsumura, F., Leddermann, M., Pereira C. L., Seeberger, P. H. "Immunogenicity of the spacer moiety limits the antigen specific antibody response against synthetic oligosaccharides" (Manuscript under preparation).

[3] a) Yang, Y., Martin, C. E., Seeberger, P. H., "Total synthesis of the LPS core tetrasaccharide of *Neisseria meningitidis* lipopolysaccharide, a potential vaccine candidate for meningococcal diseases" *Chem. Science.*, **3**, 896-899 (2012); b) Yang, Y., Reinhardt, A., Anish, C., Seeberger, P. H. "A Synthetic Lipopolysaccharide-based Vaccine Candidate for Meningococcal Disease" (Manuscript under preparation); c) Yang, Y., Reinhardt, A., Anish, C., Seeberger, P. H. "A Synthetic Lipopolysaccharide-based Vaccine Candidate for Meningococcal Disease" patent filed through PCT.

Carbohydrates and glycoconjugates are playing an important role in human health and the fight against harmful pathogens. This burgeoning field requires fundamental insights into the role specific oligosaccharides play in human immunity. Bacteria display different types of carbohydrates that are crucial in our quest to protect humans from pathogens.

The bacterial surface is covered by capsular polysaccharides (CPS), cell-wall polysaccharides (CWPS), exopolysaccharides (EPS), secondary cell-wall polysaccharides (SCWPS), lipopolysaccharides (LPS) and others. While the analysis of cell-surface glycans has progressed, access to synthetic oligosaccharides as tools for biological evaluations are still limited. The vaccine subgroup is heavily invested in the synthesis of cell surface glycans of a host of different pathogens based on the development of protocols for the synthesis of rare sugars and new synthetic approaches. The synthetic glycans serve to evaluate biological function and to develop novel diagnostics and vaccines. Novel immunoassay methods, new vaccine carrier concepts and delivery systems are currently being explored.

In 2012, the group has focused on the CPS of *Streptococcus pneumoniae* and *Haemophilus influenzae*, LPS of *Neisseria meningitidis*, *Yersinia pestis*, and other gram negative bacteria, Lipophosphoglycans (LPG) of *Leishmania* species, CWPS of *Clostridium difficile*, rare sugars in *Escherichia coli* O111 and *Legionella*.

Streptococcus Pneumonia

The group is currently pursuing several serotypes and has finished the synthesis of a number of the targets [1]. Immunological evaluations have been followed up by challenge studies that are ongoing.

Haemophilus Influenza

The syntheses of several synthetic oligosaccharides of different length have been achieved and have been subjected to immunological evaluation [2]. The synthesis of further oligosaccharides is underway (Fig. 1). Hib oligosaccharides serve to evaluate a new carrier system for vaccine development in an effort to obviate the need to maintain a cold chain and thus reduce cost of vaccines. This class of oligosaccharides helps us address fundamental questions of glycoconjugate vaccinology.

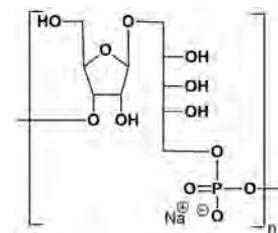


Fig. 1: Structure of *H. influenzae* CPS repeating unit.

Lipopolysaccharides

The tetrasaccharide antigen of *Neisseria meningitidis* has been subjected to immunological studies and functional evaluation (Fig. 2) [3]. Monoclonal antibodies against *Yersinia pestis* were raised against a synthetic antigen and are now being developed for a point of care diagnostic test. (Fig. 2) [4]. Various other LPS structures have been synthesized and will give rise to a unique glycan microarray [5].

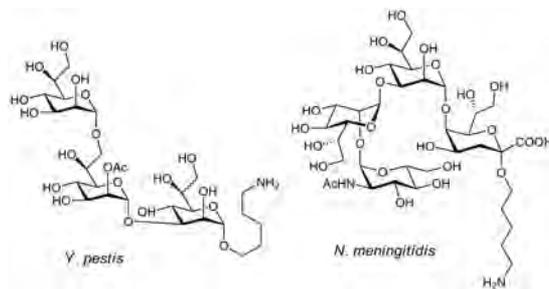


Fig. 2: Synthetic LPS structures synthesized of different pathogens

Clostridium Difficile

Following immunological studies, the *C. diff.* PS-I antigen is entering challenge studies (Fig. 3). In addition, the PS-II antigen is explored in conjunction with PS-I and the toxins A and B [6].

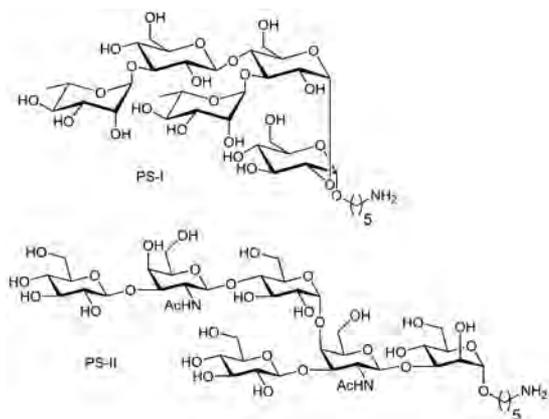


Fig. 3: PS-I and PS-II structure of *C. difficile*

Leishmania

Various LPG capping oligosaccharides have been synthesized and immunologically evaluated (Fig. 4). Sera from humans and dogs have been screened using glycan microarrays in efforts to develop novel diagnostic tests for this parasitic infection [7].

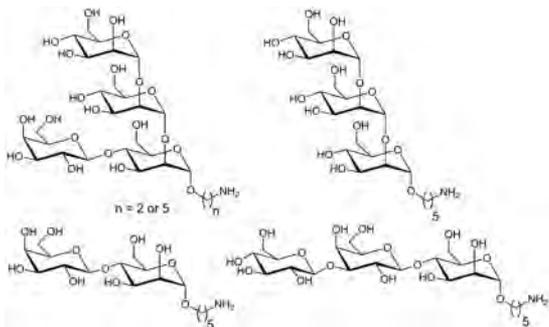


Fig. 4: Structure of capping oligosaccharides of LPG

Rare Sugars

Synthesis of rare sugar L-colitose that is present on the surface of many bacteria has been achieved (Fig. 5) [8]. Using the building block, the O-antigen repeating unit of *E. coli* O111 responsible for major health outbreak has been synthesized [9]. Other rare sugars have been synthesized using de novo approaches [10].

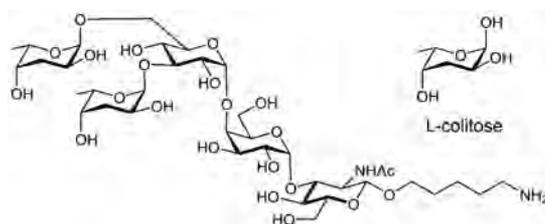


Fig. 5: Structure of the O-antigen of *E. coli* type O111 that contains the rare sugar colitose.

Vaccine Chemistry:

C. L. Pereira, B. Schumann, C. E. Martin, M. Weishaupt, O. Calin, S. Matthies, D. Rathwell, J. Hudon, J. Y. Baek, S. Eller, S. J. Park, S. G. Parameswarappa, S. Oishi, S. Govindan, Y. Yang
claney.pereira@mpikg.mpg.de

Vaccine Biology:

C. Anish, F. Bröcker, A. Reinhardt, A. Geissner, M. Leddermann, A. Wahlbrink
Chakkumkal.Anish@mpikg.mpg.de

- [4] Anish, C., Guo, X., Wahlbrink, A., Seeberger, P. H. "Detection of Plague Using Anti-carbohydrate Antibodies" (Manuscript ready for submission).
- [5] Yang, Y., Oishi, S., Martin, C. E., Seeberger, P. H. "Diversity-oriented Syntheses of the LPS Inner Core Oligosaccharides of Various Pathogenic Gram-negative Bacteria" (Manuscript ready for submission)
- [6] a) Martin, C. E., Bröcker, F., Oberli, M. A., Mattner, J., Anish, C., Seeberger, P. H. "Immunological Evaluation of a Synthetic *Clostridium difficile* Oligosaccharide Conjugate Vaccine Candidate and Identification of a Minimal Epitope" (Manuscript ready for submission); b) Martin, C. E., Bröcker, F., Anish, C., Seeberger, P. H. "Oligosaccharides and Oligosaccharide-protein Conjugates Derived from *Clostridium difficile* Polysaccharide PS-I, Methods of Synthesis and Uses thereof, in Particular as Vaccines and Diagnostic Tools" International Patent Nr. PCT/EP2012/003240.
- [7] Anish, C., Martin, C. E., Wahlbrink, A., Bogdan, C., Antoniou, M., Seeberger, P. H. "Immunogenicity and Diagnostic Potential of Synthetic Antigenic Cell Surface-Glycans of *Leishmania*" (Manuscript ready for submission).
- [8] Calin, O., Pragani, R., Seeberger, P. H. "De Novo Synthesis of L-Colitose and L-Rhodinose Building Blocks" *J. Org. Chem.*, **77**, 870-877 (2012).
- [9] Calin, O.; Eller, S.; Hahn, H.S.; Seeberger, P.H. "Total Synthesis of the *Escherichia coli* O111 O-Specific Polysaccharide Repeating Unit" *Chem Eur. J.* (2013), in press.
- [10] Leonori, D., Seeberger, P. H. "De Novo Synthesis of the Bacterial 2-Amino-2,6-Dideoxy Sugar Building Blocks D-Fucosamine, D-Bacillosamine, and D-Xylo-6-deoxy-4 ketohexosamine" *Org. Lett.*, **14**, 4954-4957 (2012).

Glycobiology of Cell Surface Glycans



Chakkumkal Anish 01.08.1978

1996-2001: Bachelor of Pharmacy (M.G. University, Kerala, India)

2002-2004: Master of Pharmaceutical sciences (1st Class Honours) majoring in Pharmaceutical Chemistry (Institute of chemical technology, University of Mumbai, Mumbai, India)

2004-2006: Senior Lecturer, Government Medical College, Calicut, India

2006-2010: PhD: "Vaccine delivery systems for polysaccharide antigens". (National Institute of Immunology, New Delhi, India)

2011 Jan-2011 Sep: Postdoctoral Scientist, Department of Biomolecular systems, Max Planck Institute of Colloids and Interfaces.

Since 10/2011: Research Group Leader, Department of Biomolecular Systems, Max Planck Institute of Colloids and Interfaces

References:

[1] C. Anish, X. Guo, A. Wahlbrink and P.H. Seeberger, Detection of Plague Using Anti-carbohydrate Antibodies, *Angewandte Chemie International* 2013 (in press).

[2] C. Anish, C.E. Martin, A. Wahlbrink[†], C. Bogdan, M. Antoniou, P. H. Seeberger Immunogenicity and Diagnostic Potential of Synthetic Antigenic Cell Surface-Glycans of *Leishmania* (Manuscript ready for submission).

[3] C. Anish, C. E. Martin, D. C. K. Rathwell, F. Matsumura, M. Leddermann, C. L. Pereira and P. H. Seeberger, Immunogenicity of spacer moiety limits the antigen specific antibody response against synthetic oligosaccharides (Manuscript under preparation)

Pathogens invading humans often express glycan structures on the cell surface that interact with the host receptors and cell surface targets. As with other major classes of biomolecules, cell surface glycans have an important biological role that span the spectrum from relatively subtle, to those that are crucial for the survival of the organism that makes them. This group is interested in the structural and functional aspects of cell surface glycans. These glycans play important roles in biological recognition processes such as immune surveillance, inflammatory reactions and infection. Understanding the interactions of glycans with its binding partners helps to define the basic processes involved in invasion and infection. Differences in cell surface glycan composition and its organization can be exploited to develop glycan based prevention and detection strategies. We investigate four different topics: 1) Cell surface glycan based Pathogen detection and diagnostic tests; 2) Bacterial Glycans as vaccine candidates (collaborations with N. Suttrop, L. Sander, M. Witzenthath at the Charite-Berlin; and U. Vogel University of Wurzburg); 3) Cell surface Glycans at the interface of host-parasite interface; 4) Glycan binding proteins and their role in host-microbe interactions. All four topics involve the basic flow of work starting from identification, characterization and functional evaluation of glycan binding to its interaction partners.

Cell Surface Glycan Based Pathogen Detection and Diagnostic Tests

Many pathogens decorate themselves with unique glycan residues that are distinct from the host. Immunological tools like antibodies or anti-glycan sera that recognize these unique differences can serve to detect the pathogen. The presence of antibodies in the serum of an infected host is a good biomarker for the diagnosis and prognosis of the infection. Two projects are currently being pursued towards these goals:

- Detection of plague (*Yersinia pestis*) based on a unique triheptose that is conserved in the lipopolysaccharide [1].
- Detection of *Leishmania chagasi* based on capping oligosaccharide residues in the lipophosphoglycan [2, 3].

Plague pathogen expresses a unique triheptose residue in the lipopolysaccharide. Synthetic triheptose oligosaccharide was conjugated to a carrier protein. The resulting glycoconjugates were immunized in mice to generate monoclonal antibodies (mAbs) specifically recognizing the lipopolysaccharides. Compared to other gram negative bacteria, generated antibodies specifically recognized plague pathogen (Fig. 1).

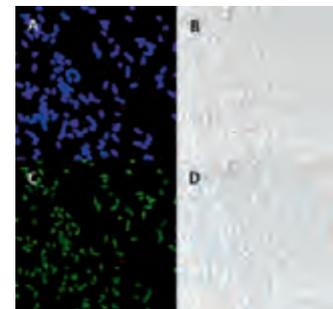
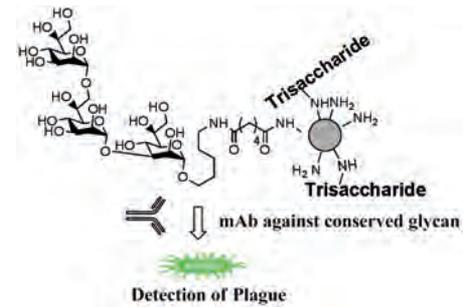


Fig. 1: Indirect immunofluorescent staining of *Y. pestis* by anti- LPS mAbs. CLSM images of immunostained *Y. pestis*; A: counter staining of bacterial DNA with DAPI B: DIC images showing unstained bacteria C: FITC specific fluorescence indicating binding of secondary antibody and D: overlay of all three layers.

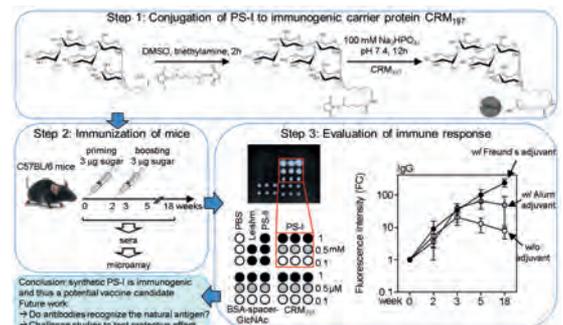


Fig. 2: Major steps involved in the immunological evaluation of glycoconjugates based on PS-1 glycan from *C. difficile*

Bacterial Glycans as Vaccine Candidates

Antibodies against bacterial cell surface glycans have been proven to be immunoprotective and three commercial vaccines against bacterial capsular polysaccharides are available in the clinic. In close collaboration with the vaccine chemistry subgroup we are evaluating the potential of synthetic oligosaccharides as vaccine candidates for bacterial infections. Our focus are the following aspects of the vaccine development programs:

- Immunological evaluation of synthetic oligosaccharides based on clostridium difficile exo-polysaccharide (PS-1) [4,5]
- Synthetic Lipopolysaccharide (LPS) -based vaccine candidate for meningococcal disease [6,7]
- Evaluation of vaccine potential of synthetic oligosaccharides based on bacterial capsular polysaccharides [8]

Synthetic oligosaccharides, based on bacterial cell surface glycans, are prepared by the vaccine chemistry group. We prepare glycoconjugates of these oligosaccharides and carry out immunization experiments in animal models. The immune response is evaluated using glycan microarrays, ELISA and surface plasmon resonance (SPR). The functional evaluation of the immune response in preventing infection is assessed by *in vitro* surrogate assays and experimental infection models. *Clostridium difficile* exo-polysaccharide-based oligosaccharides are potential candidates for vaccine development. The antigens were immunogenic in mice and monoclonal antibodies recognizing the structures were developed. Glycan microarray and SPR studies identified a minimal disaccharide epitope that retains immunogenicity (Fig. 2). Studies on clinical specimens from patients infected with *C. difficile* demonstrated the presence of antibodies recognizing these structures [4].

The synthetic oligosaccharide vaccine candidates based on meningococcal LPS and pneumococcal capsular polysaccharides are ongoing. Immunization with glycoconjugates based on these structures elicited significant antibody responses in mice. Challenge studies, bacterial immunofluorescence studies and opsonophagocytic assays to evaluate the immunoprotective effects of the elicited responses are in progress.

Cell Surface Glycans at the Interface of Host-parasite Interface

Numerous parasites elicit immune responses directed to glycan determinants within cell surface and secreted glycoconjugates in animals and humans. Parasite glycans are also important in host-parasite interactions. This realization prompted renewed interest in defining parasite-derived glycans to develop conjugate vaccines and new diagnostics for parasitic infections. In addition, we aim to understand the biochemical role of these glycans. Within this theme the group works on three projects:

- Role of extra-cellular vesicles in the infection biology of the apicomplexan parasite *Toxoplasma gondii* [9]
- Structure-function correlation studies on malarial glycosylphosphatidylinositols (GPIs) using anti-GPI antibodies
- Evaluation of *Toxoplasma gondii* GPIs as a vaccine and diagnostic marker for toxoplasmosis.

Apicomplexan parasites like Plasmodium and Toxoplasma are known to actively invade their respective hosts by hijacking and modulating the host cell responses. While the secretory proteins of these parasites have been studied in depth, no reports on the release of exosomes or microvesicles and the effector mechanisms they may mediate with the cells of the host system exist. Using *T. gondii* as a model organism we have isolated membrane vesicles released by parasites in the range of 40-150 nm. Biochemical characterization revealed the presence of certain immunodominant proteins and glycolipids like Glycosylphosphatidylinositols (GPI). We are characterizing the vesicles released by virulent and non-virulent strains of Toxoplasma and the possible roles they play in

modulating the host cells in the context of invasion or innate responses against these parasites.

Monoclonal antibodies against malarial GPIs have been studied using glycan microarrays and STD NMR for epitope mapping. The mAbs recognize both natural as well as synthetic GPIs. Further studies on parasite binding and the potential of anti-GPI antibodies in limiting the invasion of parasite to RBCs are in progress.

We have investigated the potential of *T. gondii* GPIs using synthetic glycan based arrays for the diagnosis of toxoplasmosis [10]. Screening of clinical specimens from patients infected with *T.gondii* showed significantly higher levels of anti-GPI antibodies indicating the biomarker potential of GPIs. We are further investigating the immunogenicity of *T. gondii* GPI glycoconjugates to evaluate their potential as vaccine candidates.

Glycan Binding Proteins and their Role in Host-microbe Interactions

Identifying and characterising glycan binding proteins on host cell surface is important to understand their role in the host-pathogen interactions. To meet this aim, we use the glycan array platform to screen cell lysates; clinical specimens as well purified recombinant proteins.

- Role of parasite GPIs during host cell activation [11, 12]

GPIs present on the cell surface of the Apicomplexan parasites participate actively in the stimulation of immune host cell system and/or in the host cell invasion process. Using the synthetic glycan array platform we identified a cell surface isoform of moesin that interacts specifically with GPIs (Fig. 3). The moesin-GPI interaction is essential for macrophage activation *in vitro* mediating a pro-inflammatory response. Due to increasing drug resistance, targeting the GPI-moesin recognition process should enable novel modes of therapeutic intervention against Apicomplexan infection.

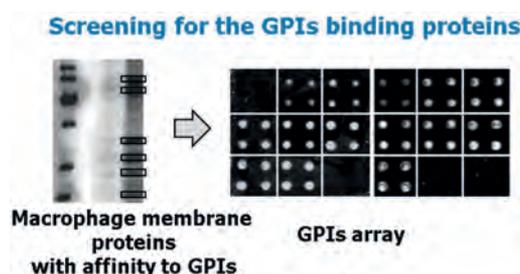


Fig. 3: Screening of malarial parasite GPI binding proteins to macrophage membrane proteins

C. Anish, N. Azzouz, R. Kurucz, B.P. Monnanda, F. Bröcker, A. Reinhardt, A. Geissner, M. Leddermann, A. Wahlbrink
 Chakkumkal.Anish@mpikg.mpg.de

[4] C. E. Martin, F. Bröcker, M. A. Oberli, J. Mattner, C. Anish*, P. H. Seeberger*, Immunological Evaluation of a Synthetic *Clostridium difficile* Oligosaccharide Conjugate Vaccine Candidate and Identification of a Minimal Epitope, Journal of American Chemical Society, 2013, (in press)

[5] C. E. Martin, F Bröcker, C. Anish, P.H. Seeberger. "Oligosaccharides and Oligosaccharide-protein conjugates derived from *Clostridium difficile* polysaccharide PS-I, methods of synthesis and uses thereof, in particular as vaccines and diagnostic tools" International Patent Nr. PCT/EP2012/003240.

[6] Y. Yang, A. Reinhardt, C. Anish, P. H. Seeberger., A Synthetic Lipopolysaccharide-based Vaccine Candidate for Meningococcal Disease, patent filed through PCT.

[7] Y. Yang, A. Reinhardt, C. Anish, P. H. Seeberger., A Synthetic Lipopolysaccharide-based Vaccine Candidate for Meningococcal Disease (Manuscript under preparation)

[8] C. L. Pereira, A. Geissner, C. Anish and P. H. Seeberger "Towards the development of a synthetic carbohydrate-conjugate vaccine candidate for serotype 4 of *Streptococcus pneumoniae*" (Manuscript under preparation)

[9] B. Monnanda, N. Azzouz, D. Kolarich, M. Thorsten, C. Anish and P. H. Seeberger, Role of Extra-Cellular Vesicles in the Infection Biology of the Apicomplexan Parasite *Toxoplasma gondii* (Manuscript under preparation)

[10] Azzouz, N., Götze, S., Tsai, A-H., Silva, D.V., Seeberger, P.H. Synthesis of diverse glycosylphosphatidylinositol glycans and glycolipids from *Toxoplasma gondii* and their application as diagnostic markers and vaccines. European Patent 12177602.5-2404 (2012).

[11] Azzouz, N., Kamena, F., Laurino, P., Kikkeri, R., Mercier, C., Cesbron-Delauw, M.F., Dubremetz, J.F., De Cola, L., Seeberger, P.H. (2013) *Toxoplasma gondii* secretory proteins bind to sulfated heparin structures. *Glycobiology*. 23;106-20 (2013).

[12] Azzouz, N, Kamena, F., Lepenies, B., Liu, X. and Seeberger P.H. Role of Moesin during Macrophage Activation by Glycosylphosphatidylinositols *in vitro* (Manuscript in preparation)

Synthesis and Properties of GPI-Anchors



Daniel Varón Silva 09.04.1974
1992-1998: Diploma in Chemistry, Department of Chemistry, National University of Colombia, Bogotá, Colombia
1998-2002: Research associate, Department of Chemistry, Colombian Immunology Institute Foundation, Bogotá, Colombia
2003-2007: PhD in Chemistry, Bioorganic Chemistry, University of Bayreuth, Bayreuth, Germany
2007-2008: Postdoctoral Fellow, Laboratory of Organic Chemistry, Swiss Federal Institute of Technology, Zurich, Switzerland
2009-2010: Postdoctoral Fellow, Department of Biomolecular Systems, Max Planck Institute of Colloids and Interfaces, Berlin, Germany
Since 06/2010: Group Leader, GPI and Glycoproteins group, Department of Biomolecular Systems, Max Planck Institute of Colloids and Interfaces, Berlin, Germany

Glycosylphosphatidylinositols (GPIs) are complex glycolipids that are found in eukaryotic cells either attached to the C-terminus of proteins or in free form. GPIs contain a phosphoethanolamine unit connecting the C-terminus of the protein to the glycan, a conserved pseudo-pentasaccharide core and a lipid attached to the core glycan via a phosphodiester [1]. The conserved GPI structure can be further decorated by various substituents including additional phosphoethanolamine units, an additional fatty acid ester and oligosaccharide branches. The lipid subunit is variable and may include diacylglycerol, alkylacylglycerol or a ceramide, with chains of different length and varying degrees of unsaturation (Fig. 1).

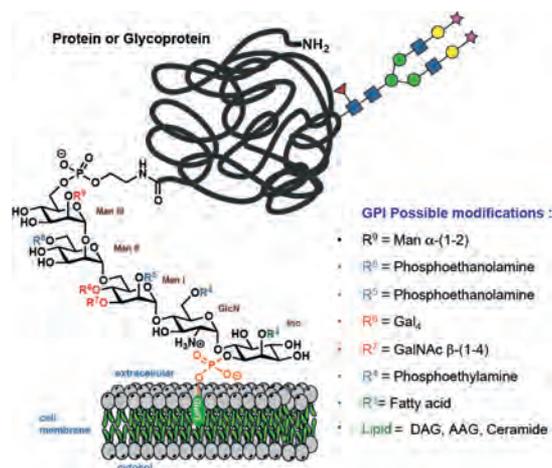


Fig. 1: Structure and possible modifications of GPI anchors. (DAG Diacylglycerol, AAG: Alkylacylglycerol)

The primary biological role of GPIs is to localize the attached protein to the outer surface of the plasma membrane bilayer [2]. However, it is suggested that GPIs play a role in the association of anchored proteins with lipid rafts and are, thereby, involved in diverse processes such as regulation of innate immunity, protein trafficking, and antigen presentation [3].

Development of a General Strategy to obtain GPIs

Studies that would link a specific function to a structurally unique GPI rely on availability of homogeneous material of these glycolipids. To address this need we have developed a general synthetic route to obtain well-defined GPI glycolipids [4]. Our strategy is based on modular assembly of common building blocks and relies on a fully orthogonal set of protecting groups that enables the regioselective introduction of phosphodiester and efficient assembly of the GPI glycans (Fig. 2). This general strategy has been applied to the syntheses of different branched and structurally distinct GPIs: the GPI of *T. gondii*, the low molecular weight antigen of *T. gondii* (Fig. 2), the GPI anchor of *T. congolense* VSG and the GPI of *T. brucei* VSG 117 [5].

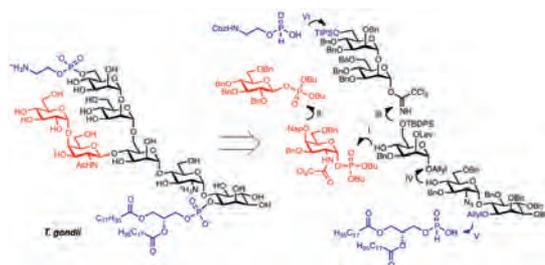


Fig. 2: Assembly sequence of the low molecular weight antigen from *T. gondii* using the general strategy

The assembly of the glycan is dictated by the positioning of the temporary protecting groups, which is kept constant across the set of common building blocks. The glycosylations required for the assembly of different GPI glycans are performed between similar coupling partners making the reactions conditions broadly transferable between different GPI syntheses. Both the late stage phosphorylations and glycosylations that form glycosidic bonds around the central mannose have been optimized with respect to yield and stereoselectivity, and shown to be competent in syntheses of diverse GPI targets. This work constitutes the first general approach to the synthesis of diverse GPI structures and the first synthetic route capable of producing GPIs with various substitution patterns including: monosaccharide and complex oligosaccharide branches with synthetically challenging glycosidic bonds, branches at both C3 or C4 position of Man I, di- and triphosphorylated structures, and generally diverse GPIs isolated from different organisms. With the ability to produce homogeneous native GPI structures and the flexibility that can be used to accommodate further modifications and produce unnatural analogues, this general strategy for the synthesis of GPI structures will enable extensive investigation into the biological roles of these glycolipids.

Biophysical Studies with GPI-Fragments

Insights into the behavior of GPIs and GPI-anchored proteins (GPI-APs) in cell membranes could contribute to the understanding of the roles GPIs play in biological processes. In this context, we have synthesized different lipidated GPI-core fragments and have evaluated in collaboration with the interfaces department the structural characteristics and conformational behavior of GPIs in well-defined membrane models. This biophysical study revealed the unprecedented crystalline two-dimensional structure of GlcNAc1-6myo-Ino-1-phosphodistearoylglycerol monolayers. These monolayers are characterized by two commensurate lattices: the oblique lattice of the alkyl chains and the molecular lattice formed owing to highly ordered head groups (Fig. 3). The head-group ordering is observed regardless of incubation period probably because a hydrogen-bond network rigidifies the monolayer structure and can be disrupted on highly concentrated urea subphases [6].

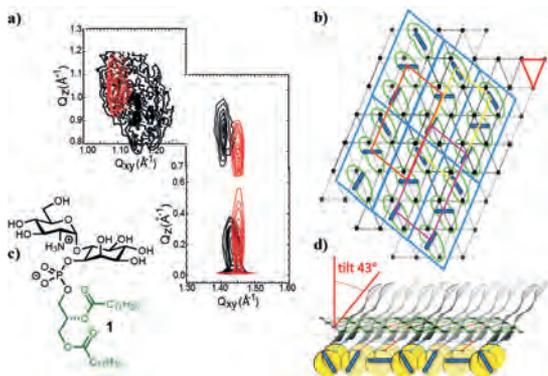


Fig. 3: a) Contour plots of corrected X-ray intensities as a function of in-plane (Q_{xy}) and out-of-plane (Q_z) scattering vector components of monolayers of 1 on PBS (2 mNm^{-1} black, and 30 mNm^{-1} red). b) Representation of the commensurable lattices describing the lateral order of the alkyl chains and of the molecules. Repeating unit cells (red, yellow, and magenta) c) Structure of the GPI-Core fragment 1. d) Representation of the molecules at the air/water interface: lateral view.

Studies on mixed monolayers of the GPI-fragments and POPC demonstrate that above a certain concentration of the fragment 1, phase-separation occurs owing to the strong head-group interactions. Below this concentration, the fragment mixes with the liquid disordered POPC and induces order in a highly cooperative way. Thus, the GPI fragment 1 tends to create ordered phases as it either forms a highly crystalline structure or induces liquid ordered domains (rafts). This ability could have important implications for the interactions of GPI-APs and GPIs in cell membranes.

Additional to high purity compounds, and the studies on membranes, to disclose structure-activity relationship (SAR) of GPIs, it's necessary to obtain structural information of the GPI-glycans. In collaboration with theory department we have performed a thorough conformational analysis and NMR characterization of GPI glycan fragments [7]. A spreadsheet compilation of data from regular MD trajectories covering a complete collection of substructures provides a survey of the overall conformational character of the fragments. We have performed biased MD simulations on a selected set of substructures. The biased dynamics permit us to explore free energy landscapes of glycosidic angles. The analysis clearly identifies the dimannoside $\alpha 1 \rightarrow 6$ linkage as critical with respect to sampling efficiency and accuracy. Corresponding data sets from regular MD runs were then used, in combination with the results on disaccharides, to verify that the tetrasaccharide can be viewed as a sequence of independent glycosidic linkages, the conformational preferences of which are essentially inherited from disaccharide substructures (Fig. 4).

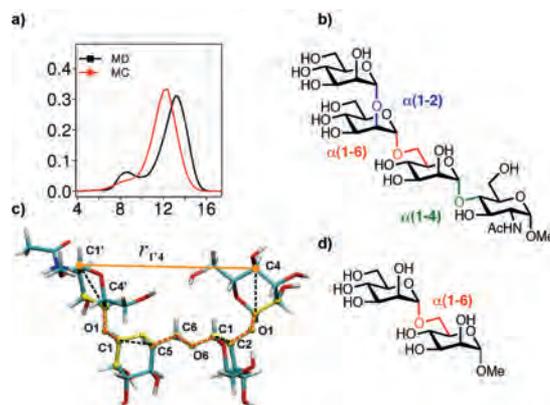


Fig. 4: a) Distribution $p(r_{1,a})$ for the end-to-end distance from MD data (black) and the MC result (red). b) Structure of the GPI tetrasaccharide GPI fragment. c) Translation of an all-atom tetrasaccharide backbone into a reduced topology. d) Critical $\alpha(1 \rightarrow 6)$ dimannoside.

GPI-Anchors and Infection Diseases

Certain pathogenic parasites express non-protein-linked, free GPIs, which have been suggested to regulate the host immune response during parasitic infections [8]. However, in most cases, the heterogeneity and difficult isolation of pure GPIs have limited the evaluation of their function and the relationship with the GPI structure.

The parasite *T. gondii*, causing toxoplasmosis, expresses two different GPIs; one of them is a free GPI and is known as the low-molecular weight antigen. This GPI was synthesized using the general strategy and immobilized on glass slides. Recognition studies with anti-GPI monoclonal antibodies showed a specific recognition of this GPI structure, implying a structure-immunogenicity relationship and suggesting their applicability in parasitic disease research. Furthermore, *T. gondii* GPIs bearing a thiol linker have been prepared and used to obtain GPI-conjugates that are valuable tools in toxoplasmosis research and are currently under evaluation. Other synthetic GPIs have also been printed in micro-arrays and used to evaluate the presence of antibodies anti-GPI in other infections. Similarly to *T. gondii*, during the infection of *T. gondii* specific immunological responses anti-GPI has been probed and the obtained antibodies did not show cross reactivity with other parasitic GPIs, demonstrating the importance of having well-defined molecules to disclose biological functions. Further studies with these and other GPI are in progress.

D. Varón Silva, K. Arnsburg, S. Götze, M. Grube, B.-Y. Lee, D. Michel, and I. Vilotijevic
daniel.varon@mpikg.mpg.de

References:

- [1] Ferguson, M. A. J., Homans, S. W., Dwek, R. A., and Rademacher, T. W.: Glycosyl-Phosphatidylinositol Moiety that Anchors Trypanosoma-Brucei Variant Surface Glycoprotein to the Membrane, *Science*, **239**, 753-759, (1988).
- [2] Paulick, M. G., and Bertozzi, C. R.: The glycosylphosphatidylinositol anchor: A complex membrane-anchoring structure for proteins, *Biochemistry*, **47**, 6991-7000, (2008).
- [3] Kinoshita, T., Fujita, M., and Maeda, Y.: Biosynthesis, remodelling and functions of mammalian GPI-anchored proteins: Recent progress, *J. Biochem.*, **144**, 287-294, (2008).
- [4] Tsai, Y.-H., Götze, S., Azzouz, N., Hahn, H. S., Seeberger, P. H., and Varon Silva, D. A: General Method for Synthesis of GPI Anchors Illustrated by the Total Synthesis of the Low-Molecular-Weight Antigen from Toxoplasma gondii, *Angew. Chem. Int. Ed.*, **50**, 9961-9964, (2011).
- [5] Tsai, Y.-H., Götze, S., Vilotijevic, I., Grube, M., Silva, D. V., and Seeberger, P. H.: A general and convergent synthesis of diverse glycosylphosphatidylinositol glycolipids, *Chem. Sci.*, **4**, 468-481, (2013).
- [6] Stefaniu, C., Vilotijevic, I., Santer, M., Varón Silva, D., Brezesinski, G., and Seeberger, P. H.: Subgel Phase Structure in Monolayers of Glycosylphosphatidylinositol Glycolipids, *Angew. Chem. Int. Ed.*, **51**, 12874-12878, (2012).
- [7] Wehle, M., Vilotijevic, I., Lipowsky, R., Seeberger, P. H., Varon Silva, D., and Santer, M.: Mechanical Compressibility of the Glycosylphosphatidylinositol (GPI) Anchor Backbone Governed by Independent Glycosidic Linkages, *J. Am. Chem. Soc.*, **134**, 18964-18972, (2012).
- [8] Tsai, Y.-H., Grube, M., Seeberger, P. H., and Varon Silva, D.: Glycosylphosphatidylinositols of Protozoan Parasites, *Trends Glycosci. Glycotechnol.*, **24**, 231-243, (2012).

Microreactors as Tools for Organic Chemists



David Tyler McQuade 18.08.1971
1989-1993: Bachelor of Science majoring in Chemistry and Biology (University of California-Irvine, CA, USA)
1993-1998: Doctoral Thesis: Further studies of 1,6 methano[10]annulene-derived contrafacial amphiphiles and synthesis of tripod detergents for membrane protein solubilization and crystallization (Department of Chemistry, University of Wisconsin-Madison, WI, USA)
1998-2001: NIH Postdoctoral Fellow (Department of Chemistry, MIT, Boston, MA, USA)
2001-2007: Assistant Professor of Chemistry and Chemical Biology (Cornell University, Ithaca, NY, USA)
2007-2012: Associate Professor of Chemistry and Biochemistry (Florida State University, Tallahassee, FL, USA)
Beginning 08/2013: Professor of Chemistry and Biochemistry (Florida State University, Tallahassee, FL, USA)
Since 04/2012: Research Group Leader, Department of Biomolecular Systems, Max Planck Institute of Colloids and Interfaces

The efficient synthesis of molecules requires control over chemical reactivity and reaction conditions. Advances in reaction condition control have accelerated new method development and discovery. Recent tools include automated synthesizers, microwave reactors, and flow/microreactors [1,2] reactors.

In the Microreactors as Tools for Organic Chemists (MTOC) group, flow reactors are used for three purposes:

- To develop continuous chemical processes. Specifically, MTOC is creating cost effective routes to medicines critical for the developing world (with C. Correia, K. Gilmore, D. Kopetzki and Prof. Seidel-Morgenstern - Max-Planck-Institut für Dynamik komplexer technischer Systeme in Magdeburg).
- To create novel chemical methods. Microreactors provide unique environments that enable new chemistry. Flow reactors are being used by the MTOC to synthesize bifunctional reactive intermediates and multi-functional fluorophores, for example (D.T. McQuade, F. Bou-Hamdan, A. O'Brien and M. Plutschack; with Prof. Dr. Meggers).
- To perform oligosaccharide synthesis. Microreactors enable optimization of glycosylations, creation of novel glycosylation methods and production of novel saccharide-based materials.

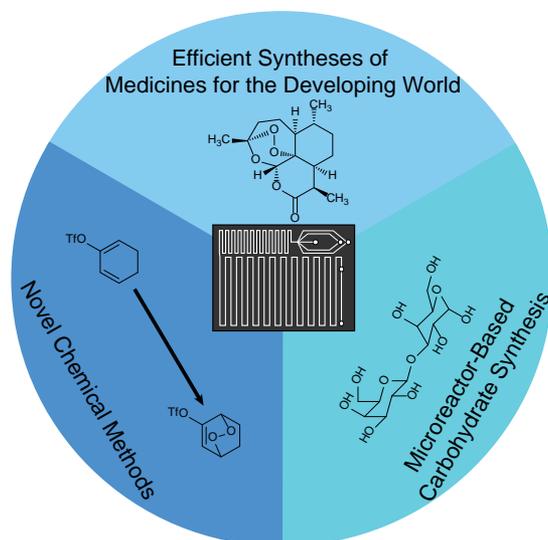


Fig. 1: The three working groups within the Microreactors team (Biomolecular Systems Department)

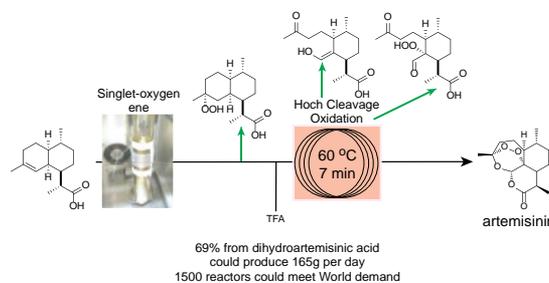
Efficient Syntheses of Medicines for the Developing World

Continuous synthesis enables the low-cost manufacturing of medicines. Millions of people in the developing world cannot afford life-saving medicines. Access to medicines such as anti-malarial and anti-viral agents would be increased if production costs could be decreased. The MTOC is actively developing advanced chemical syntheses of key active pharmaceutical ingredients used to treat malaria and HIV.

The team has recently synthesized the anti-malaria drug artemisinin using a continuous photochemical process. The process begins from dihydroartemisinic acid (DHA) [3], a starting material now available on large scale via fermentation (Scheme 1).

The initial configuration used a mercury arc lamp and provided 39% yield of artemisinin from DHA.

Recently, the process was optimized to 69% yield from DHA. The increased yield leads to a throughput of 165g of artemisinin per day using visible light LED illumination. The MTOC is currently synthesizing the artemisinin-based APIs artemether, artemotil and artesunate. In addition, we are developing novel continuous routes into other medicines where decreased cost could increase access to those in great need of these agents.



Scheme 1: Recently reported continuous synthesis of artemisinin starting from dihydroartemisinic acid.

Novel Chemical Methods: Leveraging Continuous Reactors

Continuous reactors have been used by chemical engineers for over a century, but micro- and meso-reactors (flow reactors, collectively) have only recently become broadly available to the synthetic organic chemist. These reactors offer a number of significant advantages including:

- (1) controlled heat transfer;
- (2) controlled mixing, both fast and slow;
- (3) increased photon-flux in photochemical reactions;
- (4) increased electrode surface-to-reactor volume ratio (electrochemistry);
- (5) increased solution-solid phase interactions;
- (6) controlled use of highly reactive/toxic materials; and
- (7) increased capacity to run serial reactions.

Over the past 8 years, the MTOC team has developed a wide range of flow reactor-based chemistries.[4] Most recently, the team has focused on transformations facilitated by light.

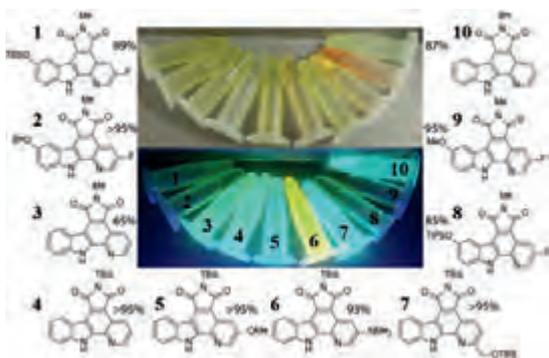


Fig. 2: The fluorescent products resulting from an in-flow photoelectrocyclization.

Fig. 2 illustrates ten fluorophores produced in a recent collaboration with Prof. Dr. Meggers group where a photoelectrocyclization was performed in flow, resulting in substantially better yields and product quality relative to batch methods.[5]

Homogeneous catalysts are expensive and methods enabling their continuous re-use while still retaining their active/selectivity represents an unmet challenge. The MTOC team has recently reported two new approaches to supporting catalysts specifically for use in flow. The first method uses a monolith-based approach.[6] Monoliths are highly porous solids and are typically prepared using polymers such as acrylates that do not exhibit wide chemical compatibility. The MTOC prepared polystyrene monoliths using a photoinitiated-radical polymerization (K. Krüger and K. Tauer). These monoliths were readily functionalized with catalysts and demonstrated wide chemical compatibility.

The MTOC has also created a carbon-nanotube-based catch and release strategy for supporting catalysts (Fig. 3).[7] Catalysts were appended to pyrene and captured using a column of carbon nanotubes. When the nanotube bed was heated, the catalysts were released and could be used in a flow reactor. At the exit of the flow reactor, a cooled carbon-nanotube packed bed then captured the catalyst, allowing product to pass freely. This capture and release strategy was used for multiple rounds of reactions without significant loss of catalytic activity.

Microreactor-Based Oligosaccharide Synthesis

Complex oligosaccharides play a fundamental role in cell-cell, bacteria-cell and virus-cell interactions. While the importance of these recognition interactions is becoming increasingly clear, the chemical synthesis of these biopolymers remains a significant challenge.

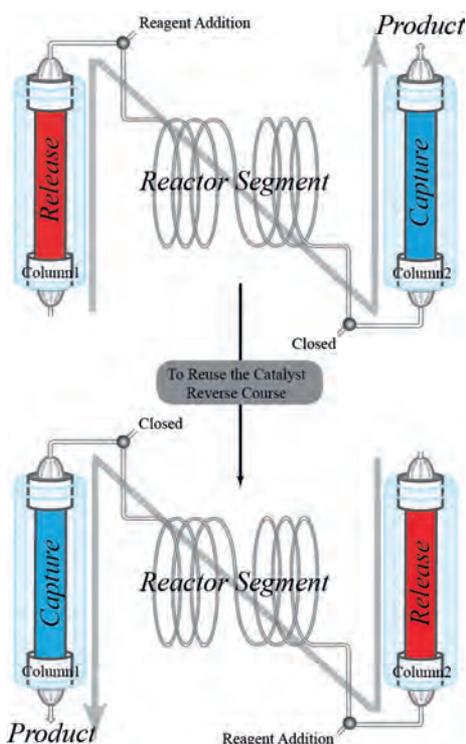


Figure 3: A carbon-nanotube-based capture and release catalyst system. Captured catalysts are released by heating and used immediately within the reactor segment. Once exiting the reactor segment, the catalysts are then recaptured on cooled nanotubes. The system is then reversed to recycle the catalyst.

The MTOC group is contributing to this area by:

- developing new strategies to optimize glycosylations;
- creating new flow-based glycosylation reactions;
- synthesizing sugar monomers continuously and
- creating new sugar-based materials in flow.

Fig. 4 shows a recent example from the MTOC where a flow glycosylation is achieved using mild gold-based catalysis. This method will enable the coupling of glycosyl-monomers that contain acid-sensitive functional groups (S. Bhunia).

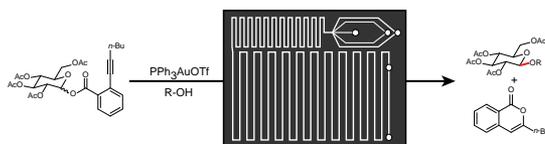


Fig. 4: Flow-based glycosylations using gold-catalysis

D.T. McQuade, F. Bou-Hamden, S. Bhunia, C. Corriea, J. Cullen, K. Gilmore, D. Kopetzki, A. O'Brien, M. Plutschack, S. Vukeli, Y. Suzuki
 Tyler.mcquade@mpikg.mpg.de.

References:

- [1] Laurino, P.; Odedra, A.; Mak, X. Y.; Gustafsson, T.; Geyer, K.; Seeberger, P. H., *Microfluidic Devices for Organic Processes*. In *Chemical Reactions and Processes under Flow Conditions*, Luis, S. V.; Garcia Verdugo, E., Eds.; pp 118-16 (2010)
- [2] Geyer, K.; Gustafsson, T.; Seeberger, P. H., *Developing Continuous-Flow Microreactors as Tools for Synthetic Chemists*. *Synlett*, (15), 2382-2391 (2009).
- [3] Levesque, F.; Seeberger, P. H., *Continuous-Flow Synthesis of the Anti-Malaria Drug Artemisinin*. *Angewandte Chemie-International Edition*, **51** (7), 1706-1709 (2012).
- [4] Recent examples include: O'Brien, A. G.; Horvath, Z.; Levesque, F.; Lee, J. W.; Seidel-Morgenstern, A.; Seeberger, P. H., *Continuous Synthesis and Purification by Direct Coupling of a Flow Reactor with Simulated Moving-Bed Chromatography*. *Angewandte Chemie-International Edition*, **51** (28), 7028-7030 (2012). Bou-Hamdan, F. R.; Seeberger, P. H., *Visible-light-mediated photochemistry: accelerating Ru(bpy)₃(3⁺)-catalyzed reactions in continuous flow*. *Chemical Science*, **3** (5), 1612-1616 (2012). Levesque, F.; Seeberger, P. H., *Highly Efficient Continuous Flow Reactions Using Singlet Oxygen as a „Green“ Reagent*. *Organic Letters*, **13** (19), 5008-5011(2011).
- [5] McQuade, D.T.; O'Brien, A.G.; Dörr, M.; Rajaratnam, R.; Eisold, U.; Monnanda, B.; Löhmansröben, H.-G.; Meggers, E.; Seeberger, P.H. submitted.
- [6] Bou-Hamdan, F. R.; Krüger, K.; Tauer, K.; McQuade, D. T.; Seeberger, P. H., *Visible Light-Initiated Preparation of Functionalized Polystyrene Monoliths for Flow Chemistry*. *A. J. Chem.*, **66** (2), 213-217 (2013).
- [7] Suzuki, Y.; Laurino, P.; McQuade, D. T.; Seeberger, P. H., *A Capture-and-Release Catalytic Flow System*. *Helvetica Chimica Acta*, **95** (12), 2578-2588 (2012).

Precision Glycopolymers for Receptor Targeting and Drug Development



Laura Hartmann, 05.10.1979

1998-2001: Basic Studies in Chemistry (Vordiplom): Universität zu Köln

2001-2004: Advanced Studies in Chemistry (Diplom): Albert-Ludwigs-Universität Freiburg, Diploma thesis in the group of Dr. J. Tiller and Prof. Dr. R. Müllhaupt at the Freiburger Material Forschungszentrum (FMF)

2004-2007: Doctoral Thesis: Max Planck Institute of Colloids and Interfaces, Department of Colloids (Dr. H. Börner, Prof. Dr. M. Antonietti). Title: „Synthesis of monodisperse, multifunctional poly(amidoamines) and their application as non-viral vectors for gene therapy“

2007-2009: Postdoctoral Scientist: Stanford University, Palo Alto, USA, (Prof. Dr. C. Frank, Chemical Engineering and Prof. Dr. C. Ta, School of Medicine). Topic: „Novel interpenetrating polymer networks with enhanced mechanical and biomedical properties and their use for artificial cornea implants“

Since 8/2009: Independent Emmy Noether-Research Group Leader: Max Planck Institute of Colloids and Interfaces, Department of Biomolecular Systems (Prof. Dr. P. H. Seeberger) and Freie Universität Berlin. Topic: „Synthesis of monodisperse, multifunctional neoglycopolymers and neoglycopolymer-hybrids and their biomedical applications“

Precision Polymers

Over the past decades, polymer-based materials have evolved as a powerful tool in biomedical and pharmacological applications e.g. as carriers in drug and gene delivery, macromolecular therapeutics, polymeric diagnostics or 3D scaffolds for tissue engineering. Our aim is the development of the next generation of polymer based biomimetics by combining chemical precision (monodisperse molecules) and high degrees of functionality obtaining a new class of polymers, the so-called precision polymers.^[1] In contrast to classical polymeric systems, these precision polymers do not exhibit any molecular weight or size distribution but are monodisperse. Furthermore they are multifunctional systems with the functionalities being positioned along or within the polymer backbone with a specific order or sequence.

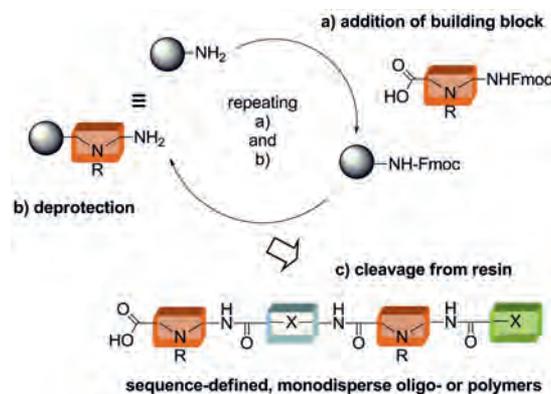


Fig. 1: General scheme of solid phase polymer synthesis: dimer building blocks are assembled on solid-support by stepwise activation, addition and deprotection. The final sequence-defined, monodisperse scaffolds are obtained directly after cleavage from the support. The whole process is automated by using a standard peptide synthesizer.

In order to develop a straightforward synthetic route to such sequence-defined, monodisperse polymer segments, solid phase-supported synthesis is applied (Solid Phase Polymer Synthesis, SPPoS) (Fig. 1).^[1,2] Tailor-made dimer building blocks are coupled sequentially offering different spacer units as well as natural and non-natural functionalities within the main or side chain (Fig. 2).^[2-5] Since for every addition a different building block can be used, different functionalities can be introduced and positioned within the chain as well as different architectures e.g. branched or ring structures can be realized depending on the choice of the monomer sequence.

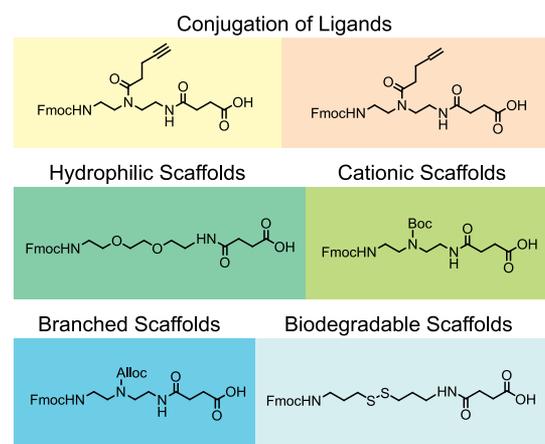


Fig. 2: Examples of functional dimer building blocks suitable for the solid phase synthesis of precision polymers.^[2-5]

With this new synthetic platform in hand, we now focus on exploring two major advantages of precision polymer based biomimetics: On the one hand the control over their chemical composition allows for deeper insights into the structure-property relations of polymers for biomedical applications, so far mainly obtained by purely empirical studies. On the other hand, they allow for the straightforward synthesis of highly complex, multifunctional systems e.g. combining natural and non-natural ligands or functionalities and therefore have a great potential for the development of multicomponent therapeutics and drug delivery vehicles.

Glycopolymers for Receptor Targeting

Special focus is devoted to the combination of our precision polymers with sugar ligands. Such carbohydrate ligands take part in many biological processes like intercellular recognition and pathogen identification, often involved with multivalent presentation of the sugar ligands on a protein scaffold. Replacing the scaffold with a polymer therefore is a straightforward approach leading to more easily accessible, more stable and multifunctional sugar and sugar-protein mimetics. Precision glycopolymers now allow for the total control over the number, density and distancing of different sugar ligands along the scaffold and thus for a systematic structure-property relation study.

In a first set of glycopolymers consisting of a hydrophilic, flexible backbone of the same length, we varied the number and distancing of sugar ligands (mannose) (**Fig. 3**) and determined the binding affinity towards the lectin receptor Concanavalin A (ConA) via surface plasmon resonance.^[3] We found a strong dependence of the binding affinity on the number as well as the distancing of the sugar ligands. To our surprise, even the monovalent system (just one sugar attached to the polymer scaffold) already shows an increase in affinity by 100 fold while the scaffold itself does not show any unspecific interactions. We conclude that some of the hydration water from the scaffold is released upon binding resulting in an entropic gain (the effect of water as 'molecular mortar'). If we go up to a trivalent system, we even see an increase in affinity of 260 fold per sugar compared to the monosaccharide ligand, one of the highest values for comparable systems reported in literature so far.^[3] Altogether these results show the importance of tailor-made polymer scaffolds for the design of novel glycomimetics.

Another advantage of our synthetic approach is the straightforward access to so-called heteromultivalent systems, presenting different sugar ligands at different positions along the polymer backbone (**Table 1**).^[4,6]

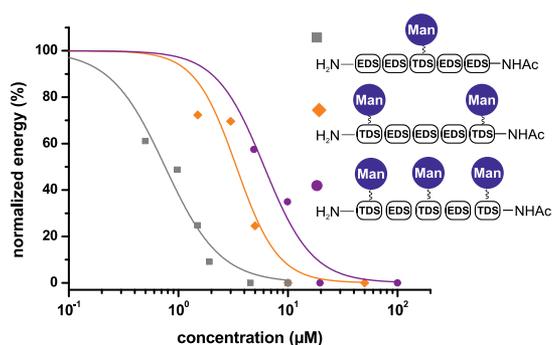


Fig. 3: A first set of precision glycopolymers shows different inhibitory concentrations depending on the number and distancing of sugar ligands along the polymer backbone (measured via SCP-RICM) [6, 8].

In a first experiment we found that the trivalent all-mannose system exhibits the same IC50 value as the trivalent heteromultivalent (Man, Gal, Man) system. So far we attribute this to a possible divalent binding mode of the two mannose ligands that is not altered by the nature of any additional ligands.^[6]

Man and Gal	Man and Glu
<p>H₂N-(TDS)-(EDS)-(EDS)-(TDS)-(EDS)-(EDS)-NHAc</p>	<p>H₂N-(TDS)-(EDS)-(EDS)-(TDS)-(EDS)-(EDS)-NHAc</p>
<p>H₂N-(TDS)-(EDS)-(TDS)-(EDS)-(TDS)-NHAc</p>	<p>H₂N-(TDS)-(EDS)-(EDS)-(EDS)-(EDS)-NHAc</p>

Table 1: Heteromultivalent Glycopolymers obtained via SPPoS

Ongoing studies expand the library of glycopolymer ligands towards more complex architectures including hydrogels as well as take a closer look at the molecular interactions of glycopolymer ligands and the targeted protein receptor.^[7,8] Currently our precision glycopolymers are tested in various biological applications such as targeted gene delivery, vaccine development and as antibacterial agents.

L. Hartmann, M. Behra, J. Keller, S. Lel, S. Mosca, D. Ponader, D. Pussak, F. Wojcik
Laura.Hartmann@mpikg.mpg.de

References:

- [1] Hartmann, L.: Polymers for Control Freaks: Sequence-Defined Poly(amidoamine)s and Their Biomedical Applications. *Macromol. Chem. Phys.*, **212** (1), 8-13 (2010).
- [2] Wojcik, F.; Mosca, S.; Hartmann, L.: Solid-Phase Synthesis of Asymmetrically Branched Sequence-Defined Poly(Oligo(amidoamines)) *J. Org. Chem.*, **77**, 4226–4234 (2012).
- [3] Ponader, D.; Wojcik, F.; Beceren, F.; Derner, J.; Hartmann, L.: Sequence-Defined Glycopolymer Segments Presenting Mannose: Synthesis and Lectin Binding Biomacromolecules, **13**, 1845–1852 (2012).
- [4] Wojcik, F.; O'Brien, A.; Goetze, S.; Seeberger, P.H. and Hartmann, L.: Synthesis of carbohydrate-functionalized sequence-defined oligo(amidoamines) by photochemical thiol-ene coupling in a continuous flow reactor, *Chem. Eur. J.*, 2013 DOI: 10.1002/chem.201203927 (2013).
- [5] Mosca, S.; Wojcik, F.; Hartmann, L.: Precise Positioning of Chiral Building Blocks in Monodisperse, Sequence-Defined Polyamides. *Macromol. Rapid Commun.* **32** (2), 197-202 (2010).
- [6] unpublished results
- [7] Behra, M.; Schmidt, S.; Hartmann, J.; Volodkin, D.V.; Hartmann, L.: Synthesis of Porous PEG Microgels Using CaCO₃ Microspheres as Hard Templates, *Macromol. Rapid Commun.* **33** (12), 1049-1054 (2012).
- [8] Pussak, D.; Behra, M.; Schmidt, S.; Hartmann, L.: Synthesis and functionalization of poly(ethylene glycol) microparticles as soft colloidal probes for adhesion energy measurements, *Soft Matter*, **8**, 1664-1672 (2012).

C-type Lectin Receptors: From Glycan Arrays to Murine Studies



Bernd Lepenies 18.09.1978
2004: Diploma, Biochemistry & Molecular Biology (University of Hamburg)
2005-2007: PhD, Biology ("summa cum laude") (Bernhard Nocht Institute for Tropical Medicine, Hamburg)
 Thesis: Role of the co-inhibitors CTLA-4 and BTLA in T cell regulation during malaria
2008: Postdoc, Chemical Biology (Swiss Federal Institute of Technology, ETH Zurich, Switzerland)
Since 2009: Group Leader, Department of Biomolecular Systems, Max Planck Institute of Colloids and Interfaces
Since 2012: Project Leader, Collaborative Research Centre (SFB) 765 (Multivalent carbohydrate interactions)

Innate immunity is of crucial importance as a first line of defense against invading pathogens. Particularly, dendritic cells (DCs) play a pivotal role in antigen presentation and the initiation of a protective immune response. DCs sense pathogens via pattern recognition receptors (PRRs) that bind to conserved pathogen-associated molecular patterns. C-type lectin receptors (CLRs) represent a major PRR family predominantly expressed by cells of the innate immune system. CLRs recognize carbohydrate structures in a Ca^{2+} -dependent manner and orchestrate innate responses to a number of pathogens including bacteria, viruses, fungi, and helminths (Fig. 1). Since ligands have yet been identified for only a limited number of CLRs, one major goal of the Glycoimmunology group is to screen for novel carbohydrate ligands of CLRs. As carbohydrate/lectin interactions usually display low affinities, multivalent ligand presentation is often required. Thus, we use different scaffolds for multivalent display of CLR ligands to allow for a specific targeting of DCs. Finally, we explore the function of CLRs *in vivo* in mouse models of infection and inflammation. CLR-deficient mice are used to investigate the role of a single CLR in inflammatory processes (Fig. 1).

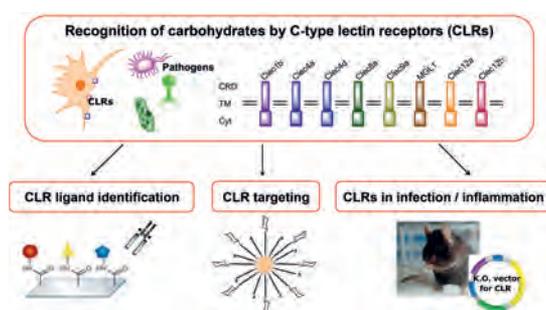


Fig. 1: Main research goals of the Glycoimmunology group. The main focus is on carbohydrate recognition by C-type lectin receptors (CLRs, top panel). In innate immunity, CLRs are predominantly expressed by antigen-presenting cells such as dendritic cells. They recognize conserved carbohydrate structures of pathogens such as bacteria, viruses, or fungi. CLRs consist of an extracellular part containing one or more carbohydrate-recognition domains (CRD), a transmembrane region (TM), and a cytoplasmic part (Cyt). Specific research topics of the Glycoimmunology group are: 1) the identification of novel CLR ligands using the glycan array platform (bottom left), 2) cell-specific drug delivery by CLR targeting with multivalent ligands (bottom middle), and 3) elucidating the role of CLRs *in vivo* using mouse models of infection and inflammation (bottom right).

Glycan Recognition by Antigen-Presenting Cells Impacts Immunogenicity

Carbohydrate recognition by CLRs influences key DC functions such as antigen presentation, cytokine release, and the expression of co-stimulatory molecules. Since all of these processes impact T cell priming and differentiation, CLR targeting is a means to orchestrate an initiated immune response (Fig. 2).

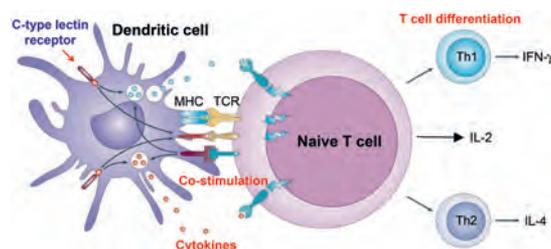


Fig. 2: C-type lectin receptor targeting to modulate immune responses. The engagement of CLRs expressed by dendritic cells (DCs) influences DC functions such as co-stimulation, and cytokine production. Naive T cells recognize peptides presented by MHC molecules on the DC membrane through their T cell receptor (TCR). To proliferate and differentiate into T effector cells, a second signal is required that is provided by co-stimulatory molecules expressed on the DC surface. Since CLR engagement impacts this process, CLR targeting might be a means to shape an initiated immune response.

Carbohydrate recognition by lectin receptors is not only important for pathogen sensing but also for binding of glycosylated vaccine antigens. As a consequence, the differential glycosylation of vaccine antigens can affect their recognition by CLRs, thus may influence immunogenicity. In recent work performed in collaboration with the MPI-DKTS in Magdeburg (E. Rapp & U. Reichl), we investigated the impact of hemagglutinin (HA) N-glycosylation on influenza virus immunogenicity [1]. HA is the most abundant protein in the virus particle membrane, thus it is an essential component of most influenza vaccines. While the importance of HA glycosylation for influenza virus entry into host cells is well-known, we were interested in the impact of HA N-glycosylation on the recognition by antigen-presenting cells and subsequent T cell priming (Fig. 2). Influenza virus HA N-glycosylation was dependent on the host cell line used for virus production. Moreover, two cell line-produced influenza A virus variants with diverse HA N-glycosylation patterns markedly differed in their immunogenicity. Namely, T cell activation and cytokine production *in vitro* and humoral immune responses *in vivo* were affected by the differential HA glycosylation. Virus deglycosylation dramatically decreased cytokine production by spleen cells and reduced HA-specific antibody responses upon immunization of mice indicating a crucial role of HA N-glycosylation for immunogenicity. Our findings have implications for cell line-based influenza vaccine design: appropriate host cell lines can be selected for virus propagation or may even be glyco-engineered to enhance immunogenicity.

In another study, we determined structure-activity relationships of fucoidans with regard to activation of antigen-presenting cells [2]. Fucoidans are sulfated polysaccharides mainly consisting of sulfated α -L-fucopyranose. They are found in various species of brown algae and brown seaweed and were reported to exhibit a wide range of biological activities including anticoagulant and antitumor effects. Native fucoidan from *Fucus evanescens* as well as hyposulfated, deacetylated, and both, hyposulfated and deacetylated derivatives of fucoidan were prepared and used to stimulate pri-

mary DCs and macrophages. Hyposulfation and deacetylation led to markedly reduced cytokine secretion by DCs and macrophages. Both, hyposulfation and deacetylation almost completely abolished cytokine production thus indicating a crucial role of sulfate/acetyl groups for the immune stimulatory activities of fucoidan.

A Platform towards Carbohydrate-Based Adjuvants and Immune Modulators

To identify immune stimulatory and immune modulatory CLR ligands, we have developed a screening platform, followed by *in vitro* and *in vivo* assays. The extracellular domains of different CLRs were expressed as fusion proteins with the F_c part of human IgG₁ molecules. The CLR-F_c fusion proteins were used as tools to screen for carbohydrate ligands of CLRs. We employed the glycan array technology that allows for high-throughput screening of lectin/carbohydrate interactions (shown in Fig. 3). Indeed, novel binding partners of CLRs were identified and interactions with already known ligands could be confirmed. Carbohydrate-protein interactions were further characterized by surface plasmon resonance (SPR) measurements. Next, CLR-recognizing carbohydrates were covalently coupled to the model antigen ovalbumin (OVA). The OVA-glycan conjugates were used in co-cultivation assays of DCs and T cells to stimulate transgenic T cells *in vitro*. In addition, mice were immunized with these conjugates to identify immune modulatory CLR ligands *in vivo*. This platform brings together CLR ligand identification and their immunologic evaluation. Hence, it is a highly useful tool for the functional analysis of CLR ligands (Eriksson, Maglinao et al., manuscript in preparation). Identified carbohydrate/CLR interactions will be investigated in detail to elucidate their role in immunity [3].

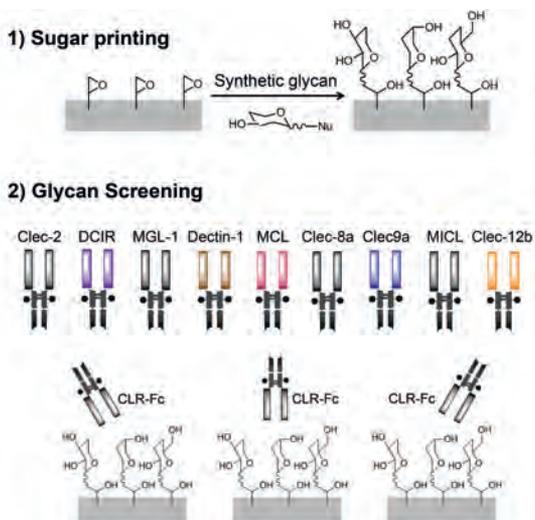


Fig.3: The glycan array platform to identify novel carbohydrate ligands of C-type lectin receptors. 1) Sugar printing: Synthetic glycans (each containing a linker with a terminal nucleophile) are covalently immobilized on epoxide-activated glass slides. 2) Glycan screening: To identify glycan ligands of CLRs, the array is incubated with the respective CLR-F_c fusion protein (some examples of CLR-F_c library members are given). Detection is then performed using a fluorescently labeled secondary antibody.

Multivalent Targeting of C-type Lectin Receptors

Due to the generally low affinities of single carbohydrate/lectin interactions multivalent ligand display is usually a prerequisite for specific CLR targeting. Recent studies indicate that multivalency is indeed a means to overcome these low affinities and exert biological effect [4, 5]. Carbohydrate ligands of the CLR macrophage galactose-type lectin (MGL) were covalently attached to a DNA backbone and presented in the major groove of the B-form duplex DNA. MGL binding was analyzed by SPR measurements and uptake studies in primary macrophages and DCs. Specific ligand binding to MGL was detected indicating the suitability of multivalent carbohydrate ligand presentation for CLR targeting [5]. Multivalent targeting approaches can also be employed to increase the targeting specificity of drugs for tumor cells. We used reversible addition-fragmentation chain transfer polymerization (RAFT) to covalently and site-specifically append a defined HPMA polymer to the cancer drug SN-38 (collaboration with J. Tsanaktsidis, CSIRO Melbourne, Australia) [6]. The poly-HPMA-SN-38 conjugates displayed excellent aqueous solubility and stability and retained the cytotoxic activity of the parent drug SN-38. *In vitro* assays using cancer and non-cancer cell lines showed the specificity of the RAFT-derived poly-HPMA-SN-38 conjugates for cancerous cells. Further specific tumor targeting might be achieved by covalent attachment of small molecules (e.g. carbohydrates) to the polymer-drug conjugates.

Carbohydrate-carbohydrate Interactions

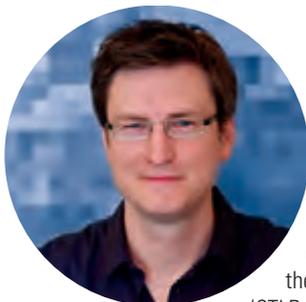
In a recently started project as part of the Collaborative Research Centre (SFB) 765 ("Multivalency as chemical organization and action principle"), we focus on the characterization of carbohydrate interactions. Interactions between carbohydrates are even weaker than carbohydrate/lectin interactions, thus are often hardly measurable. The SFB project deals with the biophysical and biological analysis of interactions between the tumor-specific carbohydrate antigens GM3 and Gg3 as well as GB4 and GalGB4. Since multivalent presentation is essential to measure these low affinity-interactions, the relevant carbohydrate antigens are functionalized on the surface of nanoparticles. Currently, we investigate whether these multivalent carbohydrate interactions are suitable for cell-specific targeting and imaging.

B. Lepenies, M. Eriksson, J. Hütter, T. Johannssen, M. Maglinao, S. Miltsch, U. Vogel, S. Zimmermann
Bernd.Lepenies@mpikg.mpg.de.

References:

- [1] Hütter, J., Rödig, J. V., Höper, D., Reichl, U., Seeberger, P. H., Rapp, E.* and Lepenies, B.*, Toward animal cell culture-based influenza vaccine design: viral hemagglutinin N-glycosylation markedly impacts immunogenicity, *J. Immunol.*, **190**, 220-30 (2013).
- [2] Khil'chenko, S., Zaporozhets, T., Shevchenko, N., Zvyagintseva, T., Seeberger, P. H. and Lepenies, B.*, Immunostimulatory activity of fucoidan from the brown alga *Fucus evanescens*: role of sulfates and acetates, *J. Carbohydr. Chem.*, **30**, 291-305 (2011).
- [3] Kolarich, D., Lepenies, B. and Seeberger, P. H., Glycomics, glycoproteomics and the immune system, *Curr. Opin. Chem. Biol.*, **16**, 214-20 (2012).
- [4] Grünstein, D., Maglinao, M., Kikkeri, R., Collot, M., Barylyuk, K., Lepenies, B., Kamena, F., Zenobi, R. and Seeberger, P. H., Hexameric supramolecular scaffold orients carbohydrates to sense bacteria, *J. Am. Chem. Soc.*, **133**, 13957-66 (2011).
- [5] Schlegel, M., Hütter, J., Eriksson, M., Lepenies, B. and Seeberger P. H., Defined presentation of carbohydrates on a duplex DNA scaffold, *ChemBiochem.*, **12**, 2791-800 (2011).
- [6] Williams, C. C., Thang, S. H., Hantke, T., Vogel, U., Seeberger, P. H., Tsanaktsidis, J.* and Lepenies, B.*, RAFT-derived polymer-drug conjugates: poly(hydroxypropyl methacrylamide) (HPMA)-7-ethyl-10-hydroxycamptothecin (SN-38) conjugates, *ChemMedChem.*, **7**, 281-91 (2012).

Specific C-type Lectin Receptor Ligands



Christoph Rademacher 05.05.1979

2001-2004: Bachelor Studies in "Molecular Biotechnology" at the University of Lübeck, Germany (with honours).

2004-2006: Master Studies in "Molecular Life Science" at the University of Lübeck, Germany (with honours)

2006-2009: Doctoral Thesis: "Investigations into Viral Entry Mechanisms and Carbohydrate-Protein Interactions using NMR" (summa cum laude, Prof. Dr. Thomas Peters, Institute of Chemistry, University of Lübeck, Germany)

2007-2009: PhD stipend from the Fonds der chemischen Industrie.

2009-2011: Postdoctoral training at Department of Chemical Physiology, The Scripps Research Institute with Prof. Dr. James C. Paulson (La Jolla, CA, USA).

2009-2011: EMBO Long-Term Fellowship
Since 11/2011: Research Group Leader, Department of Biomolecular Systems, Max Planck Institute of Colloids and Interfaces

2011-2012: Liebig Stipend from the Fonds der Chemischen Industrie

Since 06/2012: Emmy-Noether Young Research Group Leader

Carbohydrate structures represent a fundamental class of biopolymers and have been identified as important mediators of many recognition processes in health and disease. Their function is determined by the context of their presentation, as glycoproteins or glycolipids, and the structure and dynamics of their receptors. Myeloid C-type lectin receptors (CTRLs) are one subfamily of carbohydrate binding proteins of particular interest. This receptor family is defined by its consensus protein fold and for most members, the calcium-mediated recognition of self- as well as non-self carbohydrates structures. This protein/carbohydrate interaction then shapes for example the cellular response to necrotic cells or determines the immune response to invading pathogens. The details of this molecular interaction and mechanisms coupling it to immunological outcomes are not well understood. Fundamental insights are expected from these investigations into this exciting field of molecular immunology and will provide potential for the development of immune modulatory therapeutics. Therefore, state of the art biophysical techniques such as nuclear magnetic resonance and fluorescence spectroscopy, together with computational modelling are applied to address questions of high relevance for immunology [1]. In particular, these insights are utilized to design high affinity, specific and chemically defined probes to investigate the biology of C-type lectin receptors.

Computer-Aided Design and Synthesis of Ligands for CTRLs

Compared to the number of members of the C-type lectin fold family, the structural information is rather sparse. Still, a few members of the subfamily of myeloid CTRLs have been characterized by X-ray crystallography and NMR spectroscopy. The resolution of these structures is of sufficiently high resolution allowing *in silico* methods to be used to aid the search for small molecular probes for these lectins. CTRLs that obey a calcium-mediated recognition of glycans share a shallow binding site (Fig. 1). This not only explains the intrinsically low affinity of these cell surface receptors for their glycan ligands, but also imposes a challenge to any rational design of high affinity ligands for these proteins.

Available X-ray structures are chosen as a starting point, which display the respective CTRL in complex with one or more glycan ligands. The design process therefore starts from an already existing ligand pose and hence develops this into a high affinity lead structure [2]. This has advantages

compared to *de novo* design strategies and builds on the expertise of the department in the field of carbohydrate chemistry. The chemistry of carbohydrate derivatization implies certain restrictions onto the possible lead candidates and is therefore directly incorporated into the design process, allowing a rapid advancement of computational models into synthetic molecules.

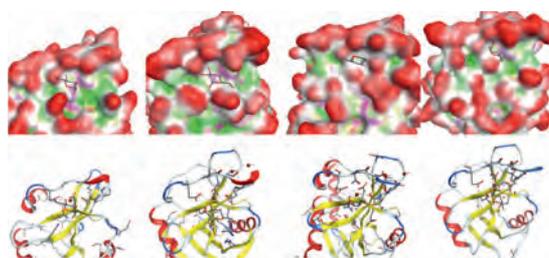


Fig. 1: C-type lectin receptor carbohydrate recognition sites. A selection of CTRL binding sites is shown, highlighting the shallow, calcium-mediated carbohydrate interaction. Upper panel: glycan in stick presentation, receptor depicted in Connolly surface representation (red: solvent exposed, green: hydrophobic, magenta: hydrophilic). Lower panel: Ribbon representation of the corresponding receptor/ligand complexes (red: α -helix, yellow: β -sheet, blue: turn).

Fragment-Based Drug Design

The pipeline of many pharmaceutical companies has experienced a decline of preclinical candidates during the last decade, raising a serious demand on novel strategies for rapid hit finding and lead progression. Since Fesik and co-worker's key contribution to the field by establishing SAR-by-NMR [3], fragment-based approaches in drug discovery have developed many facets. These approaches are no longer limited to nuclear magnetic resonance and make use of other sensitive techniques such as surface plasmon resonance (SPR) and X-ray crystallography of ligand cocktails for screening. With respect to the screening methodology, a sensitive detection is mandatory, as molecular fragments of the size of 250 Da or less are intrinsically of low affinity. What renders them interesting starting points for ligand design is their limited chemical complexity, allowing to fit many structural requirements imposed by their potential receptors. Hence, these fragment libraries have high hit-rates. These hits can then be developed into lead structures by processes such as fragment-linking or -growth [4], giving rise to an impressive list of clinical drug candidates against challenging candidates [5].

Since Fesik's first description of this procedure, many academic groups build on these findings and developed related techniques [6]. While the academic environment favours the development of preclinical candidates, many applications focus on the development of chemical probes for chemical biology. In particular, undruggable, challenging binding sites have been explored using fragment-based approaches, discovering that the static nature of structures determined by X-ray determined can be misleading [7]. Here, we use fragment-based design strategies to identify CTLR ligands from pools of small molecules. To this end, a fragment library was rationally designed using cheminformatics tools. The pool bearing over 1000 diverse compounds was assembled from commercial vendors and academic collaborations (Fig. 2). The library is now available for screening and will benefit from its diversity.

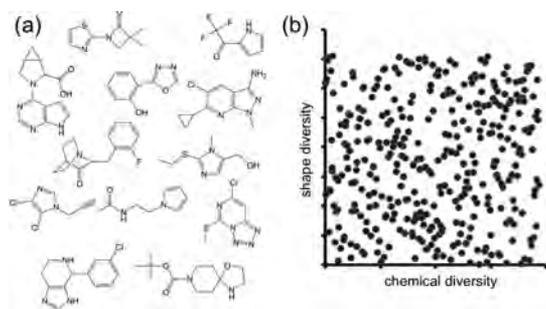


Fig. 2: Diverse fragment screening library. (a) A selection of small heterocyclic compounds is shown. (b) A scatterplot of the chemical versus shape diversity highlights the coverage of chemical space of the library. Chemical diversity is assessed using MACCS chemical fingerprint combined with the Tanimoto similarity coefficient and plotted against the diversity as determined using the 3Deigenshape function of MOE (Chemical Computing Group).

Glycan Fingerprints

CTLRs interact with a diverse set of glycan structures of self as well as non-self origin. To understand these lectin receptor interactions with their natural glycan ligands, a unifying picture of glycan diversity has to be developed that is able to cope with this complex pattern. To rationally address this problem and to approach related problems in glycobiology, we developed a formal guide to quantify glycan diversity [8]. In contrast to other biopolymers such as peptides and oligonucleotides, the branched structure of carbohydrates imposes challenging demands on the comparison of glycan structures. This rational can then guide the construction of diverse glycan libraries, a central question in the field of glycomics [8].

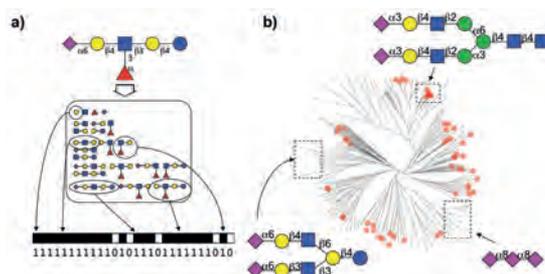


Fig. 3: Glycan Fingerprints. (a) The CFG representation of a complex glycan is decomposed into all possible fragments. The existence of all unique fragments is stored into a bit string, transferring a branched structure into a linear representation. (b) Based on the string representation of glycans, the similarity between carbohydrates can be assessed quantitatively and a non-rooted tree depiction of a glycan library is derived. Clusters of high density as well as non-represented clusters are highlighted to guide the chemistry to fill these gaps [8].

To date, the selection of glycans for carbohydrate libraries such as microarray studies was done empirically, drawing on experience. Therefore, an algorithm was developed for the analysis of glycan library diversity based upon an analogy between a simplified glycan representation of monosaccharides and glycosidic bonds, as found in the symbol notation of the Consortium for Functional Glycomics (CFG), and small molecule graphs as used in cheminformatics. This novel and powerful approach allowed us to derive a linear representation of complex glycan structures, which was then used to calculate pairwise similarities. These similarities expressed in numerical values are fundamental to finally derive diversities of groups of glycans and by that answering key questions for future development of glycobiology tools such as glycan microarrays.

Furthermore, this tool will find its application in other fields of glycobiology such as the analysis of glycosylation patterns. The glycosylation machinery is a very important component of the cell/cell communication system. It provides and stores information on the cell surface in defined recognition patterns and is dynamically adjusted. Means to quantify this diversity have been missing. The introduction of Glycan Fingerprints opens a door towards the systematic understanding of the dynamic interplay between cell physiology and glycosylation in a quantitative way. Transforming the overwhelming diversity of glycosylation into numbers will unravel new paradigms and thereby integrating today's data from e.g. mass spectrometry into a system wide framework.

C. Rademacher, J. Aretz, J. Hanske, E. Wamhoff.
Christoph.Rademacher@mpikg.mpg.de.

References:

- [1] J. Angulo, C. Rademacher, T. Biet, A. J. Benie, A. Blume, H. Peters, M. Palcic, F. Parra, T. Peters, *Methods. Enzymol.*, **416**, 12-30, (2006).
- [2] C. M. Nycholat, C. Rademacher, N. Kawasaki, J. C. Paulson, *J. Am. Chem. Soc.*, **134**, 15696-15699, (2012).
- [3] S. B. Shuker, P. J. Hajduk, R. P. Meadows, S. W. Fesik, *Science*, **274**, 1531-1534, (1996).
- [4] M. Fischer, R. E. Hubbard, *Mol. Interv.*, **9**, 22-30, (2009).
- [5] M. Baker, *Nat. Rev. Drug. Discov.*, **12**, 5-7, (2012).
- [6] C. Rademacher, J. Guiard, P. I. Kitov, B. Fiege, K. P. Dalton, F. Parra, D. R. Bundle, T. Peters, *Chem. Eur. J.*, **17**, 7442-7453 (2011).
- [7] Q. Sun, J. P. Burke, J. Phan, M. C. Burns, E. T. Olejniczak, A. G. Waterson, T. Lee, O. W. Rossanese, S. W. Fesik, *Angew. Chem. Int. Ed. Engl.*, **51**, 6140-6143, (2012).
- [8] C. Rademacher, J. C. Paulson, *ACS Chem. Biol.*, **7**, 829-834, (2012).

Deciphering the Glycocode for Understanding Intercellular Communication



Daniel Kolarich 25.03.1975

2000: Diploma, Food Science and Biotechnology (University of Natural Resources and Applied Life Sciences, Vienna)

2004: PhD, (University of Natural Resources and Applied Life Sciences, Vienna),

Topic: Mass spectrometry based glycoproteomic analysis of GMO food crops and allergens from plants and insects

2005-2007: Postdoc,

(University of Natural Resources and Applied Life Sciences, Vienna)

2007-2010: Postdoc,

(Macquarie University, Sydney, Australia)

Since 09/2010: Group Leader Glycoproteomics Group, (MPI of Colloids and Interfaces, Potsdam)

Numerous so-called glycoconjugates are crucial key players of intercellular communication. Information between cells is often mediated by secreted or membrane bound glycoconjugates such as glycoproteins. Both, the protein and the glycan moiety of such a glycoconjugate are important information carriers and in order to understand the language

cells are using for communication in health and disease scientists require robust and solid techniques that allow monitoring and deciphering of communication events on cellular level. In the context of protein glycosylation and its role in bio-messaging the human immune system is one of the best understood cellular mechanisms that has been shown to be significantly influenced by the type and action of glycans [1]. Immune cell glycan alterations play a critical role in e.g. regulating effector functions such as dendritic cell or T cell activation [reviewed in 1]. Glycan structures on immune cells interact with lectins such as C-type lectins, S-type lectins (e.g. galectins), or I-type lectins (e.g. siglecs), thus deeper insights into the cellular glycome promise to deepen our understanding of intercellular communication mechanisms [2].

In order to decipher the language of complex multicellular systems such as the human immune system detailed knowledge on both, the individual proteins and their particular post-translational modifications such as glycosylation is vital. In the last two decades the study of biomolecules has been greatly facilitated by novel developments in mass spectrometric techniques and instruments, nevertheless further advancements in technologies and approaches are required for the robust and accurate identification and characterisation of glycoconjugates derived from biological specimens.

LC-ESI MS is a Powerful Tool for Glycoconjugate Analysis

Combining nano-scale liquid chromatography (LC) online with state of the art mass spectrometric (MS) detection techniques provides us with powerful opportunities to separate, isolate and characterise femto- to picomol amounts of biomolecules derived from biological samples. Nano-scale LC separation is an important additional dimension increasing significantly the amount of information that can be obtained from a single sample simply by supplying the compounds of interest to the mass spectrometer over the entire time frame of the LC separation, resulting in an increased depth of analysis and number of ions detected from a single sample. Without this prior separation molecules present in lower concentrations might not be detected and thus information on these components would be lost. In addition, the choice of separation medium linked to the mass spectrometer provides us with the opportunity to specifically target the respective compounds of interest based on their molecular properties.

Subsequently, reversed phase separation media are usually chosen for the analysis of glycopeptides and peptides [3], whereas far better data can be obtained for oligosaccharides released from glycoproteins when subjected to LC separation using porous graphitized carbon (PGC, Fig. 1, 3) [4].

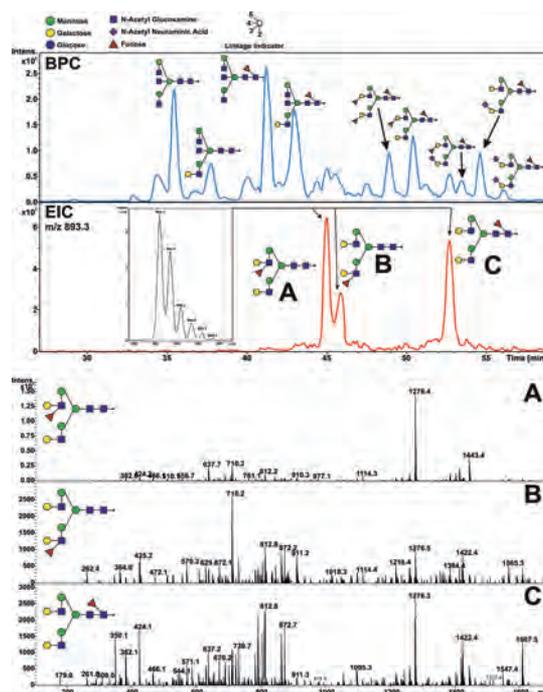


Fig. 1: Glycan structure isomers can be separated using PGC LC and signature ESI-MS/MS spectra enable unambiguous glycan identification
Figure taken from [1].

Defined Standard Compounds Help us in Developing Novel Glycoproteomics Techniques

The easy availability of well-defined biomolecules has always been a key for scientific advancements. Simple access to custom-made nucleotide or peptide sequences has turned out to be vital for any molecular biology and biochemistry research. Recent advances in automated oligosaccharide synthesis are very promising to bridge this gap in glycomics research [5]. However, glycoproteomics research requires access to molecules that can be tailored on both, the peptide and the glycan side of the molecule.

Current strategies based on total synthesis of both, the glycan and peptide moiety are suffering from limitations of establishing a native peptide-glycan bond under synthetic conditions as well as easy diversification of the glyco-moiety into larger structures. Making use of nature's glycosylation potential, the combination of controlled proteolytic digestion

with state of the art separation technologies enables us to obtain glycosylated amino acids that can further be modified to be used in standard solid phase peptide synthesis for the production of tailor made glycopeptides.

Using these synthetically produced glycopeptides and peptides we now have the opportunity to establish quantitative correlations of the different compounds that are frequently detected in a glycoproteomics experiment. The fact that these natural biomolecules exhibit significantly different chemical properties makes it impossible to extract quantitative information from MS data without having appropriate standards in hand. These well-defined standards enable determination of quantitative relationships from the detected signals and thus make label free quantitation of glycopeptides a reality (Fig. 2) [6].

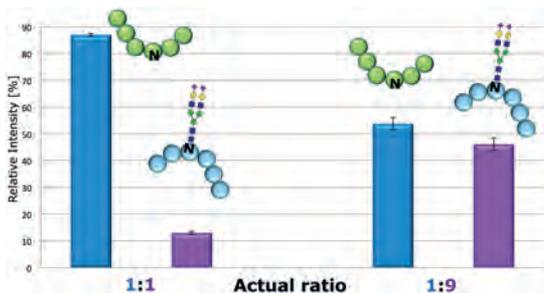


Fig. 2: The application of exactly defined and quantified peptides (green circles) and glycopeptides (blue circles) produced by solid phase peptide synthesis uncovered that glycopeptides differ significantly in their ionisation efficiency. Injection of equal amounts of the target molecules resulted in significant differences in detected signal intensities. The ability to determine and quantify these differences is an important step towards obtaining useful quantitative information for glycopeptides from MS-experiments [6].

Disease Glycoproteomics – Deciphering Intercellular Communication Signals in Inflammatory Bowel Disease and Skin Neoplasia

The glycoproteomics group is using its tools and developments to understand how the intracellular glycoprotein communication network is changing in the course of diseases. With this information in hand it is possible to gain a better understanding on disease onset and progression. In cooperation with medical institutions and international networks we are focusing on identifying and characterising glycoproteins and glycans associated with inflammatory bowel diseases, which have a prevalence of 0.8% and are associated with high morbidity, definite mortality and an increasing economic burden in particular in western countries. We are partners in the IBD-BIOM consortium, an EU-funded project joining cutting edge epigenomic, glycomic, glycoproteomic and active-

mic approaches to elucidate particular IBD associated pathways and disturbances to the immune system.

Another major focus is the determination of skin neoplasia glycoprotein signatures. With around 2-3 million cases per year skin cancer is one of the most prevalent cancer types worldwide. Malignant melanoma, one of the most dangerous types of cancer if detected late, represents around 5% of the cases. The majority of reported cases comprise the so-called non-melanoma skin cancers such as basal cell carcinoma or squamous cell carcinoma, which are seldom lethal but can be disfiguring and a psychological burden to patients if detected late or left untreated. First results obtained on basal cell carcinoma specimens provided promising data indicating that substantial changes in the glycome and glycoproteome are occurring. This information will be used to gain a deeper understanding on the onset and progression of skin neoplasia.

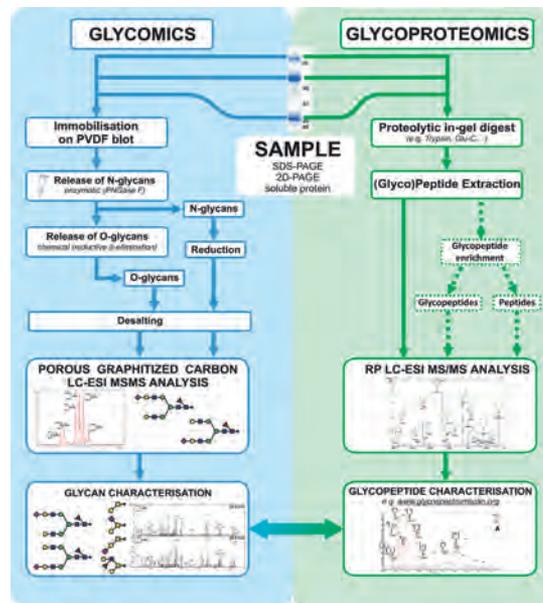


Fig. 3: Using Glycomics and Glycoproteomics detailed information can be determined from μg amounts of initial protein. LC-ESI-MS/MS techniques can be successfully applied to identify proteins and their post translational modifications to understand their role in health and disease. [3,4]. Figure taken from [3].

D. Kolarich, K. Alagesan, H. Hinneburg, U. Möginger, K. Stavenhagen
 daniel.kolarich@mpikg.mpg.de

References:

- [1] Kolarich D., Lepenies B., Seeberger P. H.: Glycomics, glycoproteomics and the immune system, *Curr Opin Chem Biol.* **16**, 214-20 (2012).
- [2] Lepenies B., Yin J., Seeberger P.H.: Applications of synthetic carbohydrates to chemical biology. *Curr Opin Chem Biol.* **14**(3): p. 404-11 (2010).
- [3] Kolarich D., Jensen P. H., Altmann F., Packer N. H.: Determination of site-specific glycan heterogeneity on glycoproteins, *Nat Protoc.* **7**(7): 1285-98 (2012).
- [4] Jensen P. H., Karlsson N. G., Kolarich D., Packer N. H.: Structural analysis of N- and O-glycans released from glycoproteins, *Nat Protoc.* **7**(7): 1299-310 (2012).
- [5] Esposito D., Hurevich M., Castagner B., Wang C. C., Seeberger P. H.: Automated synthesis of sialylated oligosaccharides. *Beilstein J Org Chem.* **8**: 1601-9 (2012).
- [6] Stavenhagen K., Hinneburg H., Thaysen-Andersen M., Hartmann L, Silva DV, Fuchser J, Kaspar S., Rapp E., Seeberger P.H., Kolarich, D.: Quantitative mapping of glycoprotein micro- and macro-heterogeneity: An evaluation of mass spectrometry signal strengths using synthetic peptides and glycopeptides, *J Mass Spectrom* 2013, in press



- 
- Heterophase Polymerization
 - Porous Polymers
 - Chimera Polymers and Novel Synthetic Methods
 - Modern Techniques of Colloid Analysis
 - Hydrothermal Carbon Nanostructures and Coatings
 - De Novo Nanoparticles
 - Poly(ionic liquid)s as innovative polyelectrolytes

COLLOID CHEMISTRY

Research in the Department of Colloid Chemistry



Markus Antonietti 06.02.1960

1983: Diploma, Chemistry
(University of Mainz)

Thesis: Bestimmung der Diffusion von photomarkiertem Polystyrol: spezielle Systeme, chemische und physikalisch-chemische Aspekte

1985: Doctorate for natural science (summa cum laude, University of Mainz)
Thesis: Diffusion in topological constraint polymer melts with Prof. Dr. H. Sillescu

1990: Habilitation, Physical Chemistry (University of Mainz) Thesis: Microgels – Polymers with a special architecture
02/1991: Associate Professor (University of Mainz)

09/1991: Full Professor (Philipps University Marburg)

Since 1993: Director (Max Planck Institute of Colloids and Interfaces, Golem),
Full Professor (University of Potsdam)

Scientific Profile

The overall size of the Department of Colloid Chemistry is about 65 people, covering a wide range of research topics. The effective constituting element of the scientific activities is the “project”, a structure headed by a senior scientist involving a mixture of technicians, graduate students and post-docs (3–8 people). Projects are related to scientists, but usually have a temporal character of about 5 years. After this time, permanent scientists (including the director) have to redefine their profile to justify the allocation of resources. In the case of non-permanent scientists, the projects usually leave the department with the promotion of the scientist, i.e. the group leaders can continue their specific research in their new academic environment (usually as professors) without competition of the institute.

In the time of this report and following these schemes, serious changes of my department already observed in the last two reporting periods continued to take place. Dr. Magdalena Titirici, group leader on “Sustainable Carbon”, accepted a position at Queen Mary University London, and the move of Prof. Dr. Xinchun Wang to Fuzhou University was completed, moving “Artificial Photosynthesis” into an International Joint Research Lab. At the same time, I hired Dr. Jiayin Yuan (“Polymer Ionic Liquids”, PILs), Dr. Filipe Vilela (“Photocatalysis”), Dr. Dariya Dontsova (“Photosynthesis”), Dr. Davide Esposito (“Processes for the raw material change”), and Dr. Tim Feller (“Electrocatalysis”) as new group leaders to start to establish their own research profile. It is fair to say that a majority of the group is now still in the primary phase of higher academic profiling, making the following report more idea that publication oriented. This turnover of leading junior scientists is beyond typical and easy, but reflects the dynamic character of the department.

The profile of the department has therefore been seriously reoriented, keeping only some of the old strongholds. The following topics are now found within the department:

- Heterophase Polymerization
- Chimera Polymers and Novel Polymerization Techniques
- Polymeric Ionic Liquids
- Service Lab Electron microscopy
- Carbon Materials and Hybrids for Energy applications
- Processes for the Raw Material Change
- De Novo Inorganic Nanostructures
- Photocatalysis and Artificial Photosynthesis

The projects below those headers are briefly explained:

Heterophase Polymerization

The notation „Heterophase Polymerization“ summarizes the techniques of suspension-, emulsion-, mini-, and microemulsion-polymerization as well as precipitation polymerization. The solvent is usually water, but heterophase polymerization in inverse media is also examined. This class of techniques, although one of the eldest in polymer science, is still most actual, as it allows the production of high polymer containing formulations in water as an environment-friendly solvent. Solvent free coatings, glues, paper and fabric production are just a small excerpt of a long list where polymer dispersions have opened new possibilities and technologies, omnipresent in daily life, but usually unseen to the public.

Central points of interest of the team working on heterophase polymerization are:

- We want to simplify the synthesis of complex polymer morphologies on a molecular level (synthesis of block & graft copolymers by emulsion polymerization) and on a colloidal level (core-shell latices, hollow spheres, one-step synthesis of reinforced materials) by a rational use of the particle interfaces in heterophase polymerization (*Dr. Klaus Tauer*).
- We use new stabilizer systems (such as PILs) to generate new latexes structures and films with switchable Hydrophobicity (*Dr. Klaus Tauer*, with *Dr. Jiayin Yuan*)
- Emulsions stability can be accomplished even without molecular stabilizers using ultraclean conditions. The mechanisms of this process are analyzed (*Dr. Klaus Tauer*)

Chimera Polymers and Novel Polymerization Techniques

Amphiphilic polymers consist of components which dissolve in different media, e.g. a hydrophilic and a hydrophobic part. Since we are able to adjust both components sensitively to the dispersion medium as well as to the dispersant, amphiphilic polymers allow the stabilization of unusual dispersion problems. The newest observation in this direction is that also block copolymers without hydrophobic contrast can self-assemble to complex structures. Focal points of interest in this project group are:

- The micelle formation and lyotropic liquid crystalline phase behavior of blockcopolymers polymers is examined in dependence of the molecular structure, the relative amount of the different components, as well as the secondary interactions between the structure forming bio-like blocks (*Dr. Helmut Schlaad*).
- The introduction of secondary interactions such as H-bridges or dipole interactions results in superstructures with more complex order and broken symmetry, which point the way to general rules of biomimetic mesoscale organization (*Dr. Helmut Schlaad*)

Polymeric Ionic Liquids

Polymerized ionic liquids or poly (ionic liquid)s (PILs) are usually synthesized by polymerization of ionic liquid (IL) monomers and constitute a subclass of polyelectrolyte that combines a part of IL's properties with the common features of polymers. PILs are not only another class of ordinary polyelectrolytes, but carry extra properties, which can be attributed to the high polarizability of the monomer units. As such, PILs hold some unique structural merits and are advantageous in a multitude of materials applications, such as gas separation/absorption, carbon preparation, energy conversion, catalysis, and many more. PILs are also surface-active and multifunctional polyelectrolytes. Though the originally designed task of PILs was only to effectively stabilize a wide variety of diverse nanoparticles, their unexpected versatile powers were quickly recognized and contribute significant to create science from the products.

· PILs with special stabilization behavior and switchable solution properties are constructed from a wider range on organic cations and anions (*Dr. Jiayin Yuan*).

· Biodegradable and biomass-based PILs are built from hydrothermal reforming chemicals (*Dr. Jiayin Yuan, Dr. Davide Esposito*)

· PILs are used via complexation and/or carbonization as mesoporous membrane materials with high chemical selectivity and permeation (*Dr. Jiayin Yuan, Markus Antonietti*).

Service Lab on Electron Microscopy

All the work described above is necessarily accompanied by a considerable amount of colloid analysis which includes special techniques of transmission and scanning electron microscopy on soft, structured matter which are runned on the base of a central service group (*Dr. Jürgen Hartmann*).

It is a big problem that due to the financial crisis of the Max Planck Society and the delay of starting the extension building this group has to work under increasingly worsening working conditions, keeping the operations alive with constant repair of now 20 years old machines.

Materials for Energy applications

Following the former project house ENERChem which was devoted to materials chemistry to handle energy problems, we still work on better fuel cells, new energy cycles, new catalysts for more efficient processes, methane activation, better batteries, ultracapacitors, decentral energy storage devices. The new activities based in Golm include:

· New C/N-polymers and carbon materials to expand the property profile of carbon (*Markus Antonietti*)

· Porous polymers as membranes for fuel cells and battery separators and as novel gas storage materials (*Dr. Jens Weber*)

· Metal free catalysis and Nitride Catalysis for water splitting, methane and ammonia activation, or CO₂-reactions (*Prof. Dr. Xinchun Wang* in the international joint laboratory, new group leader *Dr. Dariya Dontsova*)

· New engineering carbons based on ILs and salt templating as electrodes and electrode membranes for fuel cells and electrocatalysis; this also includes work on supercapacitors. Another application are metal free carbon catalysts for O₂ and H₂ activation (*Dr. Tim Fellingner*)

Processes for the Raw Material Change

Hydrothermal Carbonization is a 100 year old technique to generate carbonaceous materials from biomass in a colloidal heterophase reaction processes. We reactivated in the last 10 years this process to address questions of the sustainable/chemical synthesis of carbon nanostructures and – just recently – also organic compounds. First experiments indicate that not only the non-oil based raw material base ("sugar") is highly attractive. It is also the broad range of chemistry which can be addressed and which makes this approach attractive.

· Analysis of the elemental chemical steps of HTC and hybridization with technical monomers to generate new materials, such as mesoporous scaffolds for catalysis, battery applications and modern chromatography These activities are reported, but are transferred to London with the former group leader *Dr. Maria Magdalena Titirici*)

· Performing hydrothermal processing under distinct catalytic conditions does not lead only to carbon materials, but also to valuable organic intermediates and platform chemicals. We currently focus on lactic acid generation (for bioplastics), the synthesis of ionic liquids from biomass in water and the production and valorization of a rather clean lignin fraction (*Dr. Davide Esposito*)

De Novo Nanoparticles

Many materials, which are relevant for novel energy cycles and more efficient chemical reactions (catalysis) do not exist as nanostructures (or their synthesis is not sustainable) so that "de novo" systems have to be designed from scratch.

· We develop new synthetic pathways towards metal carbide and nitride nanostructures, which offer new options for metal/base catalysis, but also are record holders in mechanical hardness and magnetization. In general, both size and shape add to the demanded properties and must be controlled or adjusted. (*Dr. Cristina Giordano*)

- Based on paper as a reactant and printing of metal salts, we expect to develop a simple access to functional catalytic arrays and electrodes via materials transcription (*Dr. Cristina Giordano*)
- Unconventional heating devices such a focused light, microwaves, or induction coupling enables unconventional solid state processes with extreme temperature ramps and unmatched reaction control. This is explored for nanoparticle synthesis in salt melts (*Dr. Tristan Corbiere*)

Photocatalysis Artificial photosynthesis

The international joint laboratory on Artificial Photosynthesis was established in July 2008 between the Max-Planck Institute of Colloids and Interfaces (Prof. Markus Antonietti) and Fuzhou University (Prof. Xianzhi Fu). The lab is now lead by Prof. Dr. Xinchun Wang, a former MPI group leader. The artificial versions of photosynthesis, i.e. (1) the splitting of water into hydrogen and oxygen, and (2) the conversion of carbon dioxide into organics via sunlight, are both in the center of this program. An important challenge in artificial photosynthesis is the development of antenna structures or light converters that should be sufficiently efficient, stable, inexpensive, and capable of harvesting the abundant visible light in solar spectrum. There are many trials to establish stable systems for this purpose, mostly based on inorganic semiconductors with appropriately engineered band-gap. In our group we are investigating polymeric and organic-inorganic hybrid materials with controlled nanostructures as potential energy transducers for artificial photosynthesis for such applications as solar energy conversion, environmental purification, and organic synthesis.

- Melon, a carbon nitride polymer with graphitic structure, has turned out to be efficient for the direct splitting of water into oxygen and hydrogen. We improve the chemical structure of this polymer by copolymerization and textural control to improve light extinction and quantum efficiency of this process (*Dr. Xinchun Wang, Dr. Dariya Dontsova*).
- Metal doped C_3N_4 has turned out to be a valuable catalyst for a number of oxidation, photoreduction and photocoupling reactions (*Markus Antonietti, Dr. Dariya Dontsova*, together with *UNICAT/ TU Berlin*)
- The search for appropriate nanoscopic co-catalysts for oxygen liberation or CO_2 conversion is another key issue. Here we work on new carbon structures, cobalt oxides as well as on metal carbides and metal nitrides (*Markus Antonietti, Dr. Cristina Giordano*)
- The melon principle was recently generalized by polymerizing special conjugated microporous polymers (CMPs) with a special design which also allows working in direct contact with oxygen and water. These polymers are now used for polymer photocatalysis, for instance for continuous singlet oxygen generation (together with the *Seeberger* department) or other oxidative rearrangement reactions (*Dr. Filipe Vilela*)

Visions and Future Perspectives for the Next Years

The special situation with a change of overall 75% of the group leader positions promoted a recent redefinition and reorientation of the department. After a temporal phase of being too much involved in taking care of too many independent Junior careers, I personally prefer to enter a period with more coordinated research and longer term goals focussed around as director and more tightly bound junior people.

Our trials to cooperate with the National Excellence Centre on Catalysis of the TU Berlin have not only led to an exchange of staff, but are to my opinion very promising, concerning the development of completely new catalytic schemes (with TU Organic and Inorganic Chemistry) There are some high impact schemes with TU Berlin in the pipeline.

The started projects on "Energy Materials" and "Processes for the Raw Material Change" turned out to be very timely and secured my department in the last two years a leading European role in these activities. IN addition, the donation of the ERC Advanced Excellence Award has already led to some very promising co-operations and broken paradigms. It is my intention to expand these activities by further focussing and profiling.

Larger Equipment and Central Service Labs of the Department

Commercial standard techniques which are available in the department are:

- transmission and scanning electron microscopy,
- static and dynamic light scattering,
- diverse techniques of light microscopy,
- a chromatographic lab including a number of modern chromatography techniques,
- reaction calorimetry with online multidetection,
- analytical and preparative ultracentrifugation,
- thermal analysis, DSC and porosimetry,
- MALDI-TOF-mass spectrometry,
- FT-ATIR for liquid analysis.

One of the labs, the electron microscopy lab, is a so-called "central service labs", i.e. it belongs and is operated by the department, but is also designated to perform scientific routine measurements for the whole institute.

All other instrumental labs are not devoted to service operations, but are nevertheless heavily involved in inter-department projects.

Relations to Industry and Society

The department is involved in a large number of industrial projects. We promote fruitful and truly mutual relations with BASF AG and Firmenich. These operations include scientific cooperation, knowledge exchange, consulting, the solution of minor scientific problems or measurements, and knowledge transfer to create the scientific base for products of the companies.

I am a board member of 15 scientific journals, and I consult the Royal Society of Chemistry/UK in questions of international exchange and benchmarking. I am the Sekretar (chair) of Natural Sciences of the Berlin-Brandenburgische Akademie der Wissenschaften. In science policy, I regularly act as a referee in DFG, European and International science evaluations. I am in the Advisory Board of both the Thailand and the Brazil Centers of Nanotechnology. I regularly go to schools and lecture about the problems of a developing society and how to respond on the base of scientific knowledge and education.

Markus Antonietti
Director of the Department
of Colloid Chemistry

Polymer Dispersions/Heterophase Polymerizations



Colloidal processes are omnipresent in the chemical industry and particularly in polymer chemistry, heterophase polymerization is a centennial technology which nowadays produces high-tech polymeric materials with a value of several billion euros per year [1]. Thus, better understanding of heterophase polymerization and educating students on this topic is of general scientific and economic interest.

Klaus Tauer 27.09.1951

1974: Diploma, Chemistry (Friedrich-Schiller University Jena)

Thesis: Dye Sensitization of Photoconductivity of

Poly(arylene vinylene) Polymers

1978: PhD, Polymer Chemistry (Friedrich-Schiller University Jena)

Thesis: Investigations of spectral sensitization of photoconductivity of poly(arylene vinylene) polymers

1977-1991: Scientific Coworker Institute of Polymer Chemistry of the Academy of Sciences of the GDR in Teltow-Seehof

Since 1992: Group Leader (Max Planck Institute of Colloids and Interfaces, Potsdam)

Since 2004: "Privatdozent" Polymer Colloids, University of Potsdam

Schizomorphic Latex Particles

"Schizomorphic" particles, prepared by special radical heterophase polymerization techniques [2], possess the ability to change shape and morphology in dependence on the particle concentration. At very low concentrations, the particles even disintegrate from spheres into rods, rings, and webs [3] (Fig. 1). Hence, for amphiphilic block copolymer particles, conclusion regarding morphology and shape in the dispersed state, based on normal SEM or TEM images, should be made extremely cautiously.

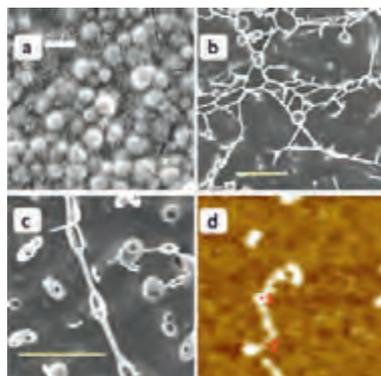


Fig. 1 Different morphologies observed for amphiphilic polystyrene-co-poly(styrene sulfonate) particles; a – SEM micrograph, dry sample from 0.4 %, bar 200 nm; b, – cryo-SEM micrograph, 0.4, bar 500 nm; c – AFM image from 0.0004%, side 400 nm (1 – 1.344 nm, 2 – 0.556 nm)

Photo-Initiated Bulk and Emulsion Polymerization

A comparative experimental study of bulk and emulsion polymerization of styrene with bis-(2,4,6-trimethylbenzoyl)-phenylphosphine oxide (BAPO) or bis-(4-methoxy benzoyl)-diethylgermanium (BAG) as photoinitiator or photoinitiator-free reveals astonishing similarities and anticipated differences [4]. Photopolymerization of styrene with initiation in the monomer phase is under homogeneous and heterogeneous conditions as bulk and emulsion polymerization, respectively, characterized by essentially the same features with respect to radical formation and chain growth. In either case the polymerization can be started photochemically with normal fluorescence tubes as light source which are also used for indoor illumination.

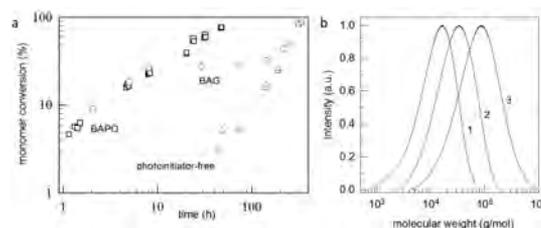


Fig. 2 a - Correlation between monomer conversion and polymerization time for photo-initiated bulk polymerization of styrene; b - Development of the molecular weight distributions (BAPO): 1 – 4, 2 – 22, 3 – 76 % conversion

The bulk polymerizations in the presence of photoinitiators continue even after complete decomposition of BAG and BAPO without the effect of dead end polymerization is being observed (Fig. 2a). For BAPO initiated polymerization this is the expected behaviour as photodecomposition of phosphine oxide chain ends entails continuous generation of initiating radicals [5, 6]. For BAG this effect seems less pronounced but nevertheless the bulk polymerization goes on for more than 100 hours after complete photoinitiator consumption, interestingly, with increasing rate as also observed for the photoinitiator-free polymerization over the entire duration.

The average molecular weight increases, independent of the polymerization procedure and recipe, with monomer conversion suggesting a certain kind of 'photo-controlled' chain growth (Fig. 2b).

Taken all experimental results together, we suggest that a photo electron transfer reaction between a styrene monomer and a repeating unit in the polystyrene chain leads repetitively to generation of radicals (actually radical ions) ensuring both polymerization in the absence of photoinitiator and increasing molecular weight with conversion [4].

Influence of Gas Phase Composition on Heterophase Polymerization

The outcome of radical styrene heterophase polymerization depends strongly on the composition of the gas phase. Experimental data show that the effect of the gas phase is quite a complex one and strongly influenced by the nature of the gas, the homogeneity or heterogeneity of the polymerization system, and the kind of initiator [7].

Evidence has been found that the influence of air goes beyond the simple action of oxygen which can cause deceleration or acceleration of the reaction. The experimental results show that the optimum polymerization conditions are obtained in the absence of any foreign gas. The connection between the preceding discussion and heterophase polymerization is given by the colloidal nature of these systems and the experimental fact that the rate of polymerization and the rate of degradation of the emulsion show essentially the same dependence on the composition of the gas phase.

Poly(Ionic Liquids) as Stabilizers in Emulsion Polymerization

Poly(ionic liquid) (PIL) nanoparticles were for the first time applied as sole stabilizers in aqueous emulsion polymerization and revealed an astonishing and unexpected behaviour [8]. In a well-dispersed state, the PIL nanoparticles serve as an unexpectedly effective stabilizer for polystyrene dispersion, enabling solids content of greater than 40 %. However, the same PIL as dry powder is hydrophobic and, in accordance with Bancroft's rule, unable to stabilize aqueous dispersions. The ambivalent behaviour of PIL is extremely beneficial for the application of aqueous dispersions because, as desired for decades, the hydrophilic dispersed state during synthesis turns hydrophobic in the dried state during application of the polymer. This conclusion is supported by contact angle measurements on corresponding polymer films made of dried latexes (Fig. 3). Water shows on polystyrene made with sodium dodecylbenzenesulfonate as a typical common hydrophilic stabilizer a contact angle of $82.1 \pm 2.1^\circ$. The contact angle for polystyrene made with PIL stabilizer is significantly larger ($95.3 \pm 1^\circ$).

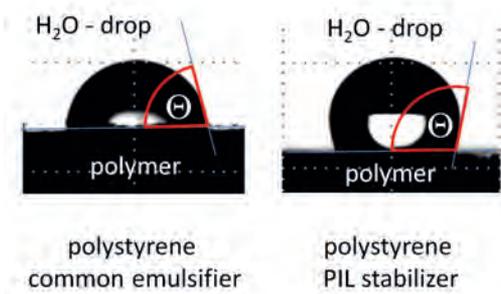


Fig. 3 Contact angle of water drops on polystyrene films illustrating the different hydrophobicity

Plant Cell Models via Polymerization

Plants adapt the geometry of their organs and tissue properties to cope with external and internal stresses and to actuate organ movement. These actuating movements function without an active metabolism, but are humidity-based systems where a swellable material acts against a stiffer cell wall. Within this project we explore the possibility to mimic the mechanical behaviour of papaya plants.

Within the SPP1420 we explored possibilities to build a humidity-sensitive actuator following the principles used by the papaya plant [9]. We mimicked the papaya cell walls by radical copolymerization in a shape-similar PTFE-template (Fig. 4 a and b). A suitable polymerization recipe comprises butyl acrylate (BA) with either glycidyl methacrylate (GMA) or hydroxyethyl methacrylate (HEMA) as comonomer (molar ratio BA:comonomer of 4:1) and 1 mol% of ethylene glycol dimethacrylate as crosslinker to avoid phase separation. The polymerization was started photochemically with BAPO (UV LED as light source) at room temperature. The parenchyma hydrogel was mimicked by subsequent polymerization of a mixture acrylic acid/methylene bisacrylamide inside the cells of the polymer grid (Fig. 4c). Initiating this polymerization with

the ceric ion redox systems leads to covalent attachment of the hydrogel to the cell walls.

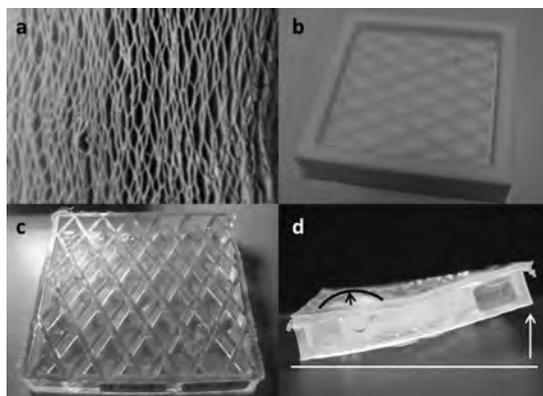


Fig. 4 a – Phloem cells of papaya plants; b – Teflon template for the production of the polymer grid; c – Artificial cells mimicking papaya phloem before filling certain cells with hydrogel via radical polymerization; d – Self-lifting of the artificial grid by swelling of the hydrogel inside selected cells of the grid proving the principle of a humidity-sensitive actuator

Due to the confinement of the hydrogel inside the cell, during swelling mechanical distortion of both the filled cells and the whole assembly of cells (Fig. 4d) happens.

Amphiphilic Block Copolymer Particle

Heterophase polymerization is a simple but powerful tool for the synthesis of special block copolymer particles. Particularly interesting is the synthesis of particles for potential biomedical applications such as pullulan decorated poly(hydroxyethyl methacrylate) particles.

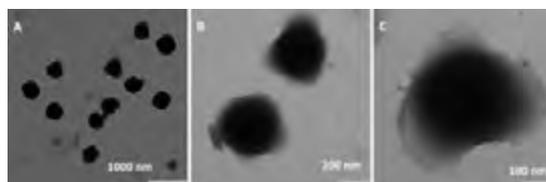


Fig. 5 Transmission electron micrographs of pullulan-g-PHEMA graft copolymer particles

Both homopolymers are biocompatible and have already been successfully used in medical applications for decades. We reported their combination in nano-particles (Fig. 5) for the first time [10].

In another study a new class of amphiphilic particles with a very special morphology has been discovered when the block copolymer synthesis is carried out in the presence of cyclic sugars [11].

K. Tauer, K. Krüger, P. Höhne, N. Weber, S. Purkayastha, R. Yu, U. Lubahn, S. Pirok, I. Shekova; in collaboration with Y. Yagci (Istanbul Technical University), J. Hartmann (electron microscopy, MPI KGF), J. Yuan (MPI KGF); klaus.tauer@mpikg.mpg.de.

References:

- [1] H. F. Hernandez, K. Tauer, „Emulsion polymerization“, In A. D. Schlüter, C. J. Hawker, J. Sakamoto (eds) *Synthesis of Polymers*, WILEY-VCH, Weinheim, 741-773 (2012).
- [2] N. Weber, M. M. Unterlass, K. Tauer, „High Ionic Strength Promotes the Formation of Spherical Copolymer Particles“, *Macromol. Chem. Phys.*, **212**, 2071-2086 (2011).
- [3] N. Weber, B. Tiersch, M. M. Unterlass, A. Heilig, K. Tauer, „Schizomorphic Emulsion Copolymerization“, *Macromol. Rapid Commun.*, **32**, 1925-1929 (2011).
- [4] K. Krüger, K. Tauer, Y. Yagci, N. Moszner, „Photoinitiated Bulk and Emulsion Polymerization of Styrene - Evidence for Photo-Controlled Radical Polymerization“, *Macromolecules*, **44**, 9539-9549 (2011).
- [5] S. Jockusch, N. J. Turro, „Phosphinoyl radicals: Structure and reactivity. A laser flash photolysis and time-resolved ESR investigation“, *Journal of the American Chemical Society*, **120**, 11773-11777 (1998).
- [6] Y. Yagci, Y. Y. Durmaz, M. Kukut, N. Moszner, „Sequential Photodecomposition of Bisacylgermane Type Photoinitiator: Synthesis of Block Copolymers by Combination of Free Radical Promoted Cationic and Free Radical Polymerization Mechanisms“, *Journal of Polymer Science Part a-Polymer Chemistry*, **47**, 4793-4799 (2009).
- [7] P. Höhne, K. Krüger, K. Tauer, „Vapor phase composition and radical polymerization – how the gas phase influences the kinetics of heterophase polymerization“, 1-18 (2012).
- [8] N. Rozik, M. Antonietti, J. Yuan, K. Tauer, „Poly(ionic liquid) Stabilizers for Aqueous Emulsion Polymerization Enable a Hydrophilic - Hydrophobic Transition during Film Formation“, *Macromol. Rapid Commun.* (2012).
- [9] P. Höhne, K. Tauer, in preparation.
- [10] S. Purkayastha, J. Hartmann, K. Tauer, „Synthesis of biocompatible poly(hydroxyethyl methacrylate) particles with pullulan shell“, *Journal of Colloid Science and Biotechnology*, accepted, (2012).
- [11] R. Yu, K. Tauer, in preparation.

From Polymer Synthesis to Porosity Analysis



Porous polymers represent a flourishing area of research, which is driven by both: academic and industrial interest. Porous polymers are relevant in a number of applications ranging from thermal insulation, gas separation or storage, catalysis to separation technologies. The group is interested in new synthetic methods and advanced characterization of nanoporous polymers, namely micro- and mesoporous polymers. Interaction with guests (including gas separation) as well as dynamic processes and stimuli-responsiveness of the nanoporous structures are among the core interests of the research unit.

Microporous polymers, i.e. polymers having pore sizes of less than 2 nm can be considered as the polymer analogue of zeolites and activated carbon and combine very high specific surface areas ($>>100 \text{ m}^2\text{g}^{-1}$) with the rich synthetic possibilities of polymer science.

Mesoporous materials have pore sizes between 2 and 50 nm. They are of interest in separation technologies, especially for larger (bio)macromolecules. However, their science is less explored compared to microporous polymers.

Sustainable Monomers and Methods

Recently, microporous polyesters and polyurethanes were synthesized from a renewable natural resource, betulin (**Fig. 1**). Betulin is the main component of the birch bark and hence not in conflict with food production. Its content can be as high as 30 wt.-% and it is easily extractable by common organic solvents.

Betulin was used as a rigid monomer to synthesize polyester and polyurethane networks with intrinsic microporosity, **[1,2]** which are made from up to 75 wt.-% of renewable materials. The stiff structure of betulin prevents close packing of the polymer chains.

Betulin can also serve as a monomer for linear, soluble polymers, which can be cast into self-supporting membranes. The obtained materials show promising results for CO_2 over N_2 selectivity and might indeed be useful as gas separation membranes **[1]**.

Next to microporous materials, betulin can also be used as the hydrophobic constituent of amphiphilic multiblock copolymers (with *Helmut Schlaad*) **[3]**.

Sustainability can also be achieved by reaction control. Replacing organic solvents by water is a promising concept and was expanded to the synthesis of fully aromatic polyimides **[4]**. The details of this new reaction are under investigation and initial steps towards morphology control of the resulting high-performance polymers could also be achieved.

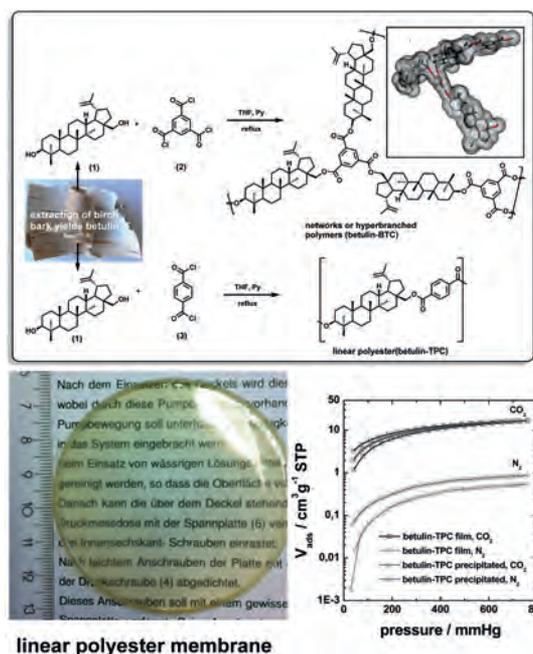


Fig. 1: chemical structure of cross-linked and soluble betulin-based polyesters, photograph of the free-standing membrane and typical gas adsorption isotherms at 273K.

Microporous Soluble Polymers

The first chiral microporous polyimides have been synthesized using a binaphthalene-based monomer. The resulting polymers showed a significant surface area, but the pores were apparently too small to allow access of larger organic molecules. The homochirality was lost upon polycondensation (partial racemisation) and no superstructure formation could be observed yet **[5]**.

Next to the synthesis of new polymers of intrinsic microporosity, interest was spent to a better understanding of the microporosity (free-volume). The influence of intermolecular interactions on the observable porosity could be proven. Hydrogen bonding can lead to pore size reductions, which can also be reversed upon temperature increase, i.e. the breaking of hydrogen bonds **[6]**.

Conjugated Microporous Polymers

Conjugated microporous polymers (CMPs) are a subclass of microporous polymer networks and are built from (fully) conjugated monomers.

The functionalization of arylene-ethynyle type CMPs by radical thiol-yne chemistry was demonstrated. The concept allows the on-demand functionalization of CMPs with functional groups **[7]**.

Jens Weber 17.05.1981

2005: Diploma, Chemistry (Technische Universität Dresden)

Topic: Physical Chemistry of Ionic-Nonionic Comb Terpolymers

2007: PhD, Polymer & Colloid Chemistry (MPI of Colloids and Interfaces, Potsdam)

Thesis: Meso- and Microporous High Performance Polymers

2008-2009: Postdoc, (Arrhenius Laboratory, Stockholm University, Sweden, with Prof. Lennart Bergström)

Since 2009: Project Leader – Porous Polymers (MPI of Colloids and Interfaces, Potsdam)

References:

- [1] J. Jeromenok, W. Böhlmann, M. Antonietti, J. Weber: Intrinsically Microporous Polyesters from Betulin – Renewable Materials for Gas Separation made from Birch Bark, *Macromol. Rapid Commun.* 2011, **32**, 1846-1851
- [2] J. Jeromenok, W. Böhlmann, C. Jäger, J. Weber: Carbon Dioxide Adsorption in Micro- and Macroporous Betulin Based Polyurethanes, *ChemistryOpen* 2013, **2**, 17-20
- [3] J. Zhao, J. Jeromenok, J. Weber, H. Schlaad: Thermoresponsive Aggregation Behavior of Triterpene-Poly(ethylene oxide) Conjugates in Water, *Macromol. Biosci.* 2012, **12**, 1272-1278
- [4] M.M. Unterlass, D. Kopetzki, M. Antonietti, J. Weber: Mechanistic Study of Hydrothermal Synthesis of Aromatic Polyimides, *Polym. Chem.* 2011, **2**, 1744-1753
- [5] N. Ritter, I. Senkovska, S. Kaskel, J. Weber: Toward Chiral Microporous Soluble Polymers – Binaphthalene-Based Polyimides, *Macromol. Rapid Commun.* 2011, **32**, 438-443
- [6] J. Weber, N. Du, M.D. Guiver: Influence of Intermolecular Interaction on the Observable Porosity in Intrinsically Microporous Polymers, *Macromolecules* 2011, **44**, 1763-1767

A contrary concept is the use of copolymerization methods in order to tune the optical bandgap of CMPs. Introducing thiophene units into a spirofluorene-based system could shift the emission color from blue to green. Additionally, it could be shown that energy transfer from the CMP to incorporated guest molecules is possible [8].

The formation of a photoactive CMP based on the acid-base responsive phenolphthalein without affecting the switching ability was demonstrated [9]. The final network can be switched between two different states (small pores, ionic charges vs. larger pores, neutral state). The porosity and the polarity (as probed by the heat of carbon dioxide adsorption) of the material could be tuned depending on the counterions (Li^+ vs. Cs^+) (Fig. 2).

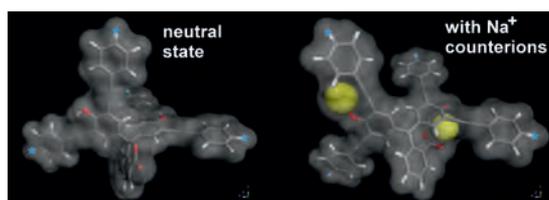


Fig. 2: 3D representation of the central motif of the phenolphthalein CMPs in the neutral and charged state. Blue stars indicate connection points. Please note the changes of the geometry (fixed coordinate systems) upon switching and the influence of the counterion (yellow) size.

Mesoporous Polymers

Mesoporous polymers can be synthesized either using templating methods or by controlled phase-separation processes. We employed hard-templating of spherical silica nanoparticles for the synthesis of mesoporous polymers.

A general problem of the hard-templating routine is the often-observed immiscibility of the aqueous silica nanoparticle dispersions with the organic monomers, which leads to phase separation. Acidified melamine-formaldehyde resin precursors could however be mixed homogeneously with the aqueous dispersion due to favorable electrostatic interactions. The dispersion could be cured to yield mesoporous hybrid materials (as a consequence of phase-separation processes), whose porosity could even be enhanced by removal of the silica [10]. The resulting porous resins showed promising behavior for gas separation applications as well as good properties for heavy metal ion removal. The low-price and scalability of the method make those materials indeed interesting for relevant technologies.

Another way to overcome the miscibility problem is to process the nanoparticle dispersion into a monolithic structure. This was achieved by an evaporative method, which resulted in monoliths made of mainly random-close packed (RCP) nanoparticles. Backfilling of the interstitial voids with liquid monomers (e.g. divinyl benzene, DVB) and subsequent polymerization yielded highly porous polymers after template removal [11]. The porosity ϕ of the polymers is directly related to the space-filling of the RCP phase (typically $\phi \sim 64\%$). The spherical mesopores have only a low polydispersity and their size

is related to the size of the used nanoparticles (~ 12 or ~ 25 nm). Specific surface areas of up to $1000 \text{ m}^2\text{g}^{-1}$ could be achieved and post-functionalization (e.g. sulfonation) of the pores is possible without loss of the porosity.

Mesoporous polymers prepared in such way are hence ideal model systems (uniform pore size) for the study of the mesopore collapse phenomenon, which is not yet understood. To elucidate the structural changes upon drying, the drying process of the solvent-filled polymers was followed by small-angle X-ray scattering (SAXS, in-house and at BESSY) (Fig. 3). It was shown that the pores undergo drastic deformation (even in the fully cross-linked state) before the solvent actually evaporates. This can be understood as a consequence of the different forces (elastic, interfacial) involved in the process. The finer details are subject to ongoing analysis.



Fig. 3: left-hand side: photograph of sulfonated mesoporous PolyDVB, inset: respective TEM micrograph; middle: in-situ SAXS patterns (drying process of dioxane filled poly(DVB) with 12 nm pores); right-hand side: intensity (black) and s-value (grey) of the peak vs. time. The drastic change of s_{max} (which relates to $> 10\%$) before the pore emptying sets in is obvious.

The hard-templating pathway was also extended to other monomer systems. Ionic liquid type monomers based on vinyl imidazolium were used in cooperation with the group of Jiayin Yuan [12]. The so-called poly(ionic liquids) are discussed as materials with potential for CO_2 separation and the impact of the mesostructure on the adsorption properties were studied. A significantly faster and higher adsorption was found, which can be attributed to the significantly shorter diffusion pathways. Beside the kinetic facts, there are some peculiarities related to the adsorption thermodynamics and the state of the adsorbed CO_2 , which require additional analysis.

Porosity Characterization

The expertise of the group in the characterization of microporous materials by various methods has also led to a number of cooperation projects with various partners. The main tools are nitrogen and carbon dioxide adsorption studies and the use of X-ray scattering, which can give additional information, even on disordered materials.

Jens Weber, Martin Blümke (Master Thesis 2012), Jessica Brandt, Pablo Haro Dominguez, Jekaterina Jeromenok (PhD Thesis 2012), Baris Kiskan, Miriam Unterlass (PhD Thesis 2011), Antje Wilke (PhD Thesis 2012) and Farzad Yazdanbakhsh (Master Thesis 2012)
jens.weber@mpikg.mpg.de

[7] B. Kiskan, J. Weber: Versatile Post-modification of Conjugated Microporous Polymers Using Thiolyne Chemistry, *ACS Macro Lett.*, **1**, 37-40 (2012).

[8] J. Brandt, J. Schmidt, A. Thomas, J.D. Epping, J. Weber: Tunable Emission and Absorption Wavelength in Conjugated Microporous Polymers, *Polym. Chem.*, **2**, 1950-1952 (2011).

[9] B. Kiskan, M. Antonietti, J. Weber: Teaching New Tricks to an Old Indicator: pH-Switchable, Photoactive Microporous Polymer Networks from Phenolphthalein with Tunable CO_2 Adsorption Power, *Macromolecules*, **45**, 1356-1361 (2012).

[10] A. Wilke, J. Weber: Hierarchical nanoporous melamine resin sponges with tunable porosity – porosity analysis and CO_2 sorption properties, *J. Mater. Chem.*, **21**, 5226-5229 (2011).

[11] A. Wilke, J. Weber: Mesoporous Polymer Networks - Ultraporos DVB Resins by Hard-Templating of Close-Packed Silica Spheres, *Macromol. Rapid Commun.*, **33**, 785-790 (2012).

[12] A. Wilke, J. Yuan, M. Antonietti, J. Weber: Enhanced Carbon Dioxide Adsorption by a Mesoporous Poly(ionic Liquid), *ACS Macro Lett.*, **1**, 1028-1031 (2012).

Smart Biohybrid Polymers



Helmut Schlaad 04.08.1967
 1993: Diploma, Physical Chemistry
 (University of Mainz)

Thesis: Studies of the Anionic
 Polymerization of Methyl Methacrylate
 in Toluene in the Presence of
 Aluminium Alkyls

1997: PhD, Physical Chemistry
 (University of Mainz)

Thesis: Studies of the Mechanism
 of the Anionic Polymerization of
 Methacrylates in the Presence of
 Aluminium Alkyls in Toluene

1998: Postdoc (University of
 Massachusetts, Lowell, USA)

Since 1999: Group Leader
 (Max Planck Institute of Colloids
 and Interfaces, Potsdam)

Since 2004: Senior Scientist
 (Max Planck Institute of Colloids
 and Interfaces, Potsdam)

2004: Habilitation, Physical Chemistry
 (University of Potsdam)

Thesis: Polymer Self-Assembly:

Adding Complexity to Mesostructures
 of Diblock Copolymers by Specific
 Interactions

Since 2010: Privatdozent
 (University of Potsdam)

References:

- [1] C. Barner-Kowollik, F. E. Du Prez, P. Espeel, C. J. Hawker, T. Junkers, H. Schlaad, W. Van Camp: *Angew. Chem. Int. Ed.* **50**, 60-62 (2011).
 [2] J. Yuan, H. Schlaad, C. Giordano, M. Antonietti: *Eur. Polym. J.* **47**, 772-781 (2011).
 [3] N. ten Brummelhuis, H. Schlaad: *Polym. Chem.* **2**, 1180-1184 (2011).
 [4] J. Yuan, N. ten Brummelhuis, M. Junginger, Z. Xie, Y. Lu, A. Taubert, H. Schlaad: *Macromol. Rapid Commun.* **32**, 1157-1162 (2011).
 [5] J. Zhao, H. Schlaad: *Macromolecules* **44**, 5861-5864 (2011).

Bioconjugates and biohybrid copolymers are interesting materials for the generation of "smart" functional colloids and hierarchical structures, for usage in for instance life science applications (targeted drug delivery, tissue engineering, etc.). New materials based on amino acids, sugars, and terpenes have been prepared by advanced polymer synthesis techniques and studied according to their stimuli-responsive behavior and hierarchical self-assembly in aqueous environment or in solid state.

Synthesis

Metal-free "living" ring-opening polymerization of heterocycles and photochemical thiol-ene/ylne click modification [1] were applied to prepare terpene-poly(ethylene oxide) (PEO) copolymers (Fig. 1a) [9], glycopolypeptides [16] and -peptoids (Fig. 1b) [11]. Glycosylation of unsaturated polypeptides could be achieved under experimentally mild and benign conditions, i.e. in aqueous media at room temperature.

Well-defined poly(2-oxazoline) (pseudo-polypeptide) star ionomers were readily synthesized by photo thiol-ylne functionalization/crosslinking of block copolymer micelles in water (Fig. 1c) [3].

Polymer brushes on inorganic substrates (gold surfaces and glass fibers) were prepared by the thiol-initiated photopolymerization of vinyl monomers [7, 12].

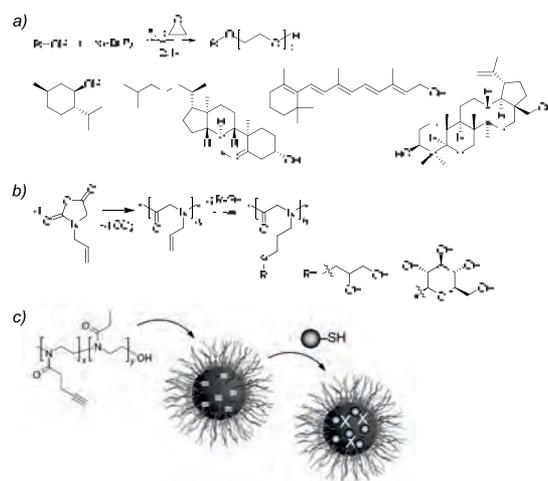


Fig. 1: Synthetic routes to biohybrid and pseudo-polypeptide polymers

Stimuli-Responsive (Smart) Polymers

Secondary structures of statistical copolypeptides of L-glutamate and glucosylated L-/DL-allyl- or DL-propargylglycine were studied in dependence of solution pH. The glucosylated and non-glucosylated samples adopted random coil conformation at neutral-basic media and α -helical conformation in acidic media, the helical content depending on the number and configuration of allyl-/propargylglycine units. The glycopolypeptides revealed enhanced helical stability and solubility down to pH 3.5 (Fig. 2). Furthermore, turbidity assays

demonstrated selective binding to the plant lectin concanavalin A [16].

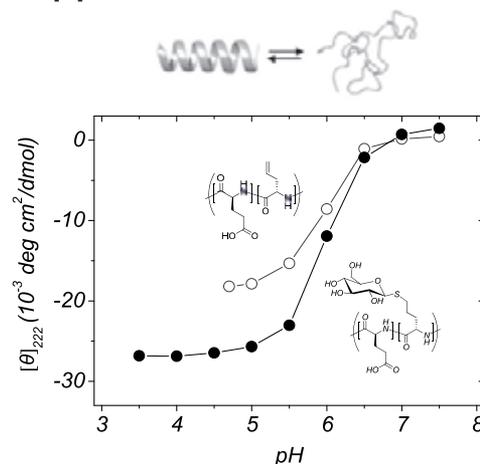


Fig. 2: pH-dependent secondary structures (helix-coil) of poly(L-glutamate) copolymers in water.

Cholesteryl-PEO and betulinyl-(PEO)₂ amphiphiles showed thermo-responsive aggregation behavior in water. The polymers precipitated or coagulated upon heating, due to the dehydration of PEO chains, and re-dispersed upon cooling. Furthermore, betulinyl-(PEO)₂ with short PEO chains (11 repeat units) showed dual thermo-responsive behavior, precipitating at high temperature and turning into hydrogel at low temperature (Fig. 3). Results suggested that the solution behavior was controlled by the type of terpene and polymer architecture [13].

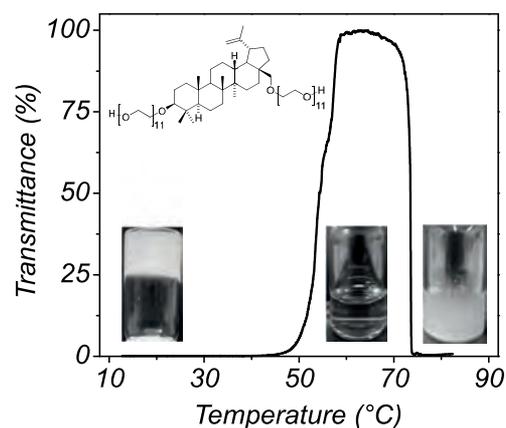


Fig. 3: Dual thermo-responsive solution behavior of a betulinyl-(PEO)₂ amphiphile at 5 wt% in water.

The thermo-responsive behaviors of poly(2-ethyl-2-oxazoline) star ionomers in water were studied according to effects of pH, ionic strength, and type of salt. The cloud point temperatures varied in a wide temperature range, from 10 to >95 °C, corresponding with the Hofmeister salt series and ionization degree of the core (Fig. 4). Effects of pH were weakened by the addition of salt, however, kosmotropic salts (Na₂SO₄) being more effective than chaotropic salts (NaSCN). For star

copolymers with an amine core, similar trends were observed as for star copolymers with a carboxylic acid core, although the presence of a chaotropic salt afforded an inversion of the effect of pH due to the specific binding of anions to the amine/ammonium groups [3, 15].

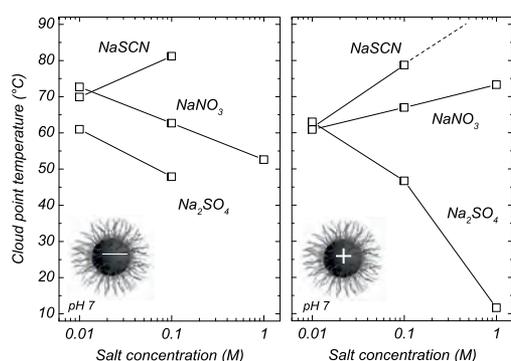


Fig. 4: Hofmeister salt effects on the thermo-responsive solution behavior of poly(2-ethyl-2-oxazoline) star ionomers in water.

Complex and Hierarchical Structures

PEO₆₄-(Z-lysine)₁₈ conjugates with monodisperse 18-mer peptide segments of predefined stereosequences showed different solution behaviors and abilities to gel tetrahydrofuran. The ability for organogelation was found to depend on the secondary structure of the peptide segment and increases in the order random coil < α -helix < β -sheet, as evidenced by measurements of minimum gelation concentration, viscosity, and aggregate morphology (Fig. 5) [6].

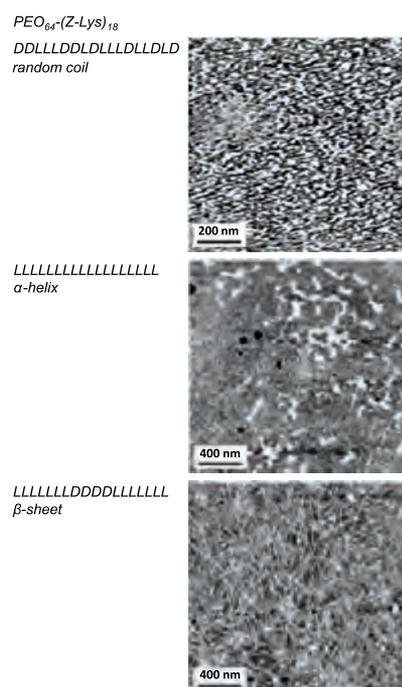


Fig. 5: AFM height images of PEO₆₄-(Z-lysine)₁₈ in tetrahydrofuran after rapid drying on silicon.

The crystallization induced self-assembly appeared to be a rather general phenomenon occurring for semi-crystalline polymers in liquid-liquid two phase systems. Crystalline hierarchical structures were produced from poly(2-isopropyl-2-oxazoline) in hot water (above LCST) or by room temperature annealing of poly(2-isobutyl-2-oxazoline) or poly(2-nonyl-2-oxazoline) in ethanol-water solvent mixtures (below UCST) (Fig. 6). The crystallization behavior of poly(2-alkyl-2-oxazoline)s was affected by external parameters such as polymer concentration, solvent composition, and temperature [8].

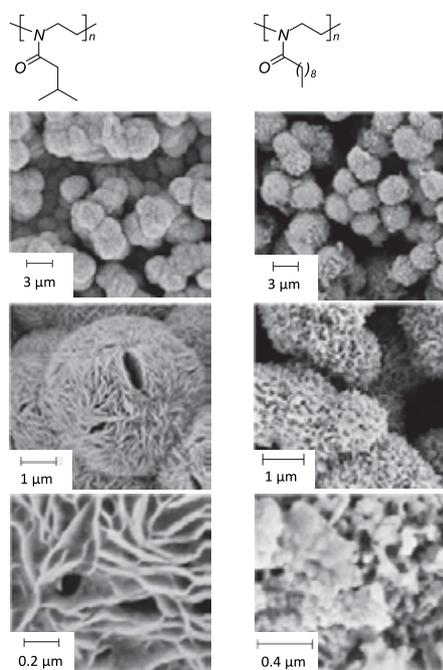


Fig. 6: SEM images of freeze-dried precipitates of poly(2-alkyl-2-oxazoline)s, alkyl = isobutyl and nonyl, as produced by solution crystallization at room temperature.

H. Schlaad, M. Gräwert, A. Völkel, N. Fiedler, H. Zou, J. Zhao, N. ten Brummelhuis, C. Valverde Serrano, I. Dambowsky, J. W. Robinson, K.-S. Krannig, C. Secker, D. Linke, V. Hoang helmut.schlaad@mpikg.mpg.de

- [6] F. Hermes, K. Otte, J. Brandt, M. Gräwert, H. G. Börner, H. Schlaad: *Macromolecules* **44**, 7489-7492 (2011).
 [7] R. Löbbicke, M. Chanana, H. Schlaad, C. Pilz-Allen, C. Günter, H. Möhwald, A. Taubert: *Biomacromolecules* **12**, 3753-3760 (2011).
 [8] C. Diehl, I. Dambowsky, R. Hoogenboom, H. Schlaad: *Macromol. Rapid Commun.* **32**, 1753-1758 (2011).
 [9] J. Zhao, H. Schlaad, S. Weidner, M. Antonietti: *Polym. Chem.* **3**, 1763-1768 (2012).
 [10] O. Casse, A. Shkilnyy, J. Linders, C. Mayer, D. Häussinger, A. Völkel, A.F. Thünemann, R. Dimova, H. Cölfen, W. Meier, H. Schlaad, A. Taubert: *Macromolecules* **45**, 4772-4777 (2012).
 [11] J. W. Robinson, H. Schlaad: *Chem. Commun.* **48**, 7835-7837 (2012).
 [12] C. Kuttner, M. Tebbe, H. Schlaad, I. Burgert, A. Fery: *ACS Appl. Mater. Interfaces* **4**, 3484-3492 (2012).
 [13] J. Zhao, J. Jeromenok, J. Weber, H. Schlaad: *Macromol. Biosci.* **12**, 1272-1278 (2012).
 [14] A. J. Soininen, I. Tanionou, N. ten Brummelhuis, H. Schlaad, N. Hadjichristidis, O. Ikkkala, J. Raula, R. Mezzenga, J. Ruokolainen: *Macromolecules* **45**, 7091-7097 (2012).
 [15] N. ten Brummelhuis, C. Secker, H. Schlaad: *Macromol. Rapid Commun.* **33**, 1690-1694 (2012).
 [16] K.-S. Krannig, H. Schlaad: *J. Am. Chem. Soc.* **134**, 18542-18545 (2012).

PhD and Diploma/Master thesis:
 N. ten Brummelhuis (PhD, 2011),
 C. Valverde Serrano (PhD, 2011),
 D. Linke (Diploma, 2011), C. Secker (Master 2012), V. Hoang (Master, 2012).

Electron Microscopic Studies of Colloidal Systems and Interfaces



Jürgen Hartmann 18.10.1953
1977: Diploma, Physics
 (Humboldt University Berlin; Institute of Low-Temperature Solid State Physics)
 Thesis: Application of Square-Wave Polarography and a Density Method for the Analysis of Bismuth-Antimon Alloys
1977–1991: Research Scientist
 (Institute for Polymer Chemistry, Teltow)
1987: PhD, Polymer Physics
 (Institute of Polymer Chemistry, Teltow)
 Thesis: Contribution to the Formation Mechanism of Coagulation Structures of Polymers Using Electron Microscopy
1992–1995: Research Scientist
 (Max Planck Institute of Colloids and Interfaces, Potsdam)
Since 1995: Group Leader
 (Max Planck Institute of Colloids and Interfaces, Potsdam)

The investigation of structure/property relationships and chemical synthesis/structure relationships of both natural and synthetic colloidal materials and interfaces is important for the development of new materials for analytical and technical applications. Transmission electron microscopy and high-resolution scanning electron microscopy are suitable techniques to investigate micro- and nano-structured synthetic organic and inorganic particles, active coatings and interfaces, membranes, composite materials and naturally-grown biomaterials. The determination of structural parameters such as the size and size distribution of colloidal particle systems, the pore size of polymeric and inorganic networks, the diameter of fibrillar nanostructures, the spatial arrangement of particles are in focus on the electron microscopic investigations. In combination with energy-dispersive X-ray spectroscopy scanning electron microscopy is a powerful analytical tool to determine relationships between the local chemical composition and surface and interface structures of solid materials. Because of the organisation of the institute, there are many closed cooperations between the electron microscopy group and other research groups. Some of the interesting results of electron microscopic investigations are presented here.

Iron oxide nanoparticles have a relatively low magnetic saturation and metallic iron has a much higher saturation magnetization, but is unsuitable for medical applications due to its toxicity. An alternative, offering both high magnetic saturation and chemical stability, is iron carbide (Fe_3C) [1]. By dispersing an aqueous iron precursor within gelatine gel, it could show that the polymer controls the nucleation of magnetite nanoparticles within the gel matrix. The biopolymer decomposes to form a carbon- and nitrogen-rich matrix around the intermediary oxide nanoparticles. This reactive template then induces carbothermal reduction of iron oxide to iron carbide. As an example for the general applicability of this method two biopolymers (chitosan and alginate) were used as gel components to produce stable iron carbide nanoparticles in the range of 10 to 30 nm [1]. The high-resolution scanning electron microscopic results show that the iron carbide nanoparticles were embedded in an amorphous matrix (Fig. 1).

Elemental analysis showed over a half of the mass to be composed of carbon (27 wt.%) and nitrogen (28 wt.%), suggesting that the amorphous matrix was formed from decomposition products of the gelatine starting material. The particle structure was confirmed using transmission electron microscopy and the mean particle diameter calculated to be $d = 20 \pm 2$ nm.

Another interesting project is the electron microscopic characterization of the structure of Pickering emulsions. For the preparation of a stable oil in water emulsion the solid nanoparticles should be able to wet the oil, as well as the water phase.

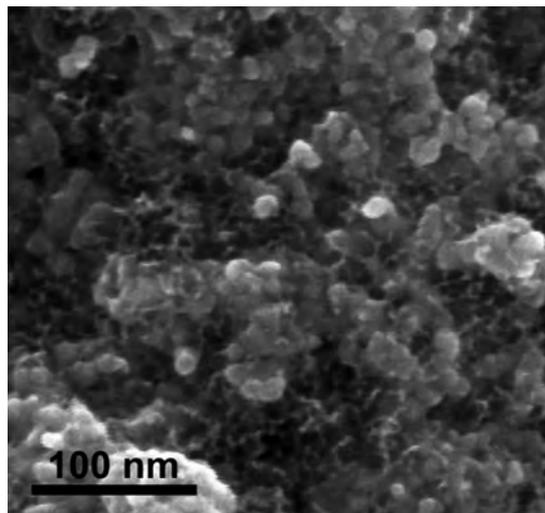


Fig. 1: Iron carbide nanoparticles synthesized using iron acetate in ammonium alginate precursor gel.

Therefore the surface chemistry of the particles must be manipulated in a proper way [2]. Here the polyacid poly(methacrylic acid sodium salt) and the polybase poly(allylamine hydrochloride) are used for the surface modification of oppositely charged alumina and silica colloids.

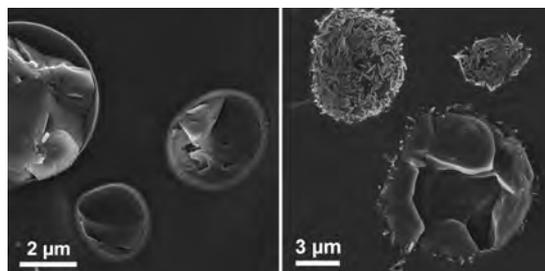


Fig. 2: Dodecane droplets with silica-PAH nanoparticles (left) and Hexadecane droplets stabilized by halloysite (aluminosilicate) nanotubes (right)

Using high-resolution cryo-scanning electron microscopy the sample preparation takes place at very low temperatures (<173 K) and the aqueous and the oil phases are in solid state. The modified solid colloids are covering the oil phase completely and stabilizing the emulsion droplets (Fig. 2).

An important project is the local modification surface structure of soft matter with laser light. Here we have investigated a method of incorporating laser responsive heat centers, gold nanoparticles, into flake like microparticles assembled from fullerene derivative [3]. The samples were prepared by centrifugation of gold nanoparticle together with fullerene derivative based microparticles. Fig. 3a is representing the morphology of the hybrid material where gold nanoparticles

are embedded in the flakes of the microparticle. Upon laser irradiation at 532 nm, the hybrid microparticle melts due to plasmonic heating of gold nanoparticles and the flower-like microparticle will smoothen the surface (Fig. 3b), which lead to a loss of hydrophobicity. Although in principle, fullerene derivative absorb light at 532 nm and could lead to a melting, it is suffice to mention that at intensity used here the melting does not occur (Fig. 4).

The incorporation of laser responsive agents, can be used to selectively modify the morphology and the physical properties of the microparticles.

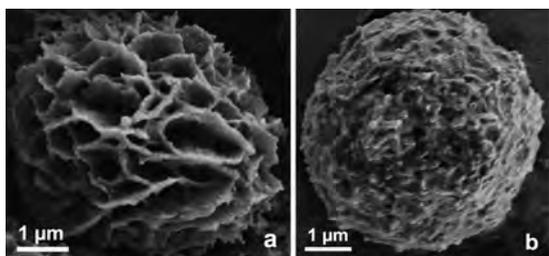


Fig.3: Gold nanoparticle embedded on flakes of fullerene derivative based microparticles (a) before and (b) after laser treatment.

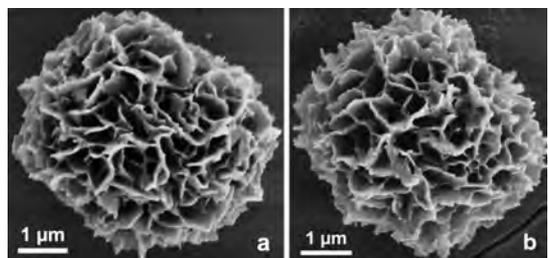


Fig.4: Stable flower-like microparticles without Au-nanoparticles (a) before and (b) after laser treatment.

One of our research activities is focused in the development of a coating system, including a non-chromate conversion coating layer and a self-priming top coating containing non-toxic corrosion inhibiting components for high-strength aluminum alloys [4]. Moreover, the presence of some alloying elements such as copper and surface defects particularly increases pitting corrosion attack by forming galvanic couples. To detect the surface defects and spatial distribution of the alloying elements scanning electron microscopy in combination with energy-dispersive X-ray spectroscopy was used.

Fig. 5 shows the surface morphology (a) and the partial phase separated structure of a polished uncoated aluminum alloy (b), where the matrix is rich in aluminium (coloured in teal) and the red coloured areas are rich in copper. The mixed colours of the elemental map represent the local composition. The mean composition of the matrix contain 93.2 wt.% Al, 1.4 wt.% Mg and 4.8 wt.% Cu (Fig. 6 teal spectrum) whereas the local areas rich in copper contains up to 50 wt.% Cu (Fig. 6 red spectrum).

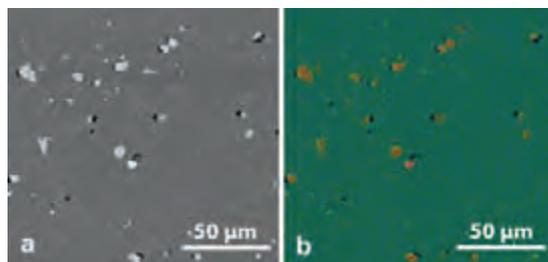


Fig.5: Surface morphology of the polished uncoated aluminum alloy (a) and the corresponding elemental map (b).

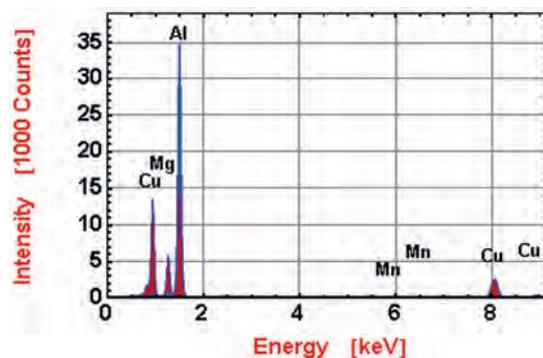


Fig.6: EDS-spectra of the uncoated aluminium alloy

The dark gray area in Fig. 5a corresponds to the aluminium matrix and the bright areas are rich in copper.

J. Hartmann, C. Giordano, I. Dönch, A.S. Hamdy, H. Asanuma, D. O. Grigoriev, D. Borisova, D. Shchukin
juergen.hartmann@mpikg.mpg.de.

References:

- [1] Schnepf, Z.; Wimbush, Stuart C.; Antonietti, Markus; and Giordano, Cristina: of Highly Magnetic Iron Carbide Nanoparticles via a Biopolymer Route. *Chem. Mater.*, **22**, 5340–5344 (2010).
- [2] Haase, M.; Grigoriev, D.; Moehwald, H.; Tiersch, B. and Shchukin, D.: Nanoparticle Modification by Weak Polyelectrolytes for pH-Sensitive Pickering Emulsions. *Langmuir*, **27**(1), 74–82 (2011).
- [3] Asanuma, H.; Subedi, P.; Hartmann, J.; Shen, Y.; Möhwald, H.; Nakanishi, T.; Skirtach, A.: Nanoplasmonic Modification of Local Morphology, Shape, and Wetting Properties of Nanoflake Microparticles. accepted in *Langmuir*
- [4] Hamdy, A.S.; Doench, I.; Möhwald, H.: Intelligent self-healing corrosion resistant vanadia coating for AA2024. *J. Thin Solid Films*, (520) 1668-1678 (2011)
- [5] Politi, Y.; Priezwasser, M.; Pippel, E.; Zaslansky, P.; Hartmann, J.; Siegel, S.; Li, Ch.; Barth, F.G.; Fratzl, P.: A Spider's Fang: How to Design an Injection Needle Using Chitin-Based Composite Material. *Adv. Funct. Mater.*, **22**, 2519–2528 (2012).
- [6] Behra, M.; Schmidt, S.; Hartmann, J.; Volodkin, D.V.; Hartmann, L.: Synthesis of Porous PEG Microgels Using CaCO₃ Microspheres as Hard Templates. *Macromol. Rapid Commun.*, **33**, 1049-1054 (2012)
- [7] Latnikova, A.; Grigoriev, D. O.; Hartmann, J.; Möhwald, H. and Shchukin, D. G.: Polyfunctional active coatings with damage-triggered water-repelling effect. *Soft Matter*, **7**, 369-372 (2011).
- [8] Purkyastha, S.; Hartmann, J. and Tauer, K.: Synthesis of Biocompatible Poly(hydroxyethyl methacrylate) Particles with pullulan shells. submitted to *Journal of Colloid Science and Biotechnology*.

Carbon Materials from Renewable Resources



Magdalena Titirici 24.03.1977
1995-2000: "Diploma" in Chemistry (University of Bucharest, Romania)
2001-2004: Doctoral Thesis: Synthesis and Evaluation of Novel Formats in Molecular Imprinting (University of Dortmund)
2005-2006: Postdoctoral Scientist Department of Colloids, Max Planck Institute of Colloids and Interfaces.
2006-2012: Research Group Leader, Department of Colloids, Max Planck Institute of Colloids and Interfaces
2012: Habilitation: Hydrothermal Carbonisation: a Sustainable Alternative to Carbon Materials (University of Potsdam) - Submitted
since 2013: Reader in Materials Science, Queen Mary University of London, UK

Introduction

Porous carbon materials are becoming of increasing interest to the developing application fields of energy storage [1] (e.g. electrodes for Li ion batteries or supercapacitors), fuel cells (e.g. novel catalysts or catalyst supports for the oxygen reduction reaction) [2] or chromatography technologies. [3]

With the development of modern technology and the need of better performing materials, a larger number of new carbon materials with well-defined nanostructures have been synthesised by various physical and chemical processes, such as fullerenes, carbon nanotubes (CNTs), graphitic onions, carbon coils, carbon fibers, and others. To date, it is probably fair to say that researches on carbon materials are encountering the most rapid development period.

Despite its wide spreading and naturally occurrence on Earth, carbon has been mainly synthesised from fossil based precursors. Pressures of an evolving sustainable society are encouraging and developing awareness amongst the materials science community of a need to introduce and develop novel porous media technology in the most benign, resource efficient manner possible. Carbon has been created from biomass from the very beginning throughout the process of coal formation. Nature is mastering the production of carbons from biomass and we only need to translate it into a synthetic process.

Hydrothermal Carbonisation (HTC)

HTC is not a new concept, but was first introduced by Bergius in 1913 who described the transformation of cellulose into coal-like materials.[4] However, while the Bergius process was based on the liquefaction of coal for the production of biofuels, our research focus is the carbonisation of biomass for the production of functional porous carbon materials.[5]

HTC is a fascinating field of research, with much about it developed in the past seven years [6] but far more to be discovered. In simple terms, it is a mimic of natural coalification on a timescale of hours rather than millions of years.[5a, 5c, 7] We recently added another piece of mechanistic understanding.[8] The term "functional carbon" inherently implies some sort of function, i.e. applicability of the material. Below I will give a few examples of sustainable synthesis of porous materials and their applications.

Emulsion Templated Macroporous Carbons as Electrodes for Enzymatic Biofuel Cells

We have designed carbon monoliths using an easy synthetic pathway based on High Internal Phase Emulsion (HIPE) as a soft-template to confine the polymerisation-hydrothermal carbonisation of both saccharide derivatives and phenolic compounds. After further thermal treatment under inert atmosphere, the as-synthesised macroporous "Carbo-HIPES" feature interesting mechanical properties, together with high electrical conductivity up to 300 S.m^{-1} . Moreover, these new conductive foams exhibit a hierarchical structure, associated with the presence of macro, meso- and micropores, leading to specific BET surface areas and DFT total pore volumes up to $730 \text{ m}^2.\text{g}^{-1}$ and $0.313 \text{ cm}^3.\text{g}^{-1}$ respectively. In view of attractive structural characteristics and intrinsic properties, these macroporous monoliths have been incorporated within electrochemical devices, as modified thin carbon disc electrodes. After immobilisation of glucose oxidase-based biocatalytic mixture, a promising improvement of the catalytic current density by a factor 2 compared to commercial glassy carbon electrodes was observed towards electro-oxidation of glucose.

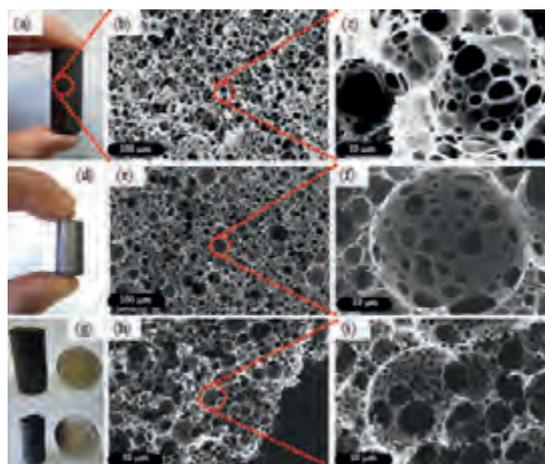


Fig. 1: First row: HTC-CarboHIPES after Soxhlet extraction and drying at $80 \text{ }^\circ\text{C}$; Second row: CarboHIPEs after further thermal treatment at $950 \text{ }^\circ\text{C}$; [9]

Hydrothermal Carbon-based Nanostructured Hollow Spheres (HS) as Electrode Materials for High-Power Lithium-Sulfur Batteries

For addressing efficient, cheap and sustainable energy storage devices, lithium-sulfur batteries (LSBs) are one of the most promising candidates for next-generation rechargeable storage devices. Indeed, while sulfur is an affordable and abundant element, its light weight leads to high theoretical specific capacity and energy density. A number of researches on cathode materials for LSBs have been carried out in the last decade. Composites made of sulfur and porous carbon have been shown to significantly improve both energy densities and cycling abilities. We focused herein on the synthesis of nanostructured carbons through the hydrothermal carbonisation of biomass-derived precursors, according to an eco-efficient and cost-effective synthetic route. We synthesized porous carbon hollow spheres (HSs) exhibiting ~80 nm internal diameters and less than 10 nm thick nanostructured shells. We have compared 3 different materials as positive electrodes in Li-S batteries: 1. hollow carbon spheres/S composites prepared by S melt diffusion; 2. hollow carbon spheres/S composites prepared by a simple mixture; 3. non-porous carbon spheres mixed with S. A fine control of the shell thickness and porosity allowed a simultaneous optimisation in the achieved specific powers, specific energies and cycling properties of the carbon-sulfur composite electrodes. The best results were obtained when using the hollow spheres infiltrated with S by melt diffusion (discharge capacity of 1000 mAh.g⁻¹ at the 1st cycle, maintains a discharge capacity of 600 mAh.g⁻¹ at the 50th cycle). Even at a very high current density of 10C (=16750 mA.g⁻¹), our cathode showed a discharge capacity of 170 mAh.g⁻¹. If we assume that a full Li-S cell using HS contains 25 wt.% of Li₂S, this full cell will provide a specific energy of 460 Wh.kg⁻¹ and a specific power of 5000 W.kg⁻¹.

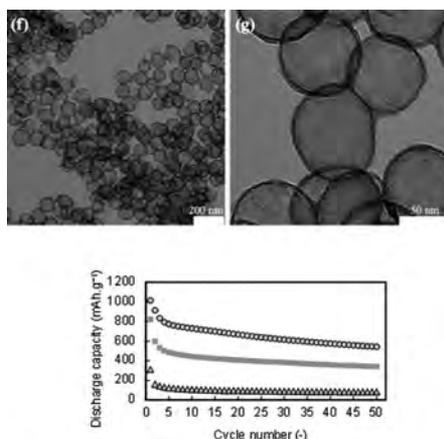


Fig. 2: Carbon-based HS. The cycling stability of the composite made by melt diffusion method is indicated by circles. The cycling performance of the mixture of HS and S is indicated by squares, while the one associated with the mixture of HTC non-hollow microspheres and S is indicated by triangles.

Sulfur and Nitrogen Doped Carbon Aerogels with Enhanced Electrocatalytic Activity in the Oxygen Reduction Reaction

We have developed one-pot, hydrothermal synthesis of nitrogen and sulfur dual doped carbon aerogels. Two comonomers, S-(2-thienyl)-L-cysteine (TC) and 2-thienyl carboxaldehyde (TCA), were used for sulfur incorporation, while the nitrogen was provided by a gelating protein, i.e. ovalbumin. [10] This approach gave rise to distinct morphologies and varying doping levels of sulfur. Nitrogen-doping levels of 5 wt% and sulfur-doping levels of 1 wt% (using TCA) to 4 wt% (using TC) were obtained. A secondary pyrolysis

step was used to further tune the carbon aerogel conductivity and heteroatom binding states. By comparing solely nitrogen-doped with nitrogen- and sulfur-doped carbon aerogels, it was observed that the presence of sulfur improves the overall electrocatalytic activity of the carbon material in both basic and acidic media.

Other few examples from our research include the development of cellulose [11] or rye-straw [12]-based porous electrodes in Lithium ion batteries, efficient CO₂ adsorbents from algae [13] as well as upgrade of bio-wastes remaining from the production of bio-ethanol into electrodes for supercapacitors. [14]

M.M.Titirici, N. Brun, S. Wohlgemuth, C. Falco, L. Yu, L. Wang
Magdalena.titirici@mpikg.mpg.de.
m.m.titirici@qmul.ac.uk

References:

- [1] D. S. Su, R. Schlögl, *ChemSusChem* **3**, 136-168 (2010).
- [2] E. Antolini, *Energy & Environmental Science* **2**, 915-931 (2009).
- [3] J. H. Knox, B. Kaur, G. R. Millward, *Journal of Chromatography A* **1986**, **352**, 3-25.
- [4] F. Bergius, *J. Soc. Chem. Ind.*, **32**, 462-467 (1913).
- [5] a) M. M. Titirici, M. Antonietti, *Chem. Soc. Rev.*, **39**, 103-116 (2010); b) B. Hu, K. Wang, L. Wu, S.-H. Yu, M. Antonietti, M.-M. Titirici, *Advanced Materials*, **22**, 813-828 (2010); c) M. M. Titirici, A. Thomas, M. Antonietti, *New J. Chem.* **2007**, **31**, 787-789; d) S. Meyer, B. Glaser, P. Quicker, *Environmental Science & Technology*, **45**, 9473-9483 (2011).
- [6] M.-M. Titirici, R. J. White, C. Falco, M. Sevilla, *Energy & Environmental Science*, **5**, 6796-6822 (2012).
- [7] B. Hu, K. Wang, L. H. Wu, S. H. Yu, M. Antonietti, M. M. Titirici, *Adv. Mater.*, **22**, 813-828 (2010).
- [8] a) C. Falco, N. Baccile, M.-M. Titirici, *Green Chemistry* **2011**, **13**, 3273-3281; b) C. Falco, F. Perez Caballero, F. Babonneau, C. Gervais, G. Laurent, M.-M. Titirici, N. Baccile, *Langmuir*, **27**, 14460-14471 (2011).
- [9] N. Brun, C. A. Garcia-Gonzalez, I. Smirnova, M. M. Titirici, *ChemSusChem*, DOI: 10.1002/cssc.201200692 (2012).
- [10] S.-A. Wohlgemuth, R. J. White, M.-G. Willinger, M.-M. Titirici, M. Antonietti, *Green Chemistry*, **14**, 1515-1523 (2012).
- [11] Liping Wang, Christina Schütz, German Salazar-Alvarez, M.-M. Titirici, in preparation.
- [12] Liping Wang, Zoe Schnepf, M. M. Titirici, *J. Mater. Chem. A*, **1** (17), 5269 - 5273 (2013).
- [13] M. Sevilla, C. Falco, M.-M. Titirici, A. B. Fuertes, *RSC Advances*, **2**, 12792-12797 (2012).
- [14] C. Falco, J. M. Sieben, N. Brun, M. Sevilla, T. van der Maelen, E. Morallón, D. Cazorla-Amorós, M.-M. Titirici, *ChemSusChem* **6**, **2**, 374-382, (Feb. 2013).

Novel Synthetic Routes for Nanoparticles Production



Cristina Giordano 07.05.1974

2002: Diploma, Chemistry
(Chemistry Department,
University of Palermo, Italy)

2005: PhD, Chemistry
(Chemistry Department,
University of Palermo, Italy)

Thesis: Physico-Chemical Investigation
of Nanoparticles Confined in
Microheterogeneous Systems

2005-2007: Professor Assistant
(Chemistry Department, Palermo)

2007-2008: Post-doc
(Max Planck Institute for Colloids
and Interfaces, Potsdam)

Since October 2008: Group Leader
(Max Planck Institute for Colloids
and Interfaces, Potsdam)

2011: Winner of the Zsigmondy Stipen-
dium of the German Colloid Society.

Introduction

Ceramic materials are largely present in our everyday life in many different fields, from (bio)medicine to electronics, catalysis, photocatalysis, etc. Metal nitrides (MN) and metal carbides (MC) are a special class of ceramics with features extending oxides. Together with excellent mechanical properties and chemical stability MN/MC possess electrical conductivity and catalytic activity, which place them –function-wise – between ordinary ceramics and pure metals. Despite this high potential, the use of MN/MC is still comparably limited, mainly due to synthesis limitations. Classical approaches require in fact very high temperatures, toxic precursors or complicated multi-step processes. In the last few years, in our group alternative pathways have been designed, also allowing shaping and processing and several MN/MC nanoparticles and nanostructures have been produced for targeted applications in a sustainable way [1].

Nanoparticles for Energy Applications

In a word in constant evolution, scientists have the delicate issue to provide suitable materials to fulfill the contemporary necessities. This is especially important in energy related matter, where valid alternatives to the current systems must still be found. Also here, despite the wide range of possibilities, the attention is still mainly devoted to some selected classes of materials, while MN/MC could provide a valid alternative to other well-establish systems (metals and noble metals for instance). In order to produce a variety of MN/MC structures in a sustainable way, a sol-gel-type process was set up using suitable N/C sources (from small molecules like urea to polymers like gelatine), which also act as stabilizing agents. The attention was focused on energy related materials, particularly interesting for classical and novel catalytic processes (VN, MoC, WC, etc), photocatalysis and photovoltaics (TaON, $Zn_{1.7}GeN_{1.8}O$ and GaN@InN), electrochemistry and battery applications (e.g. $Fe_3C@C$, $MnN@C$).

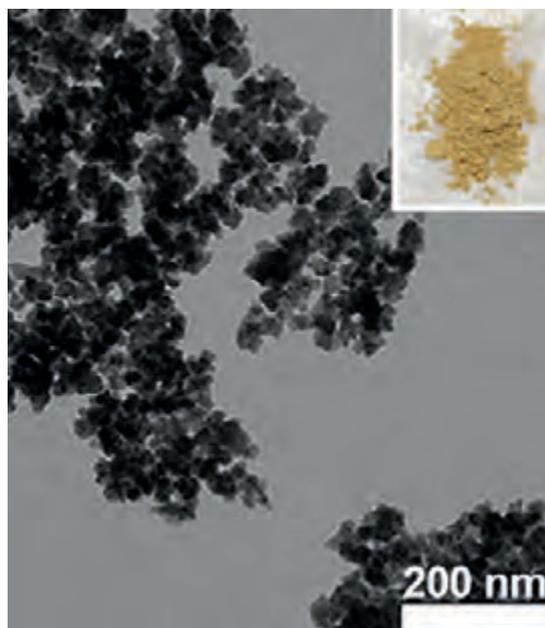


Fig.1: TEM picture of $Zn_{1.7}GeN_{1.8}O$ nanoparticles, in the inset the corresponding powder sample [2]

From Paper to Carbon Electrodes by Printing

Bio-structures display a high degree of complexity and can be used to bring features such as porosity, high surface area and complex design into a final ceramic material. With this aim, a simple synthesis toward hierarchical microstructures of magnetic iron carbide (Fe_3C) starting from pure cellulose was designed. In this study, ordinary filter paper was turned into mesostructured iron carbide/graphene nano-assemblies with high structural perfection. Shape retention at the macroscopic scale was also proved by calcination of a "crane-origami" (Fig. 2) previously embedded in a Fe sol- precursor solution. In these composites the iron carbide nanoparticles add functionality, e.g. a high saturation magnetization, conductivity, filtration properties and (electro)catalytic activity, while the polymer/carbon matrix gives processability and shape.



Fig.2: An origami (paper) crane previously soaked in a suitable iron salt solution then calcined, turns in a magnetic object (and thus attracted by a rectangular magnet, left) made of small Fe_3C nanoparticles embedded in a graphitic matrix (inset, right)

Furthermore, by using the paper as a support and combining it with a catalytic ink (by ink-jet printing), functional carbon/ceramic arrays and 3D structures were produced. The process allows turning mere cellulose into mesostructured graphene nano-assemblies and can be used as the basis for further processing, for instance copper electro-deposition [3].

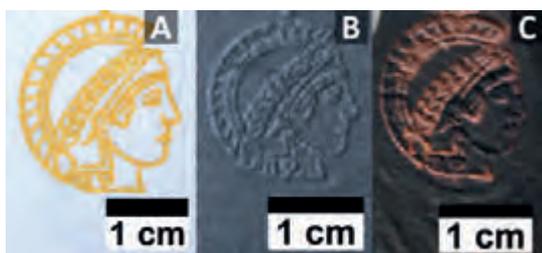


Fig. 3: A) Printed sample, B) after calcination, C) after copper deposition

Towards Hybrid Systems: $\text{Fe}_3\text{C}@ILs$

After progresses toward sustainable synthesis as pure phase, the production of MN/MC based hybrids and/or nanocomposites (by functionalization with a suitable second phase) was a further step in our research. The coupled phase can be a poly-ionic liquid (PILs) or a carbon phase, and can act as a mere dispersant but can also facilitate further processing (e.g. casting or coating) [4]. For instance, nanoparticles with magnetic properties embedded in a PIL matrix, couple the magnetic properties with the PIL characteristics [5].

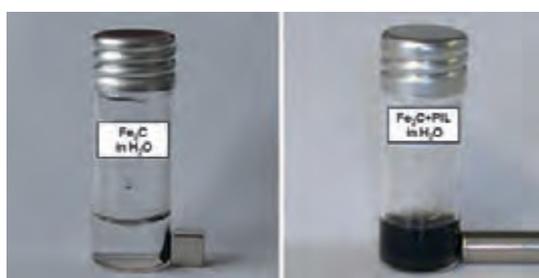


Fig.4: Fe_3C nanoparticles dispersed in water can be attracted by an external magnet, while stay stably dispersed in a PIL solution.

C. Giordano, G. Clavel, S. Glatzel, V. Maurice, K. Otte, C. Vaupel.

Cristina.Giordano@mpikg.mpg.de

References:

- [1] Giordano C., Antonietti M., "Synthesis of Crystalline Metal Nitride and Metal Carbide Nanostructures by Sol-Gel Chemistry", *Review in Nano Today*, **6**, (2011), 366
- [2] Schliehe C., Giordano C., "Bottom-up Synthesis of $\text{Zn}_{1.7}\text{Ge}_{1.80}$ Nanoparticles for Photocatalytic applications", under revision
- [3] Glatzel S., Schnepf Z., Giordano C., "From paper to structured carbon electrodes by inkjet printing, *Angew. Chem. Int. Ed.*, **52**, 2355-2358, 2013
- [4] Giordano C., Corbier T., "A step forward in metal nitride and carbide synthesis: from pure nanopowders to nanocomposites", *Colloids and Polymer Science*, DOI 10.1007/s00396-012-2865-x
- [5] Schliehe C., Yuan J., Glatzel S., Siemensmeyer K., Kiefer K., Giordano C., "Iron nitride and carbide: from crystalline nanoparticles to stable aqueous dispersions", *Chemistry of Materials*, **24**, 2716-2721, 2012

Poly(ionic liquid)s: Synthesis and Materials Application



Poly(ionic liquid)s for Functional Materials

Poly(ionic liquid)s or polymerized ionic liquids (PILs), stand for a special subclass of polyelectrolytes which connect ionic liquid (IL) moieties through a polymeric backbone to form a macromolecular architecture. In such a structural configuration, some of the unique properties of ILs are brought to the polymer chains. Meanwhile the general properties of polymers are preserved. This generates a unique type of functional polymer materials. Nowadays PILs are catching steadily increasing interest in numerous applications in a broad range, such as solid polymeric ion conductor, universal stabilizer, microwave adsorbing agents, CO₂ capture, electroactuator, etc. Our group is dedicated to making new structured PILs, and applying them as/in carbon precursor, thermoresponsive soft matters, and catalysis.

while the general properties of polymers are preserved. This generates a unique type of functional polymer materials. Nowadays PILs are catching steadily increasing interest in numerous applications in a broad range, such as solid polymeric ion conductor, universal stabilizer, microwave adsorbing agents, CO₂ capture, electroactuator, etc. Our group is dedicated to making new structured PILs, and applying them as/in carbon precursor, thermoresponsive soft matters, and catalysis.

PILs as Carbon Precursor

Imidazolium- and pyridinium-based ILs have been used as valuable carbon precursor due to their negligible vapor pressure, high thermostability and abundance in heteroatoms. The advantage of PILs over ILs in the carbon production lies in the shape controllability at various length scales. PILs were previously reported to produce graphitic, mesoporous and conductive carbon nanostructures using metal salts as activation agent. In our current research activities, metal salts were excluded to hold the heteroatoms to modulate their chemical and electric properties. In one example, via electrospinning technique, nitrogen doped carbon fibers and membranes were synthesized from PILs with well-defined chemical structures (Fig. 1). In detail, vinylimidazolium or vinylpyridinium type PILs with an allyl functionality and a dicyanamide anion in each repeating unit were electrospun into fibers together with a trithiol crosslinker molecule (TRIS) and a radical initiator (ACVA). The fibers were radically crosslinked and then carbonized at 1000 °C to form nitrogen doped carbon fibers and membranes. The SEM image in Fig. 1 visualized a fiber monolayer on a silicon wafer and a freestanding carbon membrane prepared by this method. The fibers were 0.2 to 2 μm in diameter and showed a satisfactory conductivity of 200S/cm.

In another example, via layer-by-layer technique, cationic PIL poly(3-cyanomethyl-1-vinylimidazolium bromide) and anionic polyelectrolyte poly(ammonium acrylate) as the deposition pair coated the silica particle surface uniformly. Carbonization at 1000 °C and template removal delivered carbon hollow spheres of 200 to 600 nm in size, 7.2 wt % in nitrogen content and with a high surface area of ca. 400 m²/g.

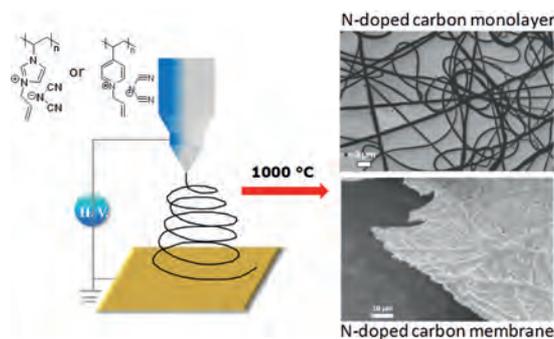


Fig. 1: Synthetic route to nitrogen-doped carbon fibers and membranes from electrospun PILs. The right side presents the SEM images of a nitrogen-doped carbon monolayer and a freestanding membrane.

PILs as Thermoresponsive Polymers

Ion responsiveness of PILs is a well-known feature. The thermal switching behavior of PILs currently catches huge attention, however less is known. We studied the low critical solution temperature (LCST) behaviour of an anionic PIL poly(4-tetrabutylphosphonium styrene sulfonate) (PTPSS). Unlike some neutral polymers like poly(N-isopropylacrylamide) (PNIPAM) with a stable transition temperature, PTPSS changes its transition temperature in a wide range upon concentration variation. Fig. 2 illustrates that the cloud point (T_{cp}) for PTPSS was 82 °C at 20 g/L, and decreased gradually to 67, 61 and 52 °C at 50, 100 and 200 g/L. In all cases, the phase transition was very sharp.

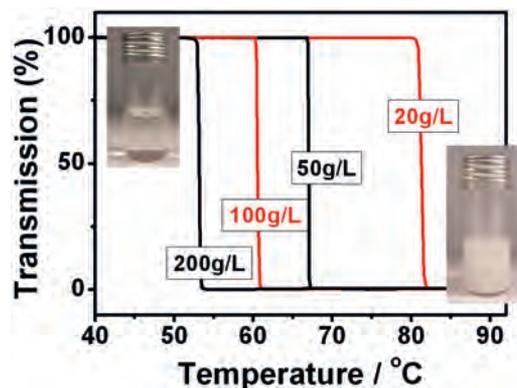


Fig. 2: Transmission vs. temperature plots of the aqueous solutions of PTPSS at different concentrations.

Jiayin Yuan 04.11.1979

1998-2002: Bachelor of Science majoring in Chemistry (Shanghai Jiao Tong University, Shanghai, China)

2002-2004: Master of Science majoring in Chemistry (University of Siegen, Siegen Germany)

2005-2009: Doctoral Thesis: One-dimensional Hybrid Nanomaterials Based on Cylindrical Polymer Brushes. (University of Bayreuth, Bayreuth, Germany)

2009-2010: Postdoctoral Fellowship Department of Colloid Chemistry, Max Planck Institute of Colloids and Interfaces

Since 2011: Research Group Leader, Department of Colloid Chemistry, Max Planck Institute of Colloids and Interfaces

References:

- [1] Zhao, Q.; Zhang, P.; Antonietti, M.; Yuan, J.: Poly(ionic liquid) Complex with Spontaneous Micro-/Mesoporosity: Template-Free Synthesis and Application as Catalyst Support. *J. Am. Chem. Soc.* **134**, 11852-11855 (2012).
- [2] Zhao, Q.; Fellingner, T.-P.; Antonietti, M.; Yuan, J.: Nitrogen-Doped Carbon Capsules via Poly(ionic liquid)-Based Layer-by-Layer Assembly. *Macromol. Rapid Commun.* **33**, 1149-1153 (2012).
- [3] Yuan, J.; Wunder, S.; Warmuth, F.; Lu, Y.: Spherical polymer brushes with vinylimidazolium-type poly(ionic liquid) chains as support for metallic nanoparticles. *Polymer* **53**, 43-49 (2012).
- [4] Wilke, A.; Yuan, J.; Antonietti, M.; Weber, J.: Enhanced Carbon Dioxide Adsorption by a Mesoporous Poly(ionic liquid). *ACS Macro Lett.* **1**, 1028-1031 (2012).
- [5] Soll, S.; Antonietti, M.; Yuan, J.: Double Stimuli-Responsive Copolymer Stabilizers for Multiwalled Carbon Nanotubes. *ACS Macro Lett.* **1**, 84-87 (2012).

Foreign salts were an additional tool to modulate their solution behaviour. While KBr shifted the transition to high temperatures, tetrabutylphosphonium bromide and the monomer salt could lower it down even to room temperature. Indeed, the LCST-type phase transition of PTPSS is very unique and is dependent on the polymer concentration and external salts. PIL copolymers could show also tunable and designable LCST-like solution behavior. **Fig. 3** displayed double stimuli-responsiveness behaviour of a PIL copolymer poly(NIPAM-co-1-ethyl-3-vinylimidazolium bromide) [poly(NIPAM-co-EVImBr)] in aqueous solution. The copolymer remained stable in aqueous solution upon heating or adding KBr salt, as the other non-stimuli affected part always takes over the stabilizing role. Only the simultaneous combination of both effects could destabilize the solutions with a precisely adjustable T_{cp} in a wide temperature window by tuning the copolymer composition and the ionic strength. Such a solution behaviour was a synergistic effect of the PNIPAM fraction, a LCST-type neutral polymer with a transition temperature at 32 °C and the bromide-containing PIL, a polyelectrolyte sensitive to ionic strength. This “double key principle” could be coupled with the stabilization function of the PIL to process carbon nanotubes. By stabilizing carbon nanotubes with this type of multi-responsive copolymers, the aqueous stability of CNTs is variable over a wide temperature range.

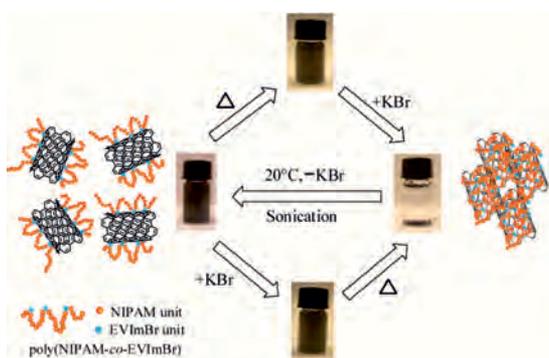


Fig. 3: Schematic Illustration of “double key switching system” to formulate a temperature and ionic strength responsive MWCNT dispersion by using a poly(NIPAM-co-EVImBr) copolymer stabilizer.

PILs in Catalysis

PILs can work as catalyst, catalyst support or pre-catalyst. Our group focused in the last two years on the supporting function of PILs in catalysis. Due to the charge feature, PILs can stabilize catalytically active metal nanoparticles. For example, a spherical PIL brush system based on a crosslinked

polystyrene core and densely grafted poly(1-ethyl-3-vinylimidazolium bromide) shell could serve efficiently as support for noble metal nanoparticles, such as Pt or gold. The catalytic system based on PIL-Pt could catalyze the reduction of nitrophenol, a widely found pollutant in industrial waste water, by sodium borohydride. Furthermore, the catalytic activity of the metal nanoparticles embedded in the PIL spherical brushes was found to be modulated by externally added salt. A significant decrease in the catalytic activity was observed at high NaBr concentration.

In another system, porous interpolyelectrolyte complex nanostructures of cationic PIL and poly(acrylic acid) (PAA) were tested as catalyst support for aerobic oxidation reaction. The complex was prepared via a novel precipitation route via dropping a mixture solution of PIL and PAA in DMF into ethanolic ammonia solution (**Fig. 4**).

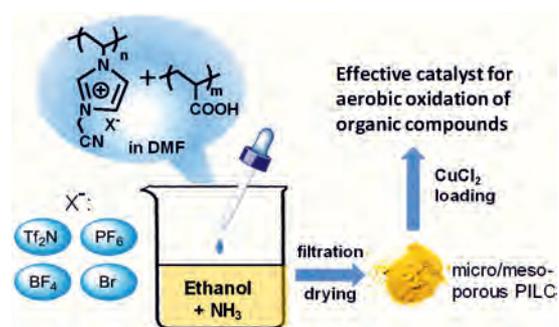


Fig. 4: Synthetic route to micro/mesoporous PIL complex based on poly(3-cyanomethyl-1-vinylimidazolium) PILs and PAA, and their application for aerobic oxidation of organic compounds.

The porous materials, termed poly(ionic liquid) complex (PILC) was precipitated out because of the *in-situ* neutralization of PAA and the corresponding complexation of PAA with poly(3-cyanomethyl-1-vinylimidazoliumbis(trifluoromethanesulfonyl)imide)) in a non-aqueous medium. Nitrogen sorption measurements indicated a total specific surface area of up to 310 m²/g in these PILC materials. The PILC materials could load copper salts in an unconventional ion pair binding mode, which allowed for an uptake of 25 wt% of CuCl₂ into the PILC matrix. The resulting hybrids were used as an effective heterogeneous catalyst for the aerobic oxidation of hydrocarbons under mild conditions. Both high activity and selectivity were achieved for this catalytic system.

J. Yuan, D. Kuzmicz, J. M. Balach, K. Grygiel, Q. Zhao, S. Soll, S. Prescher, Y. Men
jiayin.yuan@mpikg.mpg.de

[6] Schliehe, C.; Yuan, J.; Glatzel, S.; Siemensmeyer, K.; Kiefer, K.; Giordano, C.: Iron Nitride and Carbide: from Crystalline Nanoparticles to Stable Aqueous Dispersions. *Chem. Mater.* **24**, 2716-2721 (2012).

[7] Men, Y.; Li, X.-H.; Antonietti, M.; Yuan, J.: Poly(tetrabutylphosphonium 4-styrenesulfonate): a poly(ionic liquid) stabilizer for graphene being multi-responsive. *Polym. Chem.* **3**, 871-873 (2012).

[8] Koebe, M.; Drechsler, M.; Weber, J.; Yuan, J.: Crosslinked Poly(ionic liquid) Nanoparticles: Inner Structure, Size, and Morphology. *Macromol. Rapid Commun.* **33**, 646–651 (2012).

[9] Yuan, J.; ten Brummelhuis, N.; Junginger, M.; Xie, Z.; Lu, Y.; Taubert, A.; Schlaad, H.: Diversified Applications of Chemically Modified 1,2-Polybutadiene. *Macromol. Rapid Commun.* **32**, 1157-1162 (2011).

[10] Yuan, J.; Soll, S.; Drechsler, M.; Mueller, A. H. E.; Antonietti, M.: Self-Assembly of Poly(ionic liquid)s: Polymerization, Mesostructure Formation, and Directional Alignment in One Step. *J. Am. Chem. Soc.* **133**, 17556-17559 (2011).

[11] Yuan, J.; Schlaad, H.; Giordano, C.; Antonietti, M.: Double hydrophilic diblock copolymers containing a poly(ionic liquid) segment: Controlled synthesis, solution property, and application as carbon precursor. *Eur. Polym. J.* **47**, 772-781 (2011).

[12] Yuan, J.; Marquez, A. G.; Reinaucher, J.; Giordano, C.; Janek, J.; Antonietti, M.: Nitrogen-doped carbon fibers and membranes by carbonization of electrospun poly(ionic liquid)s. *Polym. Chem.* **2**, 1654-1657 (2011).

[13] Yuan, J.; Antonietti, M.: Poly(ionic liquid) Latexes Prepared by Dispersion Polymerization of Ionic Liquid Monomers. *Macromolecules* **44**, 744-750 (2011).

[14] Yuan, J.; Antonietti, M.: Poly(ionic liquid)s: Polymers expanding classical property profiles. *Polymer* **52**, 1469-1482 (2011).

NANOSTRUCTURED MATERIALS FOR ENERGY STORAGE, CONVERSION AND PHOTOCATALYSIS

Design of 3D-Conjugated Polymers as Heterogeneous Photocatalysts



Filipe Vilela 15.06.1976

1996-2002: Licentiate in Chemistry

Faculty of Sciences University of Lisbon, Portugal

Thesis: Synthesis and Reactivity of New N (pyridil)Carbamates for Pesticides

2004-2007: Ph.D.

Department of Pure and Applied Chemistry, University of Strathclyde, Glasgow, UK

The Strathclyde Route to Branched Vinyl

Polymers in Suspension Polymerization:

Architectural, Thermal and Rheological

Characterization of the Derived

Branched Polymers

2007-2011: Research Fellow

Department of Pure and Applied

Chemistry, University of Strathclyde, Glasgow, UK

Self-Assembling Conjugated

Macromolecules for Organic Field

Effect Transistors and Solar Cells

Since 2011: Research Group Leader

Department of Colloid Chemistry,

Max Planck Institute of Colloids and

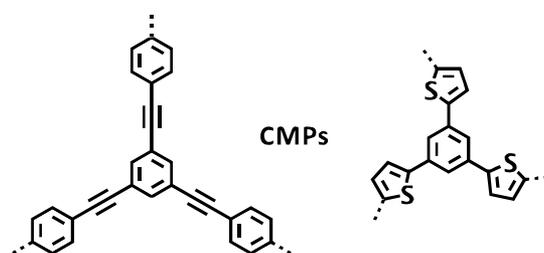
Interfaces, Potsdam, Germany

Conjugated Microporous Polymers for

Heterogeneous Photocatalysis

Introduction

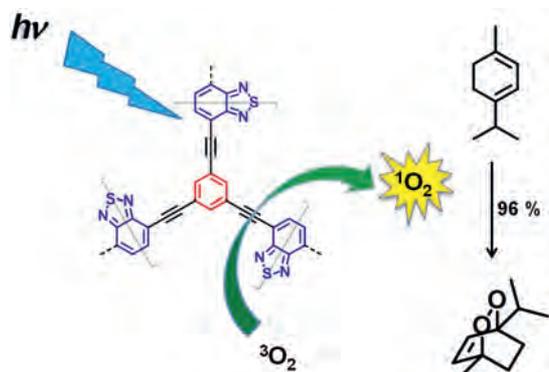
Organic conjugated oligomers and polymers are an important class of semiconductor materials, attracting great interest in applications such as organic light emitting diodes (OLEDs), photovoltaics, organic field effect transistors, electrochromic devices and sensors. Optimization of a device performance is a major challenge in this field and there is a range of electronic and structural features that can be manipulated to improve a material's suitability towards a particular device. The design and construction of an ideal material for organic semiconductor devices requires careful consideration of a range of physical properties. Conjugated microporous polymers (CMPs) offer the same advantages of conventional conjugated polymers, with extended π -systems where the electronic levels can be controlled rendering materials that are semiconducting and have a wealth of applications. Furthermore, and given the distinct morphological properties of CMPs, (including porosity and high surface areas) π -conjugated microporous materials have been gaining more and more attention recently. CMPs have been widely studied in areas such as gas separation and storage, taking advantage of their high surface areas and porosity. More recently, conjugated polymer networks are making their way into catalytic systems as heterogeneous catalysts.



The general concept of our research is to develop novel photoactive conjugated polymer networks, (CMPs) with a high level of control over their electronic and structural properties for application in Heterogeneous Photocatalysis, an important technology in solar energy conversion and sustainable chemistry.

Background

Having established the potential for photoinduced charge transfer of a CMP to an acceptor molecule, it is valid to assume that this class of materials has the potential to act as heterogeneous photocatalysts (on their own merit) and/or as metal catalyst supports (again heterogeneous). Indeed, our current research in this field has made some notable breakthroughs where a novel CMP synthesized has shown to be able to act as a photosensitizer in the production of singlet oxygen for ene type reactions. This poses a major advancement as current photosensitizers are generally dissolved in the reaction media and once the reaction is completed the desired product is obtained via costly and cumbersome separation techniques in order to remove the catalyst. With the CMP, a simple filtration is sufficient to remove it from the reaction media and this heterogeneous photocatalyst can be readily reused without significant loss of its catalytic activity.



Singlet oxygen generation via photoactivation of benzthiadiazole bearing CMP for conversion of α -terpinene into ascaridole

Methodology

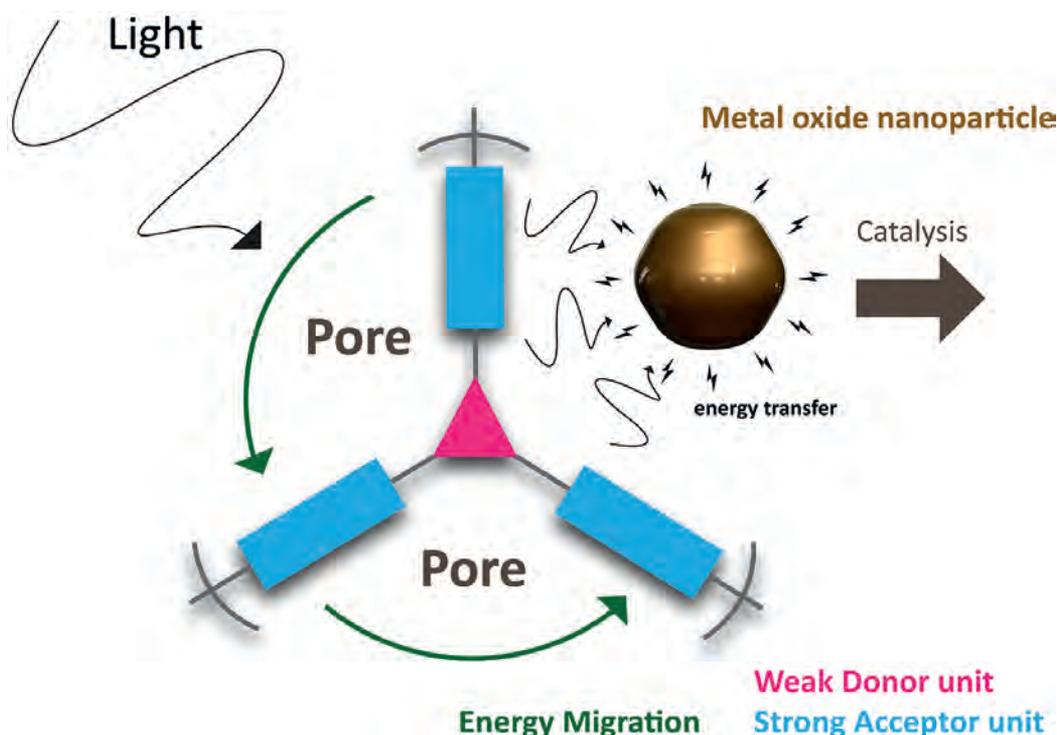
In the first instance, and employing the CMPs synthesized according to knowledge already gathered, heterogeneous photocatalytic reactions (including: singlet oxygen activation, trifluoromethylations, CO₂ reduction and water-splitting) are attempted solar light simulators as source of photons to excite the polymer network at room temperature (the absence of heat represents a major advantage over other common catalytic systems and is in line with sustainability). The reasoning behind the choice of the reaction will be determined by the energetic levels, (HOMO and LUMO), of the CMPs that meet the requirements for a particular reaction. Also, and once the structural factors that determine the photocatalytic activity have been identified, novel CMPs will be synthesized accordingly. Synthesis and characterization of novel CMPs with a high level of control of their morphological properties is also fundamental for a high performing heterogeneous catalysis. Surface area, pore size and pore volume (including pore connectivity and percolation within the material) influence the interfacial level where the catalytic event takes place. Synthesizing CMPs in the presence of silica nanoparticles (for instance) can provide a useful method to template the polymeric material, increase its surface area and achieve defined pore size once the template is removed. Synthetic post-modification of the CMPs can also help control surface

area and introduce new features that include water compatibility of the CMP and coordination sites to metal nanoparticles (application of photocatalytic reactions in water and in the absence of volatile organic compounds, VOCs, is again in line with sustainable and green chemistry). Also, metal nanoparticles can be incorporated into the polymer voids in order to enhance and access different photocatalytic reactions. Ultimately, and having achieved important milestones, such as control of electronic and morphological properties of the CMPs; ensure the chemical stability of the polymer framework during photocatalysis; incorporation of inexpensive and abundant metal nanoparticles within the porous materials; photocatalyze organic reactions in polar solvents and water and in the absence of VOCs; the aim will be to develop a material (or combination of materials) that can catalyze economical and sustainable reactions which replace traditional and expensive metals (palladium, ruthenium, iridium, etc.) such as in carbon-carbon formation, epoxidation of olefins, CO₂ reduction and water-splitting directly using solar light as the source of photons.

F. Vilela, L. Chabanne, L. Jia, H. Urakami, Z. Vobecka, K. Zhang
Filipe.Vilela@mpikg.mpg.de

Relevant References:

- [1] Urakami, H., Zhang, K., Vilela, F.: Modification of conjugated microporous poly-benzothiadiazole for photosensitized singlet oxygen generation in water. *Chemical Communications* **49**, 2353-2355 DOI:10.1039/C3CC38956A (2013).
- [2] Zhang, K., Kopetzki, D., Seeberger, P., Antonietti, M., Vilela, F.: Surface area control and photocatalytic activity of conjugated microporous poly(benzothiadiazole) networks. *Angewandte International Edition* **52**, 1432-1436 DOI:10.1002/anie.201207163 (2013).
- [3] Vilela, F., Zhang, K. and Antonietti, M.: Conjugated Porous Polymers for Energy Applications. *Energy and Environmental Science* **5**, 7819-7832 DOI: 10.1039/C2EE22002D (2012).



- Independent Researchers
- (Quasi) Planar Interfaces – Fluid Interfaces
- Solid Interfaces
- Non-Planar Interfaces

INTERFACES

Research in the Department of Interfaces



Helmut Möhwald 19.01.1946

1971: Diploma, Physics
(University Göttingen)

Thesis: Messungen der absoluten Polarisation optischer Übergänge an Molekülen und Molekülkomplexen in Flüssig-Kristallinen Lösungsmitteln

1974: PhD, Physics

(University Göttingen, Max-Planck-Institut für Biophysikalische Chemie, A. Weller, E. Sackmann)

Thesis: Lokalisierte und delokalisierte Tripletzustände in Einkristallen von Elektron-Donor-Akzeptor-Komplexen: ESR- und emissionspektroskopische Untersuchungen zwischen 4K und 300K

1974-1975: Postdoc (IBM San Jose)

1975: Research Assistant
(University of Ulm)

1978: Habilitation, Physics

(University of Ulm) Thesis: Transporteigenschaften und Phasenübergänge in organischen Charge-Transfer Kristallen

1978-1981: Scientific Coworker

(Dornier-System, Friedrichshafen)

1981: Associate Professor C3,

Experimental Physics (TU München)

1987: Chair C4, Physical Chemistry,

(University of Mainz)

Since 1993: Director and Scientific

Member (Max Planck Institute of

Colloids and Interfaces, Potsdam)

Since 1995: Professor, Physics and

Physical Chemistry (University Potsdam)

Since 2001: Honorary Professor

(Zhejiang University, Hangzhou)

Since 2004: Honorary Professor

(Fudan University, Shanghai)

Since 2006: Honorary Professor

(Institute of Chemistry at the Chinese Academy of Sciences, Beijing)

I. General Strategy

Interfaces are most important on one hand to understand and control colloidal systems with their large fraction of specific surface, on the other hand most processes start at an interface, and therefore they determine many physical and chemical properties. From a basic science point of view they exhibit peculiarities as low – dimensional systems and are anisotropic systems where molecules can be oriented. Macromolecules like proteins and peptides may change their secondary and tertiary structure and thus their function at interfaces. Within the institute`s strategy of building and understanding hierarchical structures they are positioned at the lowest length scale which one may also consider the base. Accordingly the main aim of the department is to understand and to control molecular interfaces as regards structure, dynamics and properties. As an offspring of this the knowledge could be used to prepare complex films, coated colloids and capsules. For this the department has established a zoo of techniques to characterize colloids and interfaces and, especially concerning studies of liquid interfaces, we are probably best equipped world – wide. The latter is also due to the fact that there has been a continuous development of methods over years. Part of these developments has been commercialized within four start-up companies.

As a general trend in all groups the interfaces increase in complexity, i.e. planar interfaces mostly also contain proteins, polypeptides or nanoparticles. If the interface contains only small molecules the dynamics is of prime importance. This concerns reorganization of molecules, their diffusion as well as collective motion like flow under a surface pressure gradient.

On the other hand the mission is also to concentrate on basic science and therefore schemes had to be developed to transfer technology and knowledge to groups and partners oriented towards application.

The research concerns predominantly experiments between chemistry and physics with little molecular synthesis and biology, and also theory is mostly employed only in collaborations. It has been organized within five groups which are largely independent from the director but interact with me in varying intensity. Some scientists are also under my direct supervision which has been in special necessary when the group leader had left or if there was a topic to be taken up independent of the immediate interest of a specific group.

II. Research Highlights

II. 1 Planar Interfaces

The specially advanced expertise and methodology to study Langmuir monolayers at the air/water interface has been made use of in many model studies of systems interesting for various type of applications, to name but a few:

- It was shown that the formation of beta sheets of specifically designed peptides is influenced by different cations (Cu, Zn) as well by the interface where they are located. In all cases studied interfacial forces dominated the ionic forces (cooperation Prof. B. Kokschi, FU Berlin).

- New zwitterionic phospholipid membranes have been developed that appear most suitable for DNA transfection (coop. Prof. Dobner, Univ. Halle). This cooperation has now been extended by a company interested in RNA delivery.
- As most exciting new direction I consider studies of monolayers of lipids with designed carbohydrate head groups synthesized in the group of V. da Silva in the department of Biomolecular Systems. C. Stefaniu in the Brezesinski group by grazing incidence X-Ray diffraction observed a crystalline lattice of the carbohydrates in addition to the one of hydrocarbon chains. In cooperation with M. Santer from the Theory department the structure that is determined by hydrogen bonds could be solved. This opens new ways of cooperation between 3 departments where the molecular recognition of this attractive class of molecules can be studied with atomic resolution, including the consequences for coupled enzymatic reactions at membrane surfaces (**Fig. 1**).

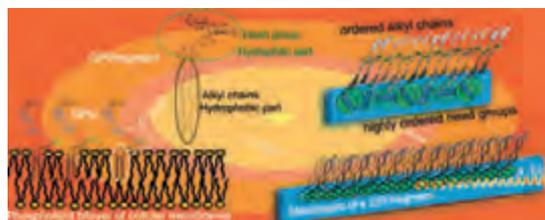


Fig.1

The group of R. Miller has been continuing their studies of thermodynamics and rheology of charged amphiphiles at water/air and water/oil interfaces. By systematic variation of the chain length they demonstrate that the adsorption isotherms can only be described by a Frumkin model that is extended by a term taking into account the Coulomb interactions of the head groups and the corresponding ion cloud. This model is also successful to describe surface rheology.

By systematically varying the chain length of alkanes and aliphatic oil they could show that the continuous film of detergent at the oil/ water interface incorporates the oil only if the oil has a specific chain length. This is understood as a compromise between van-der Waals forces and entropic forces that oppose the incorporation and orientation of the oil in the surfactant film (**Fig. 2**). The relevance of these studies for emulsion stabilization is reflected in various industrial co-operations of the group.

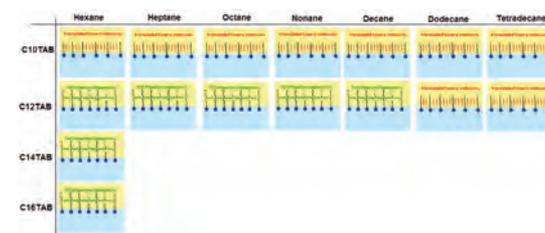


Fig.2

The group of *H. Riegler* has very much refined their optical and force microscopic observations of nucleation and growth of liquid bubbles on structured surfaces, thus yielding most quantitative data on interfacial interactions. They demonstrate that melting at steps on a surface may proceed by a nucleation and growth scenario which differs from that on flat surfaces or in bulk (coop. dept. Theory). In model studies of spin coating they calculate concentration profiles developing during the process and show that precipitates form at the liquid/air and liquid/solid interface. The latter can in addition be controlled by suitable surface structuring at the nm level. This is most relevant for a cooperation project with Helmholtz Center Berlin where nanosized aggregates of the phthalocyanines are used to fabricate bulk heterojunction solar cells.

They show that the contact angle of small droplets depends on their size and derive a model from which they obtain the line tension. They can quantitatively describe the size dependence of the contact angle by long range van der Waals forces assuming reasonable Hamaker constants.

They observe fast or delayed coalescence of sessile droplets of water/ oil mixtures. It depends little on viscosity but drastically on the surface tension difference. This indicates the importance of Marangoni flow and a corresponding model has been developed (coop. TU Cottbus). The quantitative description has been very much refined, and also the experiments have become most sophisticated by measuring the flow, controlling tightly environmental conditions (T, humidity) and numerically solving the corresponding hydrodynamic nonlinear equations (Fig. 3). Much of the work has been published in high impact journals, but it has also attracted industry funding, in special for wafer cleaning. (Fig. 3)

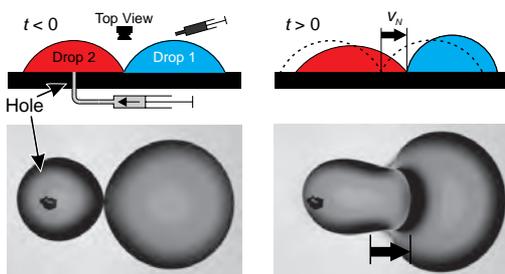


Fig.3

II. 2 Non-Planar Interfaces

The group of *D. Shchukin* has been engaged in basically two directions.

- (A) Development of stimuli sensitive nanocontainers to be embedded in enabling the development of self-repairing coatings and studies of functions of self-repairing coatings.
- (B) Development of sonochemistry as a tool for surface modification.

Under (A) nanotubular (halloysite) or nanoporous inorganic carriers were developed that via a polyelectrolyte multilayer shell exhibited stimuli sensitive release of incorporated corrosion inhibitors. Also polymeric capsules were developed via particle stabilized oil droplets (Pickering emulsions). After embedding in

a coating they then could show that the different local pH near a defect can cause inhibitor release and thus annealing. It could be shown that size (between .5 and 5 mikrom.) and location of particles are most relevant for optimum corrosion protection. These studies are most promising for applications and will be pursued partly removed from the institute's main stream with the aim of developing a start-up company.

The activities under (B) were concentrated on determining the importance of surfaces to control cavitation. It was shown by microcontact printing that bubble nucleation in water can be confined to hydrophobic surface areas, and this will enable new ways of in-situ studies that are now in progress. Meanwhile it has been possible to quantify the cavitation density and to observe nanobubbles on a patterned surface by scanning force microscopy (Fig. 4) as well as by optical microscopy (V. Belova in coop. U. Göttingen).



Fig. 4

The group of *A. Skirtach* has been most successful in making use of plasmonic interactions of metal nanoparticles and metal films. It has been made use of into three different directions:

- Following previous work on local heating by IR absorption Au nanoparticles were adsorbed to erythrocytes and cells to induce release of molecules from inside. This work has now become very elaborate to study the effect on certain channel proteins (coop. Charite and Jacobs Uni Bremen).

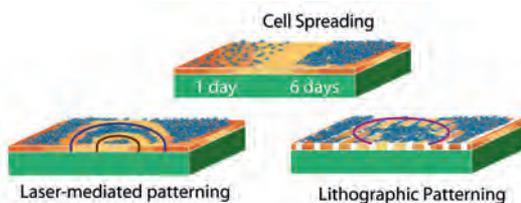


Fig.5:

- The high optical field enhancement near metal nanoparticles is well known. Adsorbing these particles into porous silica spheres one can achieve a high local density of these particles inside cells, and they are reachable by molecules inside the cell. This enables Raman detection and imaging of cellular components with light intensities close to sun light (coop. dept. Biomaterials).
- Via light induced melting patterns of nanoparticle distributions can be produced on a surface. As these change the surface mechanical properties also cell attachment follows this pattern. As alternative way singlet oxygen may be produced by light via the particles, and this in turn effects the growth and death of cells leading to cellular patterns (coop. University Bayreuth, dept. Biomaterials)

In the joint German-French lab on sonochemistry sonoluminescence spectra could be obtained from single bubbles existing of broad emission of a continuum from which a plasma temperature could be derived and the narrow emission from atomic or radical species, both depending drastically on the acoustic pressure. For rare earth ions it was shown that these ions were part of the plasma and not in the adjacent water phase. The work in this collaboration is now also extended towards composites of hydrogels in cooperation with the Biomaterials department.

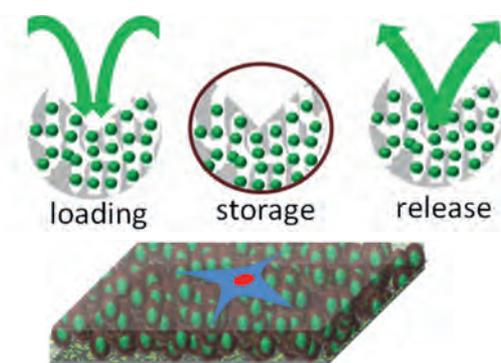


Fig. 6:

The work on cavitation has been successfully extended by 2 postdocs (V. Belova, Lu Zhang) to online measure cavitation and to quantify the influence of geometric surface features on cavitation. On the other hand cavitation has been extensively used to prepare porous surfaces (E.V. Skorb, **Fig. 6**) This offspring of the Shchukin group is now systematically extended to load the pores with drugs and to observe the response of cell attachment and growth (coop. Biomaterials).

As a most curiosity driven structure microtubes from designed peptides have been produced, and their structure resolved with molecular resolution (X.H. Yan). It was shown that these tubes can guide optical waves, but it will last for long till a physician will use the deposable light guide in an operation.

III. Future Development

Major changes of staff in the last two years have been:

- In 2011 *A.G. Skirtach* accepted a professorship in Biophotonics at University Gent. Members of the group are still working in the institute, engaged in many cooperations.
- In 2012 *D.G. Shchukin* accepted a call for a chair at University Liverpool. Also his group continued working on the many well-funded projects in the institute.
- *X.H. Yan* has received a professorship from the 1000 young talents program and just starts at the Institute of Process Engineering of the Chinese Academy of Sciences in Beijing.

Continuing collaboration with these groups it has been possible to maintain a size of about 50 people, hence to further shrink the department only in its last year of existence. Because of the strong external funding it has also been possible

to finance this size in spite of the drastic reduction of the institutional funding.

As it has not yet been possible to continue with five departments, the interfaces department will be terminated with my retirement in January 2014. This means that the remaining groups have to be transferred into the existing departments at Golm. It is obvious from this report that the monolayer work of the Brezesinski already has many cooperations with all departments and also the Riegler group is well connected with theory, and so they may profit from this move.

The work on self-repairing coatings (Shchukin) has very much matured that it also withstood industrial tests. There are now intensive trials to transfer this knowledge and the people involved into a company. If this will be successful depends more on business and marketing issues not on technical ones. On the other hand the science concerning feedback-loops is often found in nature, e.g. to regulate pH, concentration of ions, enzymes, drugs, temperature or potential. Therefore it is not too surprising that it has carried *D. Shchukin* on a chair where he can broaden his research. The work on nanoplasmonics (Skirtach) has been profiting very much from in-house and external collaborations, and is expected to persist beyond my retirement above all in collaboration with the Biomaterials department. The latter collaboration will also be very promising with sonochemical surface treatment to control cellular interactions, and *E.V. Skorb* is expected to move there.

Major recognitions have been the award to *X.H. Yan* in the 1000 talents program and the election of *R. Miller* as president of the International Association of Colloids and Interfaces (IACIS). I have become member of the Academia Europaea.

As mentioned before the department of interfaces will persist another year, and it is a good tradition that a retiring director has no influence on the future direction and persons. It is also most desirable not to continue the "old" directions. Therefore I will not comment on any future perspectives of the department. On the other hand my colleagues are trying hard to maintain an institute with five departments and there is consensus that this should focus in a broad sense on physical chemistry. On the other hand I am satisfied that up to now the shrinking process has not encountered many personal hardships, as technicians, PhD students and postdocs found attractive positions. This was possible, because of the world wide connections of the department and of the institute as a whole.

Of course I would be disappointed if physical chemistry of interfaces disappeared from the institute, more importantly the Max Planck Society would not do wise to weaken an institute like ours this way. On the other hand I have no worry about the specific field. It encounters tremendous progress worldwide, and we have a considerable contribution to this. There are meanwhile more than 100 alumni from the department on professor positions or equivalent academic positions, and these will enhance science in the area. They all remember their time in the institute with pleasure and thanks, and therefore the time together has been worth it.

Helmuth Möhwald
Director of the Department of Interfaces

Peptide Optical Waveguiding

Biomimetic or bio-inspired functional materials with ordered organization at micro- or nanoscale, fabricated from peptide building blocks, are of increasing importance due to their potential application in biomedicine and nanotechnology. The self-assembled peptide superstructures with defined spatial dimensions hold great promise for creation of photonic or electronic materials. In this work, peptide optical waveguides were for the first time fabricated in the form of either solid platelets or hollow microtubes by confined assembly or crystallization of pathogenic amyloid fibrils. Peptide waveguides will naturally degrade and not leave any trace after

they have acted as an optical element. Therefore, such functional structures of materials fabricated through self-assembly of versatile peptide molecules are advantageous in guiding light for biologically based modulation and sensing.

X. Yan
yanxh@home.ipe.ac.cn

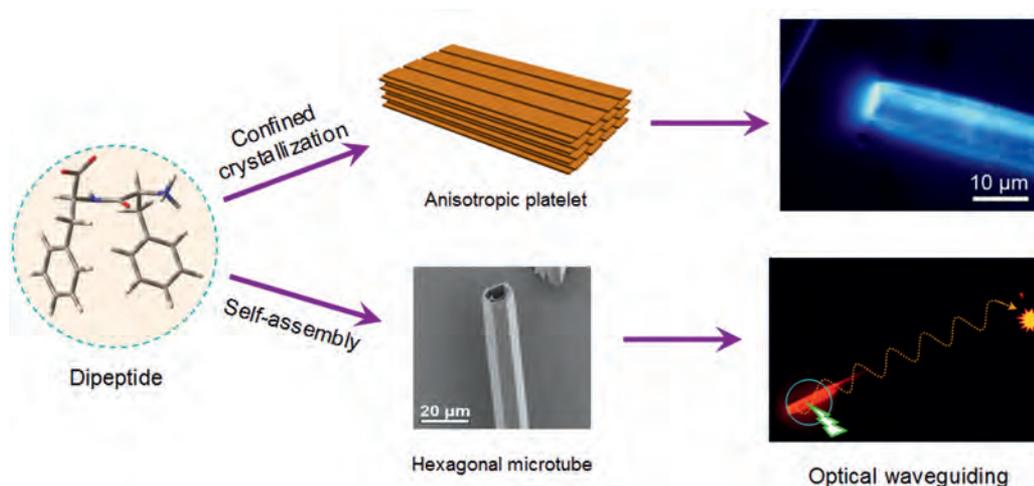


Fig. 1: Scheme and electron microscopic picture (middle bottom) of peptide assembly to platelets or tubes. The fluorescence micrograph right bottom shows at the lower left optical excitation of a microtube that is coupled out at the other end (small dot top right)

Xuehai Yan

2005-2008: Ph.D. in Chemistry (with distinction) Institute of Chemistry, Chinese Academy of Sciences (ICCAS), Beijing, China. Supervisor: Prof. Dr. Junbai Li

10.2008-07.2009: Postdoctoral Researcher Max Planck Institute of Colloids and Interfaces, Potsdam-Golm, Germany. Collaborator:

Prof. Dr. Dr. h.c. Helmuth Möhwald

08.2009-07.2011: Alexander von Humboldt Fellow, Max Planck Institute of Colloids and Interfaces, Potsdam-Golm, Germany. Collaborator:

Prof. Dr. Dr. h.c. Helmuth Möhwald

08.2011-01.2013: Independent Researcher Max Planck Institute of Colloids and Interfaces, Potsdam-Golm, Germany. Collaborator:

Prof. Dr. Dr. h.c. Helmuth Möhwald

Since 02.2013: Professor Institute of Process Engineering, Chinese Academy of Sciences, Beijing, China.

References:

- [1] Yan, X.H., Su, Y., Li, J.B., Früh, J., Möhwald, H.: Uniaxially oriented peptide crystals for active optical waveguiding. *Angew. Chem. Int. Ed.* **50**, 11186-11191 (2011).
- [2] Yan, X.H., Li, J.B., Möhwald, H.: Self-assembly of hexagonal peptide microtubes and their optical waveguiding. *Adv. Mater.* **23**, 2796-2801 (2011).
- [3] Yan, X.H., Li, J.B., Möhwald, H.: Templating assembly of multifunctional hybrid colloidal spheres. *Adv. Mater.* **24**, 2663-2667 (2012).
- [4] Yan, X.H., Blacklock, J., Li, J.B., Möhwald, H.: One-Pot synthesis of polypeptide-gold nanoconjugates for in vitro gene transfection. *ACS Nano* **6**, 111-117 (2012).

Surface Nanoarchitecture for Self-Regulated Intelligent Interfaces



Ekaterina Skorb 29.01.1983
2005: Diploma with distinction in Chemistry (Belarusian State University, Chemistry Department, Minsk, Belarus)
2007: DAAD (Deutscher Akademischer Austausch Dienst) Fellow in Max Planck Institute of Colloids and Interfaces, Potsdam, Germany.
2005-2008: Doctoral Thesis: Photocatalytic and photolithographic system based on nanostructured titanium dioxide films modified with metallic and bimetallic particles (Belarusian State University, Chemistry Department, Minsk, Belarus)
2008-2009: Researcher at Belarusian State University, Minsk, Belarus.
2009: Postdoctoral Scientist Department of Biomaterials, Max Planck Institute of Colloids and Interfaces.
2010-2011: Alexander von Humboldt Fellow
Since 01/2012: Independent Researcher, Department of Interfaces, Max Planck Institute of Colloids and Interfaces

References:
[1] E. V. Skorb et al., *Nanoscale* **2011**, 3, 985.
[2] E.V. Skorb et al., *Angew. Chem. Int. Ed.* **2012**, 51, 5138.
[3] E.V. Skorb et al., *J. Mater. Chem.* **2012**, 22, 13841.
[4] D. V. Andreeva et al., *SMALL* **2012**, 8, 820.
[5] J. Gensel et al., *Adv. Mater.* **2012**, 24, 985.

The surface nanoarchitecture providing spatially and temporally resolved stimuli response of a material and offering defined control over the behaviour of biomolecules and cells at the solid-liquid interface is in focus in our research. In particular, in our recent works **[1-5]** we suggested effective ultrasonic assisted pathways of porous material formation (metals, silicon, hybrids and nanocomposites) which can find application for drug delivery vis-à-vis being used as capsules. In **(Fig. 1)** is shown the suggested strategy for formation of surface capsules. Thus after ultrasonic treatment of an aluminum surface a mesoporous layer with good

adhesion to the bulk metal matrix is formed. The mesoporous surface layer can be loaded with a variety of agents (corrosion inhibitors, biocides, enzymes, DNA fragments, antibodies). Thus, the loaded metal layer has functionality of porous capsules. Comparing to existing encapsulation systems the surface capsules continue the bulk metal and don't need to be immobilized on the surface or incorporated into a protective coating. Furthermore, the rough surface of the metal capsules provides excellent adhesion of a protective coating.

E. Skorb
 skorb@mpikg.mpg.de

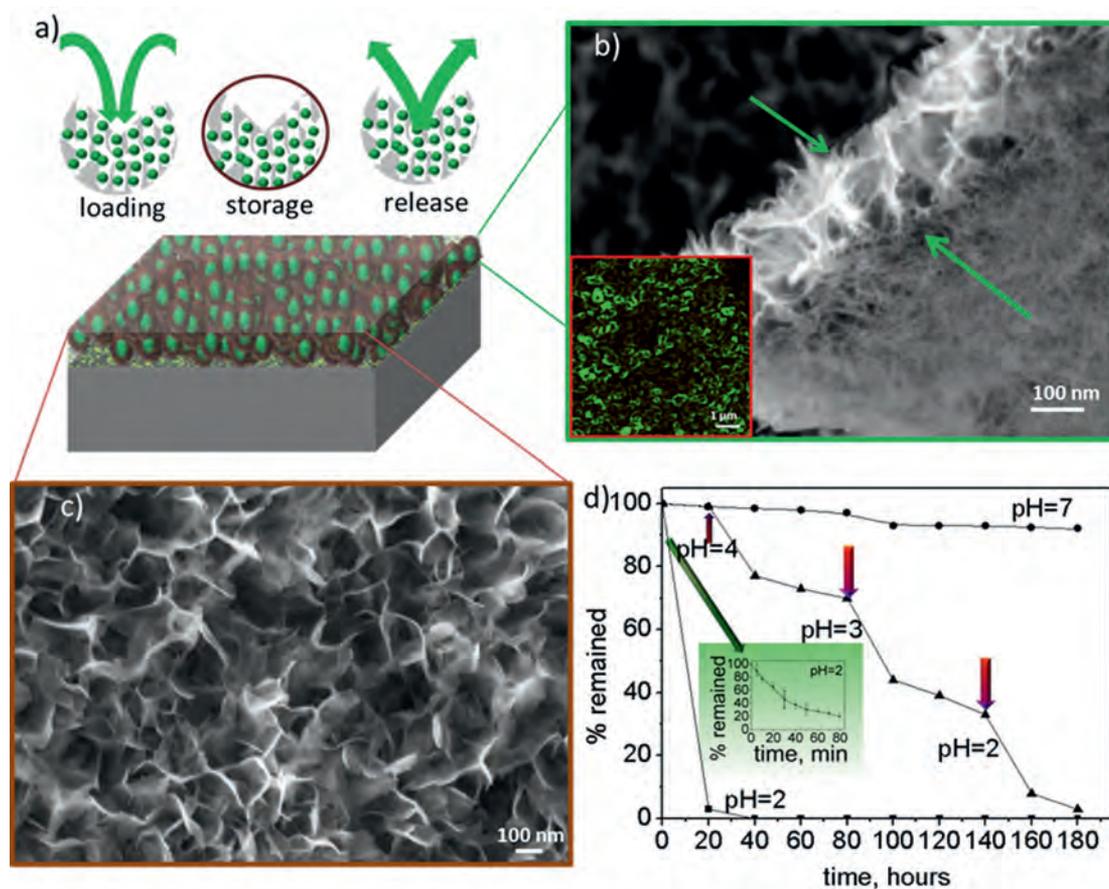


Fig. 1 (a) Schematic illustration of uploading, storage and release of active components (upper row) and general view of capsules generated at the metal surface (below). (b) SEM image of the cross section of an aluminum sponge-like layer (indicated by arrows). Luminescence confocal image (top view) of the surface capsules loaded with doxorubicin (inset). (c) TEM image of aluminum with a surface capsule layer for chemical storage (blue arrows show the loading direction, red arrows show the interface between bulk metal and capsules' layer). (d) Doxorubicin release at different pH and upon varying the pH as indicated by the red arrows. [4]

Ultrasonic Cavitation on Particle Surfaces

Ultrasound has received significant attention in the development of new functional materials and composite nanostructures due to the distinctive effect of ultrasound on materials [1-3]. The understanding of ultrasonic cavitation on solid surfaces can greatly advance the application of ultrasound. Currently, studies have been mainly focused on the evolution of cavitation bubbles formed at planar surfaces [1-4]. Nevertheless, these results have not fully accounted for the geometry of the surfaces as they neglect the contribution of feature shapes. To improve the understanding of the cavitation process, SiO₂ particles of different sizes and shapes were irradiated under a series of ultrasonic parameters (Fig. 1).

Through observing different surface changes of particles resulting from cavitation, a speculative mechanism of ultrasonic cavitation on particle surfaces was proposed. During bubble collapse, nano-sized particles will become rough and small by the high velocity collisions among particles while micron-sized particles can be broken due to the microjets and associated shock waves applied on particle surfaces.

L. Zhang, V. Belova



Lu Zhang 11.25.1983

2002-2006: Bachelor of Science (1st Class Honours) majoring in Chemistry (Liaoning Normal University, Liaoning, P. R. China)

2006-2011: Doctoral Thesis: Multi-functional Magnetic Nanoparticles for Biomedical Photonics Applications (State Key Laboratory on Integrated Optoelectronics, Jilin University, Changchun, P. R. China)

Since 2/2012: Postdoctoral Scientist, Department of Interfaces, Max Planck Institute of Colloids and Interfaces

References:

- [1] Shchukin, D.G. et al., *Adv. Mater.* **23**, 1922 (2011).
- [2] Belova, V. et al., *Ultrason. Sonochem.* **18**, 310 (2011).
- [3] Belova, V. et al., *Angew. Chem. Int. Ed.* **49**, 7129 (2010).
- [4] Belova, V. et al., *ACS Appl. Mater. Interfaces* **3**, 417 (2011).

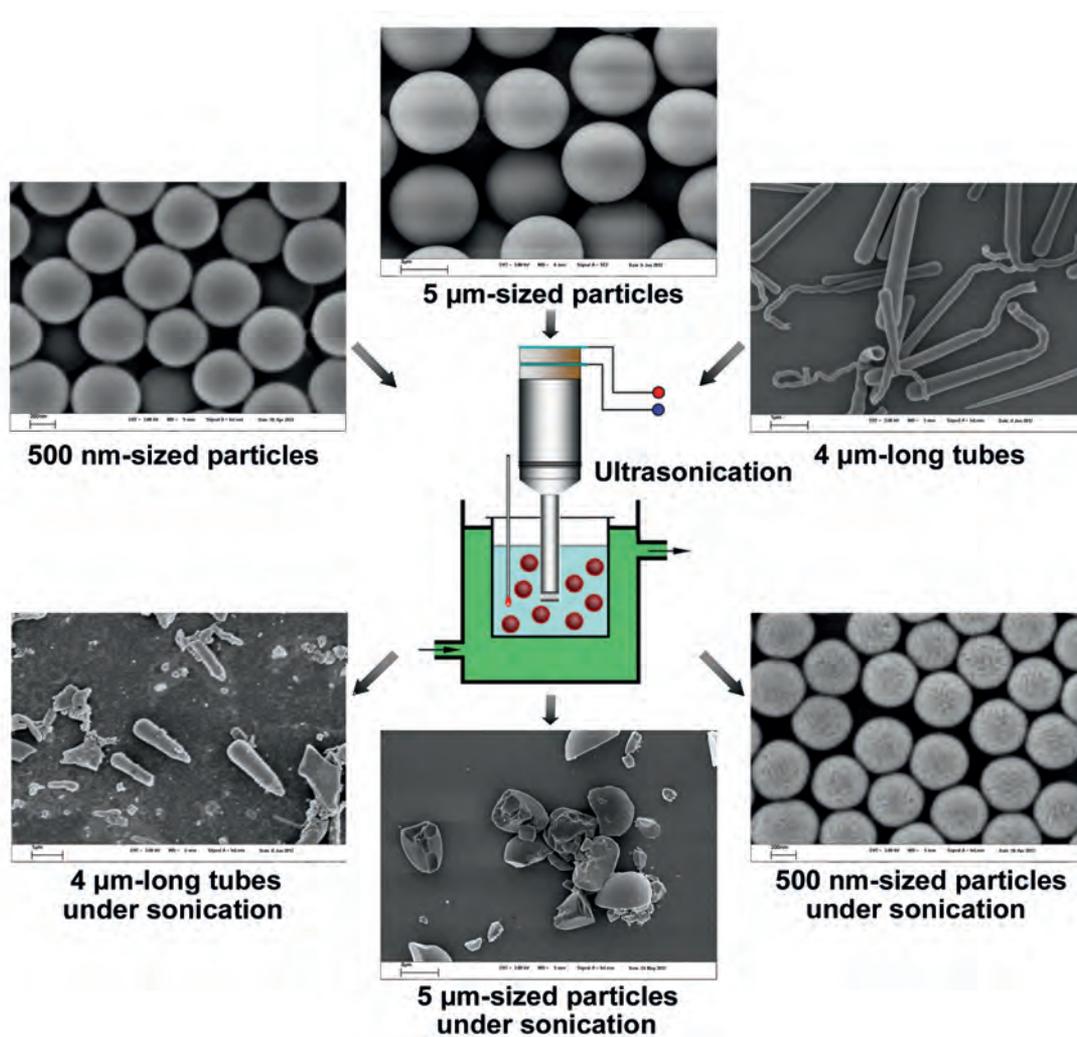


Figure 1: SEM Images of SiO₂ particles before and after ultrasonic treatment.

Langmuir Monolayers as Model Systems to Study Interactions at Interfaces



Gerald Brezesinski 02.04.1950

1974: Diploma, Biophysics (Lomonosow University of Moscow)
Thesis: The parametric pump – a physical-chemical model of the active transport of ions in cells

1981: PhD, Physical Chemistry (Martin Luther University of Halle/S.)
Thesis: Einfluss der chemischen Struktur auf das thermische Phasen- und Mischungsverhalten binärer und ternärer Phospholipid-Wasser-Systeme

1987: Habilitation, Colloid Chemistry (Martin Luther University of Halle/S.)
Thesis: Untersuchungen zum Phasen- und Mischungsverhalten ausgewählter Phospholipid-Wasser-Systeme

1981-1982: Postdoc (Biological Research Centre, Szeged, Hungary)

1982-1992: Research Scientist (Institute of Physical Chemistry, University of Halle/S.)

1992-1995: Research Scientist (Institute of Physical Chemistry, University of Mainz)

Since 1995: Group Leader (Max Planck Institute of Colloids and Interfaces, Potsdam)

Since 2009: apl. Professor, Physical Chemistry (University Potsdam)

References:

- [1] Stefaniu, C., Chanana, M., Wang, D., Novikov, D.V., Brezesinski, G. and Möhwald, H.: Langmuir and Gibbs Magnetite NP Layers at the Air/Water Interface. *Langmuir* **27**, 1192-1199 (2011).
[2] Stefaniu, C., Chanana, M., Ahrens, H., Wang, D., Brezesinski, G. and Möhwald, H.: Conformational induced behaviour of copolymer-capped magnetite nanoparticles at the air/water interface. *Soft Matter* **7**, 4267-4275 (2011).
[3] Stefaniu, C., Brezesinski, G. and Möhwald, H.: Polymer-capped magnetite nanoparticles change the 2D structure of DPPC model membranes. *Soft Matter* **8**, 7952-7959 (2012).

Aims

Monomolecular films at the air/water interface are interesting model systems to study different problems in biophysics or material science. Many parameters can be easily varied (composition, lateral packing density, surface pressure and area exposed to the medium, pH, salt concentrations, etc.). The interactions of dissolved biomolecules (DNA, peptides, enzymes) or nanoparticles [1-3] with lipid layers can be studied using surface sensitive methods. The investigation of beta-sheet forming peptides (cooperation with B. Kokschi, FU Berlin) [4, 5] as well as of antimicrobial peptides (cooperation with J. Andrä, Research Center Borstel) is ongoing. The study of non-viral transfection systems (cooperation with B. Dobner, University of Halle) will also be continued [6, 7]. In this report, the main results of our work concerning β -sheet forming peptides, new lipids designed for non-viral transfection systems, the unprecedented two-dimensional structure of GlcNAc1 \rightarrow 6myoIno-1-phosphodistearoylglycerol monolayers [8] as well as the interfacial self-assembly of polyoxometalate surfactants [9] will be described.

Selected Achievements

Triggers for β -Sheet Formation at the Hydrophobic/Hydrophilic Interface

Early stages in the aggregation process have recently been considered the cell toxic steps in amyloid diseases. Aiming at understanding various triggers for β -sheet formation (Fig. 1) such as peptide concentration, interactions with

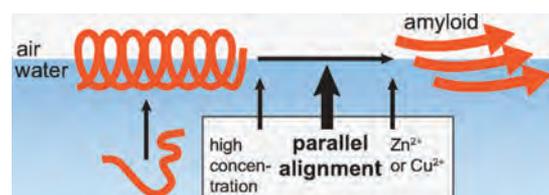


Fig. 1: Triggers for β -Sheet formation at the hydrophobic-hydrophilic interface: High concentration, in-Plane orientational order, and metal ion complexation.

hydrophobic/hydrophilic interfaces, and metal ion complexation and their interplay, we investigated a set of model peptides at the air/water interface. These peptides existing in unfolded structures in bulk transform immediately to α -helices at the interface. Depending on the primary structure of the peptide, these intermediates can start to transform into β -sheets or can be extraordinarily stable compared to the fast aggregation of the peptides at similar concentrations in bulk. In general, the interface has the strongest effect on peptide conformation compared to high peptide concentrations or metal ions. Metal ions are able to prevent aggregation in bulk but not at the interface. The effectiveness of metal ion complexation to enhance the conformational transformation into β -sheets or to stabilize the α -helix is determined by the peptide primary sequence. For example, the binding of Zn^{2+} ions is strongly dependent on the possibility of chelate formation. Therefore, it additionally accelerates aggregation

at the interface, when chelate formation is not possible in the α -helical state. Increased concentrations or a parallel arrangement of the α -helical intermediates are more effective triggers. Parallel alignment of highly concentrated α -helices (transition from 2D isotropic to 2D nematic state) at the interface always leads to aggregation. A better knowledge of these triggers may assist in understanding the fundamental mechanisms of common diseases related to amyloid formation (such as Alzheimer's disease, Parkinson's disease, or type II diabetes).

Lipids for Gene Transfection: Important Features of Lipofection

To correlate structural characteristics of lipids with their transfection results is one important step to optimize the synthesis of cationic lipids (cooperation with B. Dobner, MLU Halle). For the first time, the binding of model DNA to lipid monolayers was quantified by IRRAS. As an example, the physical-chemical properties of two malonic acid amides with completely different gene transfer activities will be shortly described. The compounds exhibit the same head group structure (lysine linked via ethylenediamine) but different aliphatic chain patterns. We identified the key parameters explaining the different transfer activities. First of all, membrane fluidity plays an important role in lipofection. The miscibility behaviour with helper lipids, as cholesterol or DOPE, is another crucial parameter. In the present case, the lipid exhibiting strong van der Waals interactions between the saturated chains as well as strong head group interactions via hydrogen bonds forms a sub-gel like phase with high packing density and incorporates much less cholesterol. Despite the fact that in literature the 3D structures of the lipoplexes are considered of utmost importance, our results show that the transfection efficiency is not necessarily depending on it. Both lipids form lamellar phases without and with cholesterol. The addition of DNA does not change the phase type showing that non-lamellar phases are not crucial for high transfection efficiency. The amount of DNA bound to monolayers of these lipids is comparable at high and low pH values (at the same area per molecule) and is depending predominantly on the charge density in the monolayer (Fig. 2).

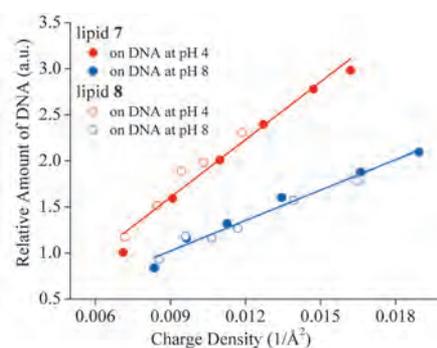


Fig. 2: Integrated reflectance-absorbance intensity of the phosphate bands of DNA bound to transfection lipids exhibiting the same head group structure but different aliphatic chain patterns (lipid 7: saturated chains, lipid 8: unsaturated chains) as function of the charge density at pH 4 and pH 8.

Subgel Phase Structure in Monolayers of Glycosylphosphatidylinositol Glycolipids

Glycosylphosphatidylinositols (GPIs) are complex glycolipids playing key roles in a variety of biological processes. Yet, their membrane structure arrangement is still lacking a deep understanding. An unprecedented ordering in monolayers of the GlcN α 1 \rightarrow 6myoIno-1-phosphodistearoylglycerol fragment **1** of GPIs was observed by GIXD. Several Bragg peaks in the mid-to-wide angle region (Fig. 3A) have been found. These peaks indicate a head group ordering (Fig. 3B) that was not observed in any of the previous studies on double-chain phospholipids including phospholipids with head groups that can be engaged in hydrogen bonding interactions. Indexing of all Bragg peaks revealed the existence of a supercell containing three molecules of **1** (Fig. 3C). This structure is reminiscent of the subgel phase structures observed in lipid dispersions after partial dehydration of the head groups during long incubation periods at low temperature. Here, the head group ordering is observed since a hydrogen bond network is formed that rigidifies the monolayer structure. The network of hydrogen bonds can be disrupted on highly concentrated urea subphases (urea acts as a chaotropic agent) leading to rotational disorder of the head groups and therefore to the loss of the molecular lattice and the restructuring of the chain lattice (Fig. 3D-F).

2D Supramolecular Structures of Polyoxometalates (POMs)

POMs and their supramolecular assemblies are materials of high relevance in different fields as catalysis, energy storage, and medicine. Using a new class of POM-based surfactants, 2D molecularly ordered supramolecular structures have been built at the air/water interface. The self-assembly of the POM units is driven by the lateral interactions between POM moieties. The crystalline structure formed by the polar head of the surfactants was quantitatively described for the first time (Fig. 4). The hydrocarbon chains are in a condensed-like state for POMs with chain length between C22 and C16.

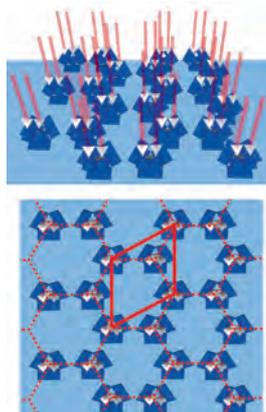


Fig. 4: Top: Side-view of a monolayer of the POM-Cn at the air/water interface. Bottom: Top-view: Hexagonal arrangement of the POM heads.

Future Plans

- (1) Chemically modified phosphatidylinositols (PtdIns) and glycosylphosphatidylinositols (GPIs) will be studied in pure and mixed systems in cooperation with our department of biomolecular systems (P. Seeberger, D. Varon Silva) and the theory department (M. Santer). These studies are also performed with the vision to study enzymatic interactions.
- (2) A new project studying the influence and function of chemically modified ceramides on the nanostructure and dynamics of stratum corneum model systems will be supported by the DFG. Our part concerns structural investigations of single and mixed 2D and 3D model systems.
- (3) Physical-chemical studies of novel peptidomimetics based on the modification of amide bonds thus combining properties of α - and β -peptides (cooperation with L. Hartmann, department of biomolecular systems).

G. Brezesinski, C. Dannehl, M. Dittrich, J. Giner Casares, M. Hörnke, D. Pawlowska, C. Stefaniu, S. Taßler
 brezesinski@mpikg.mpg.dei

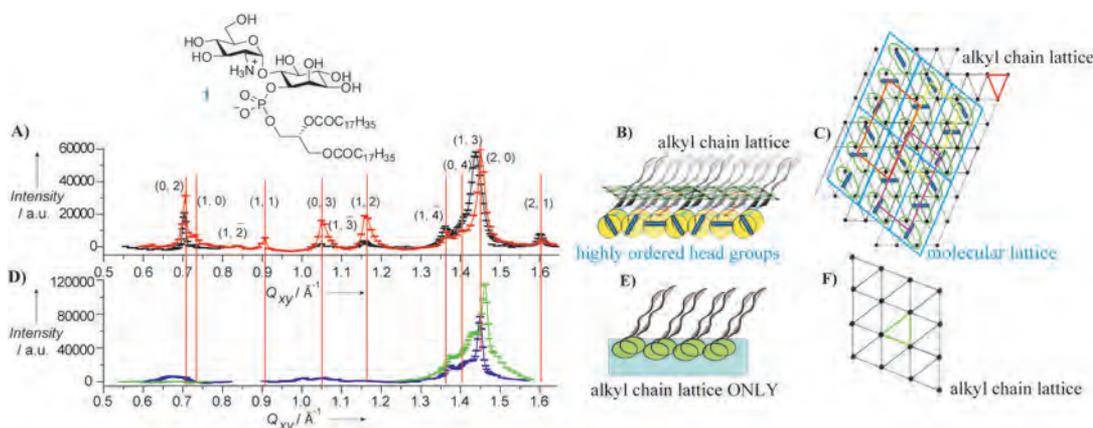


Fig. 3: A) GIXD patterns of monolayers of **1** in PBS at 20 °C (2 mN/m - black line, and 30 mN/m - red line). B) Lateral view of the molecules at the air/water interface. C) Commensurable lattices describing the lateral order of the alkyl chains (black dots, repeating unit cell - red triangle) and of the entire molecules (repeating unit cell - blue parallelogram); repeating unit cells (red, yellow and magenta) linking molecules with the same head group orientation. D) GIXD patterns obtained on 5 M urea aqueous solution at 20 °C (2 mN/m - blue line and 30 mN/m - green line). E) Lateral view of the molecules at the air/water interface. F) Chain lattice (chains - black dots, unit cell - green triangle) on the urea aqueous solution.

[4] Hoernke, M., Koksche, B. and Brezesinski, G.: Amyloidogenic Peptides at Hydrophobic-Hydrophilic Interfaces: Coordination Affinities and the Chelate Effect Dictate the Competitive Binding of Cu(2+) and Zn(2+).

ChemPhysChem **12** 2225-2229 (2011).

[5] Hoernke, M., Falenski, J.A., Schwieger, C., Koksche, B. and Brezesinski, G.: Triggers for beta-Sheet Formation at the Hydrophobic-Hydrophilic Interface: High Concentration, In-Plane Orientational Order, and Metal Ion Complexation. Langmuir **27** 14218-14231 (2011).

[6] Dittrich, M., Heinze, M., Woelk, C., Funari, S.S., Dobner, B., Moehwald, H. and Brezesinski, G.: Structure-Function Relationships of New Lipids Designed for DNA Transfection.

ChemPhysChem **12** 2328-2337 (2011).

[7] Dittrich, M., Boettcher, M., Oliveira, J.S.L., Dobner, B., Moehwald, H. and Brezesinski, G.: Physical-chemical characterization of novel cationic transfection lipids and the binding of model DNA at the air-water interface.

Soft Matter **7**, 10162-10173 (2011).

[8] Stefaniu, C., Vilotijevic, I., Santer, M., Silva, D.V., Brezesinski, G. and Seeberger, P.H.: Subgel Phase Structure in Monolayers of Glycosylphosphatidylinositol Glycolipids. Angew. Chem. Int. Ed. **51** 12874-12878 (2012).

[9] Giner-Casares, J.J., Brezesinski, G., Moehwald, H., Landsmann, S. and Polarz, S.: Polyoxometalate Surfactants as Unique Molecules for Interfacial Self-Assembly. J. Phys. Chem. Lett. **3** 322-326 (2012).

Interfacial Layer Structure of Adsorbed Ionic Surfactants at the Water-Hexane Interface



Reinhard Miller 10.07.1950

1973: Diploma, Mathematics,
(University of Rostock)

Thesis: Fredholm Operators

1977: Research Stay

(St. Petersburg University
with A.I. Rusanov)

1978: PhD, Physical Chemistry
(Academy of Sciences, Berlin)

Thesis: Adsorption kinetics and
exchange of matter of surfactants
at liquid interfaces

1988: Habilitation, Physical Chemistry
(Academy of Sciences, Berlin)

Thesis: Modelling of surfactants,
surfactant mixtures and macro-
molecules at liquid interfaces

1990/91: NCERC Fellow

(University of Toronto with
A.W. Neumann)

Since 1992: Group Leader

(Max Planck Institute of Colloids
and Interfaces, Potsdam)

Since 2011: President of the European
Colloid Interface Society (ECIS)

Since 2012: President-elect of the
International Association of Colloid and
Interface Scientists (IACIS)

The group's main activities are focused on experimental and theoretical work on the thermodynamics and non-equilibrium properties of interfacial layers at water-air and water-oil interfaces [1, 2]. One of the long-term targets is to specify interfacial properties which correlate with the key parameters of corresponding foams and emulsions.

During the last few years we have been studying intensively the adsorption of surfactants at the water/oil interface. In contrast to the water/air interface, the interaction between adsorbing surfactants and the molecules of the oil phase is of importance and may change with the chain lengths of the surfactant and the oil, respectively. In order to avoid any transfer of surfactant across the water/oil interface we selected a homologous series of cationic surfactants, namely alkyl trimethyl ammonium bromides (C_n TAB, $n = 10, 12, 14, 16$), as this class of surfactants has been extensively investigated at the water/air interface.

The equilibrium adsorption isotherms of four members of this homologous series are shown in Fig. 1 for the water/air and in Fig. 2 for the water/hexane interface. In both graphs the experimental data are shown together with calculated model isotherms using a modified Frumkin adsorption model. This so-called Frumkin Ionic Compressibility model provides the best fitting of the experimental data, while other models show significantly larger deviations.

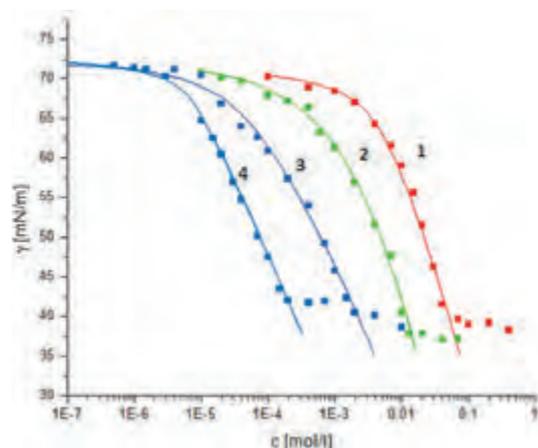


Fig. 1: Surface tension isotherms of C_{10} TAB (1), C_{12} TAB (2), C_{14} TAB (3) and C_{16} TAB (4) at the water/air surface; solutions were prepared in phosphate buffer (10 mM, pH 7); solid lines correspond to theoretical curves calculated with the Frumkin Ionic Compressibility model.

The experiments have been performed in 10 mM phosphate buffer for two reasons. First, in this way the ionic strength of the solutions was essentially the same for all surfactants at all studied concentrations. Moreover, experiments are under way for mixed protein/ C_n TAB solutions, for which a fixed pH is required.

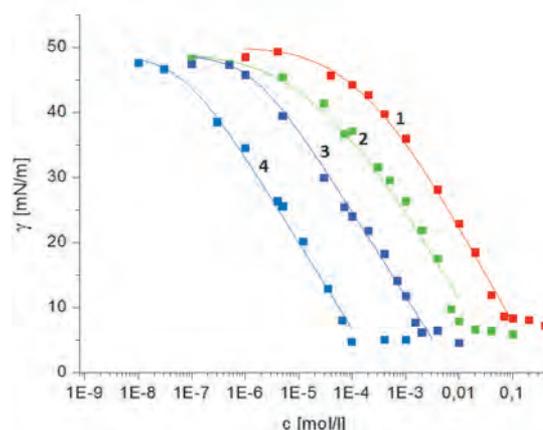


Fig. 2: Interfacial tension isotherms of C_{10} TAB (1), C_{12} TAB (2), C_{14} TAB (3) and C_{16} TAB (4) at the water/hexane interface; solutions were prepared in the phosphate buffer (10 mM, pH 7); solid lines correspond to theoretical curves calculated with the Frumkin Ionic Compressibility model.

The analysis of the isotherms provides information about the surface coverage of the interfacial layer, or the required area per adsorbed molecule, in dependence of the bulk concentration c . Note, ω is the molar area really occupied by one adsorbed molecule and not the geometric area available at the interface. As one can see in Fig. 3 for the shortest chain surfactant C_{10} TAB, over the entire concentration range, the required area per surfactant molecule is larger at the water/hexane as compared to the water/air interface.

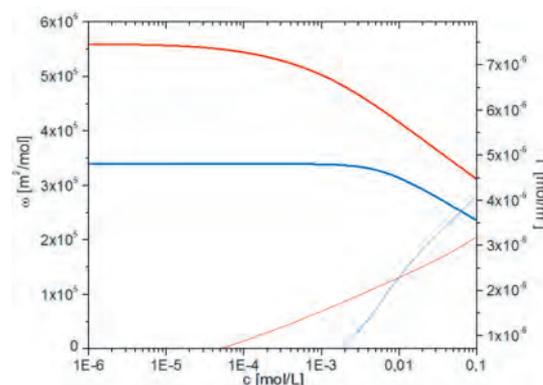


Fig. 3: C_{10} TAB adsorbed amount (thin lines) and molar area (thick lines) at the water/air surface (blue) and water/hexane interface (red) versus bulk concentration c ; model calculations were performed with the Frumkin Ionic Compressibility model.

We can also note that a remarkable adsorption of the surfactant is already observed at the water/hexane interface at a much lower bulk concentration (10^{-4} mol/l) than at the water/air interface (2×10^{-3} mol/l).

In contrast to this, the adsorption layers of the studied C_{16} TAB having the longest alkyl chain in this study, has a different structure. The adsorption at the water/hexane interface starts to be measurable at a bulk concentration less than 10^{-8} mol/l, while a real increase in the adsorbed amount at the water/air interface sets in only at a concentration of about 5×10^{-6} mol/l. At this concentration, the value of ω slowly decreases, i.e. the molecules change step by step their mean tilt angle. With increasing bulk concentration c , the molar areas and adsorbed amounts for both interfaces become almost identical, as we can see in **Fig. 4**.

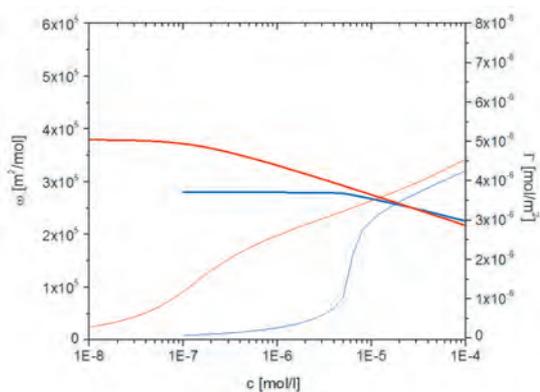
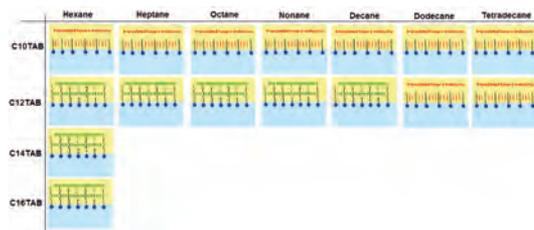


Fig. 4: C_n TAB adsorbed amount (thin lines) and molar area (thick lines) at the water/air surface (blue) and water/hexane interface (red) versus bulk concentration c ; model calculations were performed with the Frumkin Ionic Compressibility model.

From these findings we can conclude that for the short chain C_{10} TAB the interfacial layer at the water/oil interface includes hexane molecules even at the highest surface coverage, i.e. close to the CMC. In contrast, for C_{16} TAB only at low surface coverage hexane molecules are intercalated into the interfacial layer and then get squeezed out at higher surface coverage due to the stronger interaction between the long alkyl chains of the surfactant molecules. For C_{12} TAB and C_{14} TAB a transition from the behavior of a short to a longer alkyl chain is observed.

Further investigations were made with alkanes of different chain lengths (from hexane to tetradecane) and the four members of the homologous surfactants C_n TAB in order to find out if there are transitions of the intercalation/squeezing out mechanism for the alkane molecules. The results can be summarized as shown in **Scheme 1**. While the interaction between adsorbed C_{10} TAB molecules is not strong enough to squeeze out neither short nor long alkane molecules, this is the case for C_{12} TAB for short alkanes. For dodecane and tetradecane, however, the interaction between alkane and surfactant is stronger than the mutual interaction between the surfactants, and hence the oil molecules remain intercalated.



Scheme 1: Molecular interaction between surfactants and oil molecules of different alkyl chain lengths

Complementary experiments were performed with surfactant solution drops formed in an alkane vapor atmosphere [3, 4]. Although alkane molecules are not amphiphilic, they adsorb and change significantly the adsorption of the surfactant molecules. Existing thermodynamic models allow a qualitative description. However, for a quantitative understanding a new thermodynamic model has to be developed that takes the co-adsorption of surfactant and oil molecules into account. The same physical picture might be applicable also to adsorbed layers at the interface between water and an oil bulk phase. This modelling work is presently underway.

Additional experiments were performed with drop profile and capillary pressure tensiometry to study the adsorption dynamics and dilational visco-elasticity of C_n TAB layers at the water/alkane interface [5, 6]. The results have shown that with the same set of thermodynamic parameters all dynamic properties can be described. Agreement between experiment and theory was achieved, however, only when choosing concentration dependent diffusion coefficients with physically rather unrealistic values. This also points to the fact that the models existing so far reflect only qualitatively the situation at the interface and combined with an improved thermodynamics, also refined relaxation mechanisms have to be developed to reach a quantitative understanding of the interfacial dynamics.

A new approach has been also started recently using CFD simulations of the processes happening at dynamic liquid interfaces [7, 8]. These simulations include also the description of growing and oscillating drops with a free interface and adsorption/desorption processes at this interface. Based on the Open-FOAM platform drop profiles under various conditions can be calculated. These results will give access to a modification of the Gauss-Laplace-Equation valid also in a respective range of Reynolds numbers and a specified capillary geometry for forming the drops.

R. Miller, G. Gochev, A. Javadi, M. Karbaschi, N.M. Kovalchuk, J. Krägel, M. Lotfi, N. Moradi, N. Mucic, V. Pradines, I. Retzlaff, S. Siegmund, A. Sharipova, V. Ulaganathan, D. Vollhardt, J.Y. Won, R. Wüstneck, (the work was done in close cooperation with E.V. Aksenenko, D. Bastani, D. Bothe, J.K. Ferri, V.B. Fainerman, V.I. Kovalchuk, L. Liggieri, E. Mileva, B.A. Noskov, P. Ramirez, F. Ravera, Yu.B. Vysotsky) miller@mpikg.mpg.de

References:

- [1] A. Sharipova, S.B. Aidarova, V.B. Fainerman and R. Miller, Study of dynamic interfacial tension of alkyl sulphates with different alkyl chain lengths at the water/hexane interface, *Colloids Surfaces A*, **382**, 181–185 (2011).
- [2] N. Mucic, A. Javadi, N.M. Kovalchuk and R. Miller, Dynamics of interfacial layers – experimental feasibilities for adsorption kinetics and dilational rheology, *Adv. Colloid Interface Sci.*, **168**, 167–178 (2011).
- [3] V.B. Fainerman, E.V. Aksenenko, V.I. Kovalchuk, A. Javadi and R. Miller, Study of the co-adsorption of hexane from the gas phase at the surface of aqueous 10⁸ drops, *Soft Matter*, **7**, 7860–7865 (2011).
- [4] A. Javadi, N. Moradi, M. Karbaschi, V.B. Fainerman, H. Möhwald and R. Miller, Alkane vapor and surfactants co-adsorption on aqueous solution interfaces, *Colloids Surfaces A*, **391**, 19–24 (2011).
- [5] N. Mucic, N.M. Kovalchuk, V. Pradines, A. Javadi, E.V. Aksenenko and R. Miller, Dynamic properties of C_n TAB adsorption layers at the water/oil interface, *Colloids Surfaces A*, doi:10.1016/j.colsurfa.2012.08.071
- [6] A. Javadi, J. Krägel, A.V. Makievski, N.M. Kovalchuk, V.I. Kovalchuk, N. Mucic, G. Loglio, P. Pandolfini, M. Karbaschi and R. Miller, Fast dynamic interfacial tension measurements and dilational rheology of interfacial layers by using the capillary pressure technique, *Colloids Surfaces A*, **407**, 159–168 (2012).
- [7] M. Karbaschi, A. Javadi, D. Bastani, V.I. Kovalchuk, N.M. Kovalchuk, A.V. Makievski, E. Bonaccorso and R. Miller, Drop Profile Analysis Tensiometry under Highly Dynamic Conditions, *Colloids Surfaces A*, **413**, 292–297 (2012)
- [8] K. Dieter-Kissling, M. Karbaschi, H. Marschall, A. Javadi, R. Miller and D. Bothe, On the Applicability of Drop Profile Analysis Tensiometry at High Flow Rates Using an Interface Tracking Method, *Colloids Surfaces A*, doi:10.1016/j.colsurfa.2012.10.047

SOLID INTERFACES

Phase Transitions and Transport Phenomena at Solid/Air Interfaces



We are interested in a better understanding of nucleation/aggregation phenomena and in the coupling between volume flow and surface Marangoni-flow caused by interfacial energy gradients. Nucleation and aggregation phenomena are ubiquitous (from cloud formation to metallurgy). Liquid flows induced by surface tension gradients are also widely relevant e.g. for ink jet printing. Our primary aim is a better fundamental scientific understanding of these issues.

Nucleation and growth studies are performed within an international graduate school (funded by DFG) in collaboration with universities in the Berlin area and academic partners in the US (NC State University). The Marangoni-flow activities are embedded in a collaboration with Twente University (NL). A "by-product" of this collaboration is a successful study on nanobubbles [1]. Based on our expertise on nucleation, growth and Marangoni-induced transport/flow, we further started collaborations with French research groups on pit corrosion (CEA, Saclay) and on separation chemistry (ICSM, Marcoule). The focus is on basic research but there are also activities motivated by application. We collaborate with industry (LAM Research) to investigate the fundamentals of Marangoni cleaning, and we use our knowledge to optimize the architecture of molecularly thin films in organic solar cells (project funded by the BMBF).

Line Tension

Line tension effects can become relevant when interfacial energies are substantial compared to volume free energy contributions. This only occurs for very small, nano size sessile drops (or adsorbed aggregates). Minimizing the total free energy leads size-dependently to different equilibrium shapes e.g. the equilibrium contact angles depend on size. To first order the effect can be parameterized with the curvature of the contact line, hence "line tension". Experimental verifications of line tension effects are scarce. We measured this effect [2] with very small aggregates of C60 on various molecularly smooth surfaces (Fig. 1).

Although theoretically predicted since a long time, a general palpable theory of line tension based on intermolecular interactions is still missing. We develop such an approach. The predicted variation of the shape with size is in agreement with the experimental results (Fig. 1). Essentially, a line tension effect occurs when the variation of the interfacial force field contributions with drop size are comparable to the volume force field contributions. The variation of the interfacial force field is dominated by contributions from the contact line region, hence "line" tension. Line tension effects can be regarded as resulting from a locally varying, size-dependent disjoining pressure.

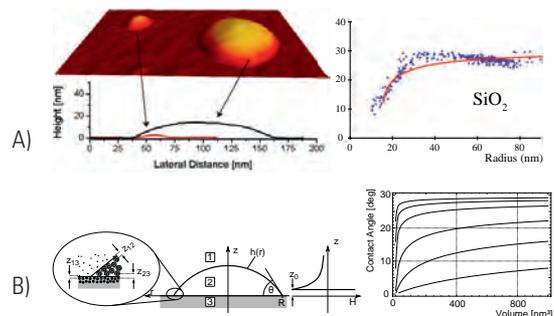


Fig. 1: A) AFM image of small aggregates and measured variation of their contact angle area with size [2]. B) Model and theoretical results.

Heterogeneous Nucleation

First order phase transitions implicate the formation of an interface between the old and the new, emerging phase. This causes a supplemental energy, a nucleation barrier for the transition. The nucleation is heterogeneous when the emerging phase is in contact with other (inert) phases in addition to the interface between old and new phase. Compared to the homogeneous case the energy barrier for heterogeneous nucleation is lower. This lowering is parameterized usually only by the contact angle between emerging and inert surface. However this single parameter approach only works for simple planar geometries. If the topography between emerging phase and inert template is non-planar, the nucleation barriers and paths also depend on the topographic details of the template.

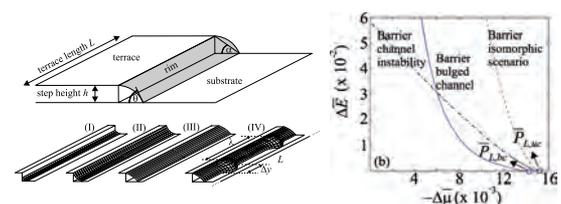


Fig. 3: Nucleation path of edge melting with a transition from a plain to a bulged channel (the bulges grow into macroscopic drops). Comparison between the nucleation barriers for various morphologies.

Experimental investigations and theoretical calculations [3] with nucleation templates with edges and grooves explicitly reveal how the nucleation barriers and pathways depend on the height and length of steps/grooves. In addition we find that with templates of reduced symmetry (e. g. long steps or grooves), the nucleation path with the lowest energy may be non-isomorphic. That means, as during the evolution from subcritical to supercritical (bulk) volumes, the new phase nucleus changes its shape (e.g. from a plain channel to bulges, (Fig. 3)). Up to now, all theoretical nucleation scenarios always assumed isomorphic volume growth for the lowest energy nucleation path.

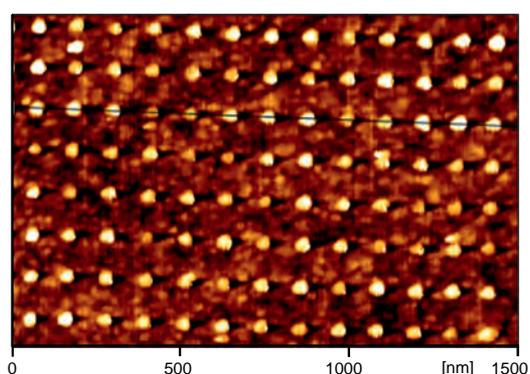


Fig. 4: C60 aggregates on nano-patterned SiO₂-substrate

Heterogeneous nucleation is also investigated with planar solid substrates that were pre-structured with an array of nano-indentations. Unexpectedly it is observed that upon spin casting from solution precipitated C60 aggregates form preferentially in the dents (Fig. 4). The dents are less than 1nm deep and the estimated reduction of the nucleation barrier by the dent geometry is quite small. To gain better insight into the spatio-temporal evolution of the nonvolatile solute (C60) during the film thinning – which in the end leads to the observed phenomena – the spin casting process itself is analysed theoretically [4].

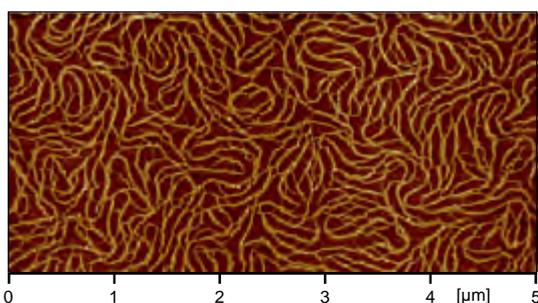


Fig. 5: Phthalocyanine net structures (height=1.5nm)

Phthalocyanine-Films for Organic Solar Cells

Molecularly thin films of Phthalocyanines (PC) were prepared with structures optimized for Heterojunction Organic Solar Cells (OSC) [5]. The PCs form interesting films with ribbon-like bundled multilayer net structures (Fig. 5). A detailed experimental analysis and model calculations reveal the nucleation and growth processes leading to the observed structures. With these films functioning OSCs were prepared via solution processing [6].

Interfacial Flow and Drop-Drop Coalescence

Upon lateral contact, sessile drops of miscible liquids are expected to merge rapidly due to capillary forces. With different liquids in both drops, upon contact, surface tension gradients form in the connecting region. This induces a Marangoni flow, which can unexpectedly cause a long delay of the drop coalescence. The main drop bodies remain separated while connected via a thin neck through which the drops exchange liquid. The delay of the coalescence is now finally understood theoretically [7]. The drop-drop coalescence system is now used as an experimental and theoretical model system to investigate the impact of surficial Marangoni flows on the hydrodynamics of thin films for different cases, such as surface tension gradients caused by local evaporation (coffee stain effect) or vapour adsorption.

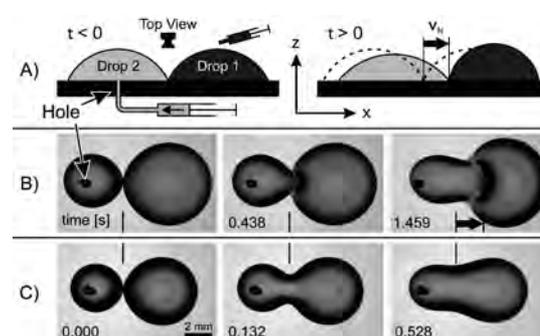


Fig. 4: A) Schematics of the experimental setup/procedure; B) non-coalescent twin drop movement (different, miscible liquids); C) instantaneous coalescence (identical liquids).

H. Riegler, F. Ghani, C. Jin, S. Karpitschka, C. Weber, C. Ebrecht, H. Gojzewski
Hans.Riegler@mpikg.mpg.de.

References:

- [1] Karpitschka, S., Dietrich, E., Seddon, J. R. T., Zandvliet, H. J. W., Lohse, D., and Riegler, H., Nonintrusive Optical Visualization of Surface Nanobubbles, *Phys. Rev. Lett.* **109**, 066102 (2012).
- [2] Berg, J. K., Weber, C. M., and Riegler, H., Impact of Negative Line Tension on the Shape of Nanometer-Size Sessile Droplets, *Phys. Rev. Lett.* **105**, 076103 (2010).
- [3] Kusumaatmaja, H., Lipowsky, R., Jin, C., Muthic R.-C., and Riegler, H., Nonisomorphic Nucleation Pathways Arising from Morphological Transitions of Liquid Channels, *Phys. Rev. Lett.* **108**, 126102 (2012).
- [4] Karpitschka, K., Weber, C. M., and Riegler, H., Physics of Spin Casting Dilute Solutions, *Phys. Rev. Lett.*, under review.
- [5] Ghani, F., Kristen, J., and Riegler, H., Solubility Properties of Unsubstituted Metal Phthalocyanines in Different Types of Solvents, *J. Chem. Eng. Data* **57**, 439-449 (2012).
- [6] Ghani, F., Bochkov, I., Fostiropoulos, K., and Riegler, H., Hybrid solution/vacuum-processed bilayer heterojunction organic solar cells: Structural characterization and performance, *Thin Solid Films* **525**, 177-181 (2012).
- [7] Karpitschka, S. and Riegler, H., Noncoalescence of Sessile Drops from Different but Miscible Liquids: Hydrodynamic Analysis of the Twin Drop Contour as a Self-Stabilizing Traveling Wave, *Phys. Rev. Lett.* **109**, 066103 (2012).

Active Interfaces and Coatings



Dmitry Shchukin 11.11.1976

1998: Diploma

Electrochemistry of Conductive Polyaniline Films
(Belarusian State University,
Minsk, Belarus)

2002: PhD, Binary TiO₂-based
Photocatalysts

(Belarusian State University,
Minsk, Belarus)

2002: Postdoc,
(Max-Planck Institute of Colloids
and Interfaces, Potsdam)

2003: Postdoc,
(Louisiana Tech University, Ruston, USA)

2004: Alexander von Humboldt Fellow,
(Max-Planck Institute of Colloids
and Interfaces, Potsdam)

2005/2006: Incoming Marie Curie Fellow,
(Max-Planck Institute of Colloids
and Interfaces, Potsdam)

Since 2006: Group Leader,
Department of Interfaces,
(Max-Planck Institute of Colloids
and Interfaces, Potsdam)

References:

[1] Latnikova, A., Grigoriev, D., Schenderlein, M., Möhwald, H., Shchukin, D. G., A New Approach Towards "Active" Self-Healing Coatings: Exploitation of Microgels, *Soft Matter* **8**, 10837-10844 (2012).

[2] Haase, M. F., Grigoriev, D. O., Möhwald, H., Shchukin, D. G., Development of Nanoparticle Stabilized Polymer Nanocontainers with High Content of the Encapsulated Active Agent and Their Application in Water Borne Anti Corrosive Coatings, *Adv. Mater.* **24**, 2429-2435 (2012).

Feedback Active Coatings

Development of multifunctional coatings, which will possess active and rapid feedback activity in response to changes in local environment, is a key technology for fabrication of future high-tech products and functional surfaces [1-6]. These new multifunctional coatings should combine passive components of "classical" coatings and active components, which provide fast response of the coating properties to changes occurring either in the passive matrix of multifunctional coatings (e.g., cracks, local pH change) or in the local environment surrounding the coating (electromagnetic irradiation). The coatings could also have several functionalities like bio-sensor activity.

The introduction of only few percents of microgel particles containing a "green" corrosion inhibitor allows significant improvement of the corrosion protection properties of a coating [1]. The effect can be attributed to improvement of the barrier properties of the coating as well as to the action of the corrosion inhibitor, which totally suppresses the corrosion process in the local area of the damage. Usage of microgels is very advantageous, since they combine the properties of both liquids and solids. The polymeric framework of the crosslinked polymeric network supplies the system with the mechanical strength, while the corrosion inhibitor retains its mobility and can be delivered to the metal surface when the coating is damaged. The synthesis of microgels is comparatively easy and can be performed in a one pot process, which increases the potential for up-scaling.

Silica armoured polystyrene composite nanocontainers were filled with 5, 10 or 20 wt-% of 8-hydroxyquinoline [2]. The aim of our work is to introduce a new type of containers based on Pickering emulsions (Fig. 1) as one of the controlled delivery and release tools for further application for uptake and release of the potentially various types of active materials in both delivery systems and multifunctional feedback active coatings. The approach was employed in self-healing coatings in order to demonstrate the application potential of the proposed new type of nanocontainers. Especially the design of multifunctional container components is crucial for this work, since it allows for a reduction of fabrication steps and involved reagents for their synthesis.

A method to spontaneously form hybrid nano-structures consisting of ceria nanoparticles supported on a porous silica colloid was reported in [3]. The structures have high surface area and can be used to adsorb useful molecules for future release. Spontaneous emulsification, which requires neither template nor externally applied energy, has been shown to be a green method to generate silica nanostruc-

tures that could find future use either in corrosion prevention or, perhaps, in other fields as easily recoverable catalyst support.

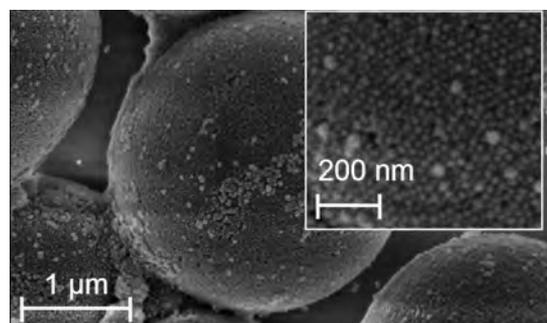


Fig. 1: SEM micrographs of silica-8-hydroxyquinoline composite containers based on Pickering emulsions [3].

The mesoporosity, monodispersity and spherical morphology of the studied silica nanoparticles favour their application as nanoreservoirs for corrosion inhibition [4]. The incorporated mechanically stable nanocarriers block the micro-pores, cracks and areas with low cross-link density in the passive SiO₂/ZrO_x coating film and improve its physical barrier properties. Furthermore, due to the pH-stimulated release of inhibitor during the corrosion process well pronounced active self-healing was provided.

A polyelectrolyte coating of poly-L-histidine and poly(methacrylic acid) was prepared and shown to be effective for sustained release of negatively charged species under physiological conditions [5]. This complex demonstrated pH-dependent release with low levels of sustained release at pH = 7-8. Controlled release on the microgram scale over 25 days was shown at physiological pH, which is advantageous and necessary for the desired *in vivo* effect, i.e. signalling of osteoblasts to the implant surface. Coatings capable of dissolution under physiological conditions are well-suited to application on porous titanium surfaces because their removal from the surface exposes the porous structure to cells, potentially allowing for greater osseointegration of the titanium implants. Stable microspheres loaded with vitamin E can be obtained by vitamin emulsification in the gum acacia solution using ultrasound treatment [6]. The obtained microcapsules were embedded into a cross-linked Ca-alginate film forming a model cutaneous drug delivery system. Vitamin E release kinetics from the Ca-alginate film with entrapped microspheres is essentially more sustained, especially in comparison with the release of free vitamin distributed in the polymer film.

Sonication as a Tool for Surface Modification

The collapse of the critical cavitation microbubble in liquids under ultrasonic treatment results in an enormous concentration of energy from the conversion of the surface energy and kinetic energy of the liquid motion into heat or chemical energy. The high local temperatures (5000-7000 K inside a cavitation bubble) and pressures combined with rapid cooling provide unique means for forming nanomaterials with non-equilibrium structure under extreme conditions [7-9]. The surface of the ultrasonically produced nanomaterials can be changed by decorating it with suitable hydrophilic and hydrophobic organic moieties.

Cavitation at the solid surface normally begins with a nucleation process, in which the defects or assembled molecules located at a liquid-solid interface act as nucleation centers and are actively involved in the evolution of the cavitation bubbles. A mixture of octadecylphosphonic acid and octadecanethiol was stamped on the Si wafer coated with different thicknesses of aluminium layer (20-500 nm) [7]. The height values between hydrophobic and hydrophilic surfaces were reduced up to 3 nm in order to equilibrate the contribution of both surfaces to the nucleation process. Only the hydrophobic surfaces provided the nucleation centers at the initial stage of sonication (up to 40 min). SEM and AFM microscopy studies of the surface topology after sonication proved that cavitation bubbles are far more likely to nucleate at the hydrophobic surface (Fig. 2).

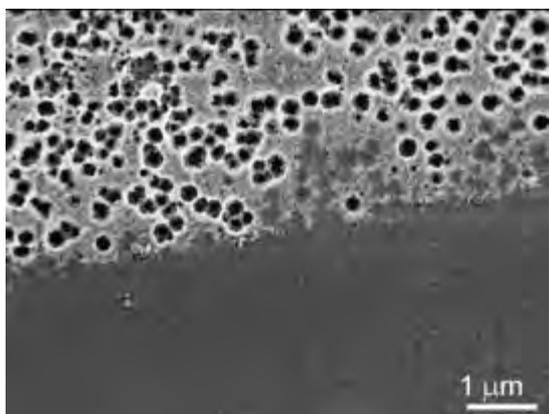


Fig. 2: SEM micrographs of the patterned Al sample after 10 min of sonication Upper part is the hydrophobized part [7].

Active defects (pits) formed only on the hydrophobic surface at the initial stage of ultrasonic treatment contribute to nucleation of cavitation bubbles during the increase of sonication time. High intensity ultrasonic irradiation induces the formation of an interfacial gas layer at the solid surface immersed in different liquid media (water saturated with different gases, such as argon, nitrogen or carbon dioxide) by accelerating the adsorption of dissolved gas [8]. Subsequently, the gas rearranges in diverse nano- or microstructures which take further part in the cavitation process. The presence of argon and nitrogen in the liquid medium accelerates the surface cavitation keeping the response selective on the patterned surfaces. By varying the gas adsorption time it is possible to accelerate or to slow down heterogeneous cavitation. Likely a secondary nucleation mechanism takes place in this system, whereas the gas can be trapped (forming assembled molecules) into the defects formed and initiates the following growth of new cavitation bubbles. We also observed that at longer sonication times (more than 40 min), the thermal mechanism of the formation of porous metal surfaces prevails over the cavitation effects [9].

D. G. Shchukin, D. Akcakayiran, V. Belova, D. Borisova, A. Brotchie, D. Grigoriev, M. Haase, M. Hollamby, A. Latnikova, G. Li, A. Peterson, A. Praast, M. Schenderlein, E. Scherke, H. Wang, D. Voronin, Z. Zheng, dmitry.shchukin@mpikg.mpg.de; d.shchukin@liverpool.ac.uk

- [3] Hollamby, M. J., Borisova, D., Möhwald, H., Shchukin, D. G., Porous "Ouzo-Effect" Silica-Ceria Composite Colloids and Their Application for Aluminium Corrosion Protection, *Chem. Comm.* **48**, 115-117 (2012).
- [4] Borisova, D., Möhwald, H., Shchukin, D. G., Mesoporous Silica Nanoparticles for Active Corrosion Protection, *ACS Nano* **5**, 1939-1946 (2012).
- [5] Peterson, A. M., Möhwald, H., Shchukin, D. G., pH-Controlled Release of Proteins from Polyelectrolyte-Modified Anodized Titanium Surfaces for Implant Applications, *Biomacromolecules* **13**, 3120-3126 (2012).
- [6] Borodina, T., Grigoriev, D., Markvicheva, E., Möhwald, H., Shchukin, D. G., Vitamin E Microspheres Embedded Within Biocompatible Film for Planar Delivery, *Adv. Eng. Mat.* **13**, B123-B130 (2011).
- [7] Belova, V., Shchukin, D. G., Möhwald, H., A New Approach to Nucleation of Cavitation Bubbles at Chemically Modified Surfaces, *PCCP* **13**, 8015-8023 (2011).
- [8] Belova, V., Krasowska, M., Wang, D., Ralston, J., Shchukin, D. G., Möhwald, H., Influence of Adsorbed Gas at Liquid/Solid Interfaces on Heterogeneous Cavitation, *Chemistry Science* **4**, 248-256 (2013).
- [9] Brotchie, A., Möhwald, H., Shchukin, D. G., Ultrasonic Modification of Aluminum Surfaces: Comparison between Thermal and Ultrasonic Effects, *J. Phys. Chem. C* **116**, 7952-7956 (2012).

Nanotechnology and Optical Manipulations of Capsules and Films



Aims

Research goals of the nano-bio-interfaces group are targeted to use the basic principles of physical chemistry for designing spherical and planar interfaces for interaction with living cells. Such approaches are envisioned to enable investigation of fundamental processes in cell biology: protein trafficking, the surface presentation of peptides, aggregation state of proteins as well as design of new interfaces for patterning and re-configurable interfaces for cell cultures. Both spherical and planar interfaces and methods are used for investigation and advanced characterization. We are also designing new Raman based sensors and amplifiers for label-free imaging.

The group is also using principles of self-assembly for designing a next generation of carriers, multicompartments and anisotropic carriers as well as gradient surfaces.

Present Work

Currently, we are continuing our work on probing polymer and lipid membrane permeability. Using the obtained knowledge, we are gaining insights into the structure and functions of proteins at the surface of cells. These principles are also used for inducing release from red blood cells (Fig. 1). It was found in our studies, that opto-nanoporation can be also used for release of molecules from red blood cells.

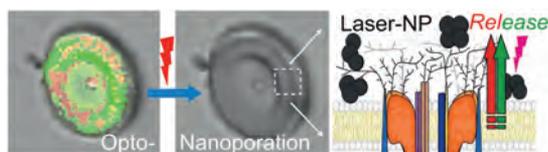


Fig. 1: Investigation of the permeability and release of molecules from red blood cells using opto-nanoporation.

Raman spectroscopy has been used to confirm binding of gold nanoparticles onto lipid membrane and oligosaccharides and proteins located on the membrane of red blood cells. Control experiments have been conducted to exclude thermal and photo-bleaching. To the best of our knowledge, this is one of the first accounts of active release from red blood cells.

Intracellular incorporation of probes is extended to include label-free (Raman based) sensors. Their performance is assessed by performing label-free imaging of cells.

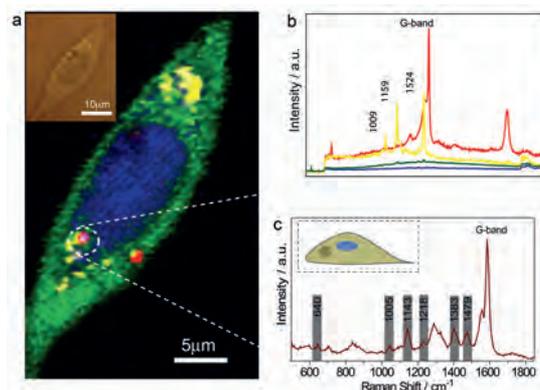


Fig. 2: Raman micro-imaging and mapping of molecular features of SiO₂, silica (red) particles functionalized with gold nanoparticles inside living cells.

Here, we are actively using Raman spectroscopy and microscopy for investigation of molecular features of molecules inside living cells (Fig. 2). Using nanoparticles and silica colloidal probes we have designed intracellular probes for label-free imaging and observed signal amplification.

It can be seen from Fig. 2 that cytosol and nucleus of a cell can be also imaged based on label-free scattering. The designed sensors are quite efficient, so that even application of light with intensity comparable to that of sun produced detectable label-free scattering signals.

We have also pursued a new approach towards controlled patterning by using a simple method of adsorbing gold nanoparticles at the surface of soft films. These become stiffer thus controlling protrusion and, therefore, masking the particles which can be later on patterned with controlled patchiness. Using such an approach fabrication of anisotropic multicompartments constructs is also possible. Peculiarly, using the same approach of adsorbing nanoparticles film stiffness is increased, improving cell adhesion on the surface. This is particularly useful for seeding cells and designing active bio-interfaces.

Interestingly, application of gold nanoparticles has been beneficial in connection with poly-L-lysine/hyaluronic acid (PLL/HA) films. These films are particularly attractive due their reservoir-like properties. However, they are also quite soft - an undesirable property for growing cells. Application of gold nanoparticles has been shown to enhance mechanical properties of such films making them stiffer. This very property has been also used in our research to design novel means of controlling patchiness of multicompartments cap-

sules and particles. Application of gold nanoparticles strengthens the films, thus enabling controlled embedding of capsules and leading to fabrication of capsules with controlled patchiness.

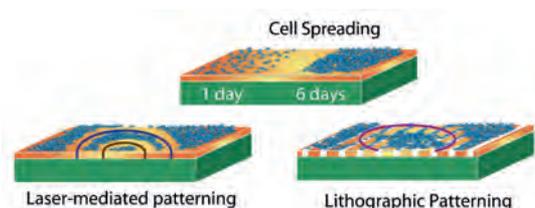


Fig. 3: Cell-patterning by laser-nanoparticle interaction.

Active bio-interfaces have been tested by controlled laser-nanoparticle induced patterning of cells (Fig. 3). In this direction remotely controlled methods were employed, and cell detachment, patterning, and regrowth were investigated. Natural continuation of this work is seen on self-assembly of nanoparticles and polymeric films.

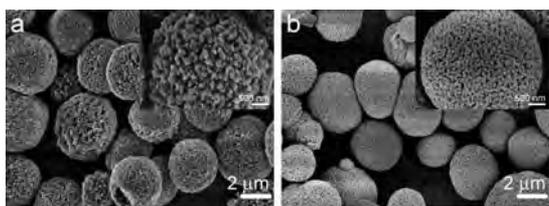


Fig. 4: Calcium carbonate biocompatible microparticles with incorporated gold nanoparticles for efficient label-free sensing.

One of the directions of research concerns development of methods for enhancement of label-free Raman signals using colloidal and interfacial modification. Figure 4 shows calcium carbonate porous microparticles before and after functionalization with gold nanoparticles. Subsequently, calcium carbonate microparticles functionalized with gold nanoparticles were used for detection of such biomarkers as glucose.

Other research areas include development of carriers for enzyme-catalyzed reactions and investigation of mechanical properties of polymeric capsules and films as well as their interaction with cells. In the former case we are developing means of protection of enzymes as well as using enzymes for intracellular degradation of capsules. In the latter case we are trying to understand mechanobiology and develop mechanically stable carriers based on understanding of these processes.

Future Goals

Using interfacial methods, we are planning to:

- design carriers for enzyme-catalyzed reactions in which enzymes are protected, while the substrate freely circulates for enzyme-catalyzed reactions;
- further develop reconfigurable and adjustable interfaces for controlling and patterning of cells;
- design gradient coatings and use them for investigation of capsule-surface interaction, motion, positioning;
- using interfacial approaches, investigate mechano-biology of microcapsules relevant for in-vivo delivery;
- develop novel and advanced anisotropic carriers and capsules;
- design novel Raman based sensors and amplifiers based on nanoparticle self-assembly. Use these probes for intracellular imaging and sensing.

Establishing an extensive network of collaborators is a instinct feature of our work; in this regard we collaborate with Department of Biomaterials, MPI of Biophysical Chem., Jacobs University of Bremen, University of Bayreuth, Greifswald University, University of Ghent, Harvard University, Charite-Berlin Clinic, Queen Mary University of London, and University of Marburg.

A. G. Skirtach, M. Delcea, A. M. Yashchenok, I. V. Marchenko, O. Inozemtseva, L. Kazakova, P. Subedi, B. E. Pinchasik and H. Möhwald
Andre.Skirtach@UGent.be

References:

- [1] A. Yashchenok, A. Masic, D. A. Gorin, Y. G. Shim, N. Kotov, P. Fratzl, H. Möhwald, A.G. Skirtach, "Nanoengineered carbon nanotubes-gold nanoparticle based Raman sensor for intracellular delivery," *Small*, DOI: 10.1002/sml.201201494 (2012).
- [2] M. Delcea, N. Sternberg, A.M. Yashchenok, R. Georgieva, H. Bäuml, H. Möhwald, A.G. Skirtach, "Nanoplasmonics for dual molecule release from red blood cells" *ACS Nano* **6**, 4169-4180 (2012).
- [3] T. Kolesnikova, D. Kohler, A.G. Skirtach, H. Möhwald, "Laser-induced cell detachment, patterning, and regrowth on gold nanoparticle functionalized surfaces" *ACS Nano* **6**, 9585-9595 (2012).
- [4] A.M. Yashchenok, D. Borisova, B.V. Parakhonskiy, A. Masic, B.E. Pinchasik, H. Möhwald, A.G. Skirtach, "Nanoplasmonic smooth silica versus porous calcium carbonate bead biosensors for detection of biomarkers," *Ann. Phys.*, **524**, 723-732 (2012).
- [5] I. Marchenko, A.M. Yashchenok, T.N. Borodina, T.A. Bukreeva, M. Konrad, H. Möhwald, A.G. Skirtach, "Controlled release from microcapsules as a function of polyelectrolyte layer numbers," *J. Contr. Release*, **162**, 599-605 (2012).



- Biopolymers
- Molecular Motors and Filaments
- Ribosomes and Protein Synthesis
- Membranes and Vesicles
- Interfacial Phenomena
- Complex Systems

THEORY & BIO-SYSTEMS



Research in the Department of Theory & Bio-Systems

Denken ohne Erfahrung ist leer, Erfahrung ohne Denken ist blind.
Immanuel Kant



Reinhard Lipowsky 11.11.1953

1978: Diploma, Physics,
(University of Heidelberg)

1982: PhD (Dr. rer. nat.), Physics
(University of Munich)

1979-1984: Teaching Associate
(University of Munich)

1984-1986: Research Associate
(Cornell University)

1986-1988: Group leader (FZ Jülich)

1987: Habilitation, Theoretical Physics
(University of Munich)

Thesis: Critical behavior of interfaces:
Wetting, surface melting and related
phenomena

1989-1990: Associate Professorship
(University of Munich)

1990-1993: Full Professorship
(University of Cologne), Director of
the Division "Theory II" (FZ Jülich)

Since Nov 1993: Director
(Max Planck Institute of Colloids
and Interfaces, Potsdam)

The main objective of our research activities is to understand the hidden dimensions of self-organization in biomimetic and biological systems. The molecular building blocks of these systems join „by themselves“ and form a variety of supra-molecular assemblies, which then interact to produce even larger structures and networks.

The associates of the department form several research groups. At present, the research group leaders and topics are:

- *Rumiana Dimova*: Biophysics Lab;
- *Thomas Weigl*: Proteins and Membranes;
- *Mark Santer*: Carbohydrates and Polysaccharides;
- *Christian Seidel*: Polymers and Polyelectrolytes;
- *Andrea Grafmüller*: Multiscale Simulations;
- *Angelo Valleriani*: Stochastic Processes;
- *Stefan Klumpp*: Regulation of Bioprocesses.

The main results of these research groups are described in separate reports on the following pages. These reports are ordered in a bottom-up manner, i.e., from small to large length scales, and related to five research areas: Biopolymers, Motors and Filaments, Membranes and Vesicles, Soft Interfaces, and Complex Systems. Here, the results of the research groups will be briefly summarized and some additional results will be highlighted.

Biopolymers

Carbohydrates and polysaccharides have been studied by the research group of *M. Santer* using molecular dynamics simulations. The focus was on two types of polysaccharides: GPI-anchors, which can link a variety of proteins to cell membranes, and lipopolysaccharides, which protect bacteria against the infection by bacteriophages. The conformational freedom of the different glycosidic bonds between the subunits of the polysaccharides was determined by calculating free energy landscapes as a function of glycosidic torsion angles: even short oligosaccharides were shown to be relatively flexible.

Proteins that act as enzymes must first bind the reaction partners as ligands. The group of *T. Weigl* considered the temporal ordering of these binding processes with respect to conformational changes of the enzymes: the enzyme may undergo conformational changes before ligand binding or the ligands may first bind and then induce conformational changes of the enzyme. The temporal ordering has no effect on the binding equilibrium, but affects the binding kinetics and, thus, may be revealed by mutations of the protein.

Molecular Motors and Filaments

Intracellular cargo is transported by teams of molecular motors that pull on the cargo via elastic stalks. The simplest case corresponds to cooperative transport by two identical motors as shown in **Fig. 1**. The influence of this elastic coupling between the motors on the transport properties has been addressed in the framework of chemomechanical networks and semistochastic models (see the report by *F. Berger* and *C. Keller*). The chemomechanical networks are relatively complex but involve only two additional parameters that can be deduced from the cargo trajectories. The semi-stochastic models reveal different interference regimes, in which the motors stall each other or pull each other from the filament.

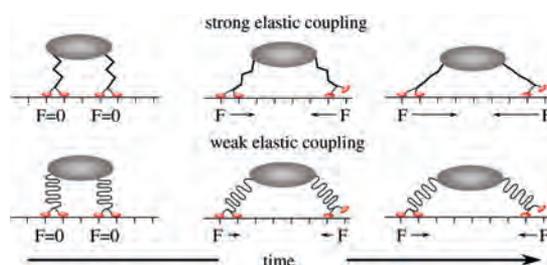


Fig. 1: Two molecular motors coupled to a cargo particle via their elastic stalks or linkers. The motors step forward stochastically and stretch their linkers, thereby inducing an elastic interaction that generates the mutual strain force F . Strong elastic coupling leads to a fast buildup of large forces, whereas weakly coupled motors experience only relatively small forces. [F. Berger et al., Phys. Rev. Lett. (2012)]

Another molecular motor, for which a chemo-mechanical network has been constructed, is myosin V that steps along actin filaments, see **Fig 2**. Furthermore, stochastic tug-of-wars between two teams of molecular motors were experimentally confirmed for the transport of early endosomes in fungi. In this case, dyneins that bind to a cargo or unbind from it can change the cargo's direction of motion, see **Fig 3**.

In the context of actin filaments, we have addressed a recent controversy about the depolymerization of actin filaments (see the report by *T. Niedermayer*). Using single filament experiments, it was shown that the depolymerization of actin filaments typically proceeds in a bi-phasic way, with an initial fast phase interrupted by a slow phase, see **Fig. 4**. In contrast to previous proposals, the interruptions were shown to be caused by the local and random dimerization of actin subunits. The theoretical analysis of the stochastic interruption times and pause durations provides a general method to determine rather small changes in the molecular interactions between the subunits of actin filaments.

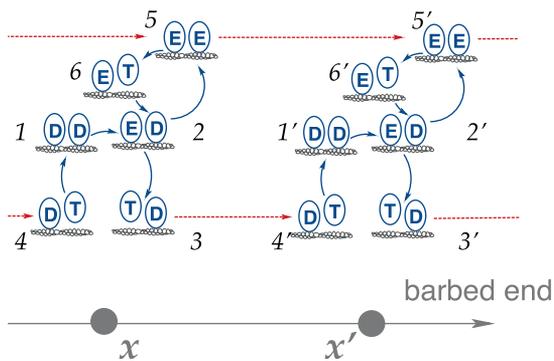


Fig. 2: Chemomechanical network for myosin V that steps along actin filaments. At each filament position x, x', \dots , the chemical network of the motor consists of six states. The motor can perform two types of mechanical forward steps, $I34'$ and $I55'$, towards the barbed end of the filament. [V. Bierbaum et al, *Biophys. J.* (2011); *PLoS ONE* (2013)]

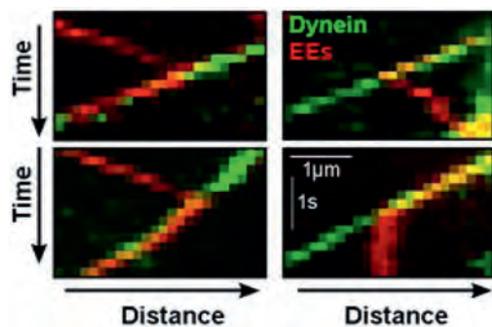
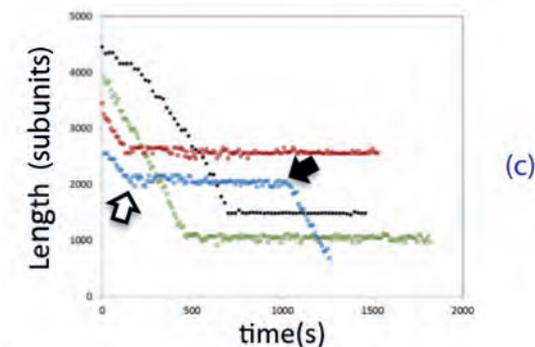
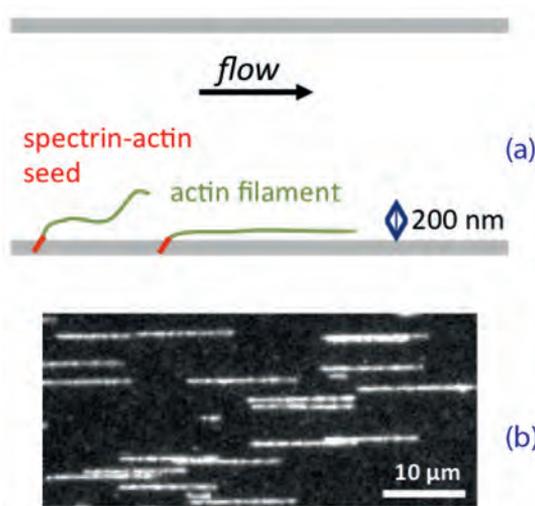


Fig 3: Changes in the direction of motion for red-labeled cargo particles by green-labeled dynein motors that bind to (left) or unbind from (right) the cargo. [M. Schuster et al, *PNAS* (2011)]

Fig.4: (a) Actin filaments are anchored to the chamber wall and aligned by a continuous microfluidic flow. Actin depolymerization is induced by fast switching to a flow channel without actin; (b) The filaments are imaged using TIRF or epifluorescence microscopy; and (c) The length of the filaments as measured during depolymerization; black data points correspond to a filament grown from MgATP-actin whereas red, green, and blue data points were obtained for three filaments grown from MgADP-actin. One pause in depolymerization occurs between the white and black arrow in (c). [T. Niedermayer et al, *PNAS* (2012)]

Ribosomes and Protein Synthesis

Ribosomes are rather complex molecular machines that synthesize proteins by translating the codon sequences of mRNA molecules into peptide chains. In order to do so, the ribosomes move along the mRNAs and translate one codon after another by binding and processing cognate tRNA molecules that are charged with the correct amino acids.

In order to understand this process of translational elongation, one has to take two important molecular features into account. First, the ribosome has three binding pockets for tRNA molecules, the A-, P-, and E-sites, see Fig. 5(a). As indicated in this figure, these three sites are aligned along the mRNA that is translated by the ribosome. Second, a tRNA can only bind to the ribosome after it has formed a ternary complex with an EF-Tu protein and a GTP nucleotide, see Fig. 5(b).

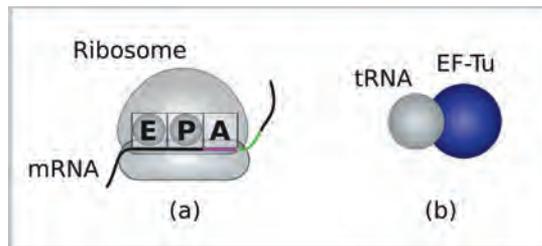


Fig.5: (a) Schematic view of a ribosome (grey dumbbell) that translates a mRNA molecule (black strand). The ribosome has three binding pockets for tRNA molecules, the A-, P-, and E-sites. These three sites are aligned along the mRNA and their separations are equal to the length of a single codon; (b) Ternary complex formed by a tRNA molecule (small grey ball), an EF-Tu protein (large blue ball), and a GTP nucleotide (not shown).

Each tRNA molecule that is processed by the ribosome first binds as a ternary complex to the A-site and is then translocated from the A- to the P-site. During the next elongation cycle, this tRNA is moved from the P- to the E-site, from which it is finally released.

A single, codon-specific cycle of translational elongation involves several ribosomal states as depicted schematically in Fig. 6. At the beginning of the elongation cycle, the ribosome contains two tRNA molecules in its P- and its E-site but has an empty A-site, which is located at the codon to be translated. In Fig. 6, this codon is colored in red. When a cognate tRNA molecule arrives at the ribosome by diffusion, it first binds loosely to the A-site but becomes fully accommodated into this site after its correct anticodon has been recognized. During the latter substeps, the E-site tRNA and the EF-Tu molecule are released from the ribosome and a new peptide bond is formed. However, before the translating ribosome is able to bind and process a cognate tRNA, it typically samples through a large number of noncognate tRNAs that also bind to the ribosomal A-site and, thus, impede binding of the cognate tRNA, see upper left cartoon in Fig. 6.

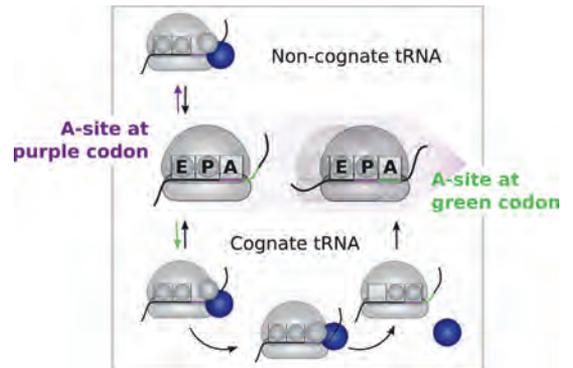


Fig.6: Elongation cycle of a ribosome corresponding to the translation of a single codon (red mRNA segment): Initially, the ribosome dwells at this codon with an empty A-site until a ternary complex arrives and occupies this site. This ternary complex is typically non-cognate (upper left cartoon) and is then released from the A-site without further processing. If a cognate ternary complex is bound (lower left cartoon), it is recognized by its anticodon and is then fully accommodated into the A-site (lower right cartoon). During this accommodation step, the EF-Tu molecule is released. After the formation of a new peptide bond (not shown), the ribosome undergoes translocation and moves to the subsequent codon (green mRNA segment) in order to start the next elongation cycle. [S. Rudorf et al, to be published]

We have recently developed a quantitative theory that takes both the formation of ternary complexes and the competitive binding between cognate and non-cognate tRNAs into account and allows to calculate the codon-specific elongation times of the ribosome. Another interesting aspect of translation that we studied theoretically is the robustness of protein synthesis with respect to variations of individual tRNA concentrations.

Membranes and Vesicles

Lipid molecules in aqueous solution self-assemble into bilayer membranes that have a thickness of about 4nm. In order to desorb from the membrane again, a single lipid has to overcome a large free energy barrier that has been determined in the group of A. Grafmüller using atomistic molecular dynamics simulations. Unexpectedly, the desorption free energy was found to increase with membrane tension because of the conformational entropy of the lipid tails.

Lipid vesicles exposed to different aqueous phases exhibit unusual morphologies and morphological transitions as discovered in the group of R. Dimova: wetting transitions, droplet-induced budding processes, and spontaneous tubulation, i.e., the formation of membrane nanotubes that are stable even in the absence of external forces. The latter process provides direct evidence that the polymer/lipid interactions lead to a spontaneous membrane curvature that generates a large membrane tension. In fact, one unique feature of aqueous phase separation in vesicles is the possibility to directly determine the membrane tensions from the (effective) contact angles as visible in the optical microscope, see Fig. 7, and from the interfacial tension between the two liquid phases.

The interactions of nanoparticles with membranes and vesicles have been studied by the group of *T. Weigl* using Monte Carlo methods to minimize the free energy of the membrane/particle systems. These studies revealed strongly attractive interactions between nanoparticles adsorbed onto vesicles. As a result of these interactions, the adhering nanoparticles aggregate on the vesicle membranes and often form linear chains enwrapped by membrane nanotubes.

Another membrane system that has been addressed is provided by double-membrane structures that play an important role in cellular processes such as autophagy, reproduction, and viral infection. In these processes, one typically starts from double-membrane sheets that become unstable and close up into double-membrane vesicles. The stability of a double-membrane sheet depends primarily on its lateral size and the spontaneous membrane curvature along its rim [R. Knorr et al, PLoS ONE (2012)].

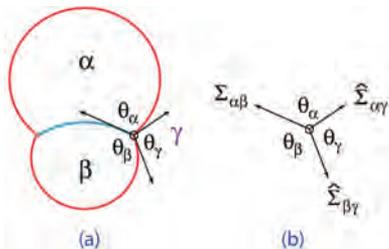


Fig. 7: (a) Morphology of vesicle membrane (red) enclosing two liquid droplets. The upper droplet contains the PEG-rich α phase, the lower one contains the dextran-rich β -phase. The interface (blue) between the droplets meets the membrane along the three-phase contact line, with the exterior phase denoted by γ . The two membrane segments and the interface define three (effective) contact angles, θ_α , θ_β , and θ_γ that can be directly measured by optical microscopy; (b) These contact angles and the interfacial tension $\Sigma_{\alpha\beta}$ of the ($\alpha\beta$) interface determine the two membrane tensions $\hat{\Sigma}_{\alpha\gamma}$ and $\hat{\Sigma}_{\beta\gamma}$.

Interfacial Phenomena

Polymer Brushes consisting of diblock copolymers undergo micro-phase separation and provide surfaces with stable nanoscale patterns, which can be used to control the organization of nanoparticles into larger aggregates as studied by the group of *C. Seidel*. Using dissipative particle simulations, a variety of different morphologies for these aggregates has been identified as well as morphological transitions, which resemble wetting transitions of liquid droplets at chemically patterned surfaces.

Morphological wetting transitions can be induced, in a rather simple way, by increasing the volume of the liquid droplets. As a consequence, these transitions also have a strong effect on surface nucleation and lead to non-isomorphic nucleation pathways. One example for such a pathway has been studied in the context of edge melting of alkane monolayers (*H. Kusumaatmaja* et al, Phys. Rev. Lett. (2012)).

Complex Systems

Most macromolecules within the living cell are continuously synthesized and degraded. Experimental data on mRNA degradation and translation have been analyzed in the group of *A. Valleriani* using stochastic modeling. In the context of

mRNA degradation, it was shown that the experimentally determined decay patterns for the mRNA degradation can be used to determine the age-dependent decay rates and the life time distributions of the mRNA molecules. In the context of translation, data on ribosomal profiling have been analyzed for different growth and stress conditions.

The independent research group of *S. Klumpp* addressed the interplay of physical constraints and functional requirements in living systems, with a focus on molecular machines involved in gene expression, genetic circuits, and cellular dynamics. Genetic circuits in bacteria are intimately coupled to cellular growth because many parameters of gene expression depend on the growth rate. These dependencies have been studied for the replication control system of plasmids. Some bacteria can respond to magnetic fields via organelles called magnetosomes that contain magnetic nanoparticles. Robust chain formation was found to require both magnetic interactions and active transport.

Another, more abstract class of complex systems that has been studied is provided by binary or 'spin' variables on scale-free networks with correlations between their vertex degrees. In assortative and disassortative networks, the high-degree vertices are primarily connected to other high-degree and low-degree vertices, respectively. In both cases, the networks can be decomposed into vertex layers, which are ordered at low temperatures and undergo successive phase transitions as the temperature is increased, see Fig. 8.

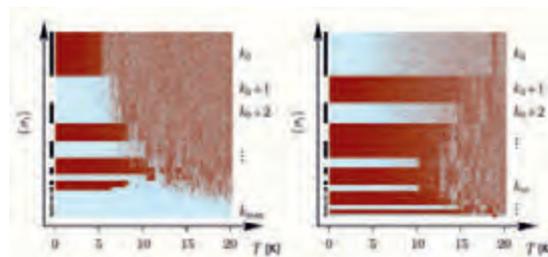


Fig 8: Typical configurations of binary or 'spin' variables on assortative (left) and disassortative (right) scale-free networks as a function of temperature T . 'Spin-up' and 'spin-down' states are shown in red and blue, respectively. Each column parallel to the y -axis shows the 'spin' states $\{i\}$ of all vertices in the network. As the temperature increases, the ordered vertex layers become disordered one after another. [J. Menche et al, Phys. Rev. E (2011)]

International Max Planck Research Schools

The department of Theory & Bio-Systems was in charge of the International Max Planck Research School (IMPRS) on "Biomimetic Systems", which was in operation from 2000 until 2012, and is also in charge of the new IMPRS on "Multi-scale Biosystems", which will start in July 2013.

For additional information about research at the Department of Theory & Bio-Systems, see the following reports and www.mpikg.mpg.de/th/.

Reinhard Lipowsky
Director, Theory & Bio-Systems Department

Glycans as Universal Tools for Proteins and Lipids



Mark Santer 27.10.1971

2003: PhD in Physics at the University of Freiburg

2003-2006: Postdoc at the Institute of Microsystems Engineering, University of Freiburg. Group leader Nanofluidics

2006-2009: Employee at the Fraunhofer Institute of Mechanics of Materials (IWM), Freiburg

2009: 2010 Postdoc at the Theory Department, MPI for Colloids and Interfaces, Potsdam

From 09/2010: Group leader

Carbohydrates and Polysaccharides at Theory & Biosystems Department

Carbohydrates are known to be important for cell-cell communication or in modifying the properties of proteins and lipids in the extracellular matrix. Still many of the possible biological roles of these oligosaccharides, or glycans, are yet to be elucidated. In addition to the specific recognition of many small saccharides by certain biomolecules, larger oligosaccharides have the potential to support a much broader, unspecific functionality, owing to their internal flexibility and overall diversity. For computational approaches complementing experimental studies, the latter aspects pose serious challenges, in particular at the atomistic level with respect to force field development and conformational sampling. To explore the behavior of glycans in a larger context when they are expected to fine-tune the interaction between biomolecules, a mapping onto reduced or effective models must be devised.

In our group, we currently pursue two long term case studies in order to establish a corresponding ladder of descriptions. The first study deals with the class of so-called Glycosylphosphatidylinositol(GPI)-Anchors emphasizing the interaction with lipids (with *D. Varon Silva* and *P.H. Seeberger*, Department of Biomolecular Systems, MPIKG; *C. Stefanu* and *G. Brezesinski*, Department of Interfaces, MPIKG), and the second with specific carbohydrate-protein interactions (with *S. Barbirz*, University of Potsdam and *G. Widmalm*, University Stockholm) important for infections of gram-negative bacteria by bacteriophages.

GPI Anchors as Glycolipids

GPIs are glycans that covalently link proteins to the outer leaflet of cell membranes [1]. The carbohydrate part is in close proximity to both, a protein and a lipid component at the same time, see Fig. 1.

For the atomistic representation of the complete GPI, only the connection to the protein is available from force field databases. For the part comprising glucosamine, phosphoinositol and the lipid (glucosamine- α 1-6myoino-1-phosphodistearyl-glycerol, highlighted by the red frame in Fig. 1), an adaption of the force field has been developed. For complex molecules such as this, there are few opportunities to validate the force field prediction against structural data from experiment. In a joint effort, we have investigated this molecule within Langmuir monolayers of crystalline order [2].

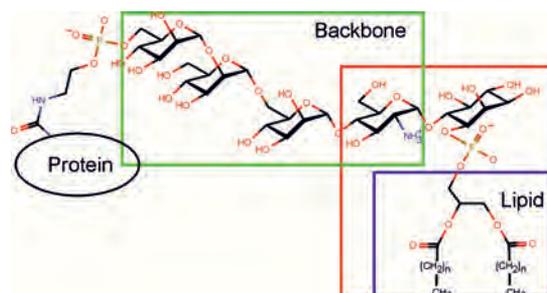


Fig. 1. Chemical structure of a lipidated GPI molecule with protein and carbohydrate backbone. The part indicated by the red frame has been studied as a separate molecule in [2].

The Nature of the GPI Anchor Backbone

Apart from the established role as an anchoring device for proteins, there is only indirect evidence for many other possible functions of the GPI, such as being a mediator for the association of the attached protein with lipid rafts. One complication here is the heterogeneity of the molecule, its composition sensitively depends on the protein attached. For developing computational models, the invariant GPI backbone is a natural and convenient starting point. But even the seemingly basic and simple question whether this backbone is a rather flexible link or maintains a characteristic structure can only be answered comprehensively after a mapping of the atomistic to an adequate reduced model has been accomplished (Fig. 2). The different notions of the backbone -flexibility vs. rigidity-, can actually be reconciled by stating that the backbone assumes a rather rigid structure that can little be stretched, but is to some extent compressible by forces of physiological magnitude (starting at roughly 10pN) [3].

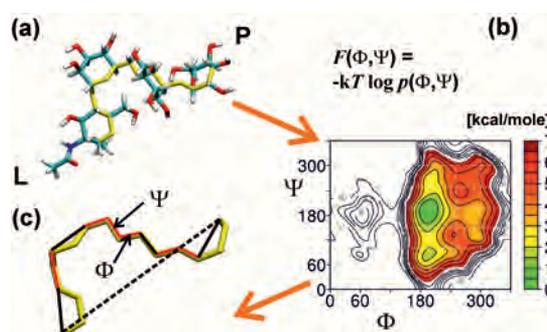


Fig. 2. (a) GPI backbone with four carbohydrate rings in stick representation. "L" and "P" indicate the direction towards the lipid and the protein, respectively. Highlighted atoms (yellow) are those retained in a reduced description. The data from all-atom MD simulations are projected onto the relevant degrees of freedom, the glycosidic torsions (c). They largely determine conformational characteristics such as the end-to-end distance (dashed line). Sugar rings are effectively represented by non-rotatable bonds (black). The free energy landscape of a corresponding pair of dihedral angles, obtained from their distribution function p , is shown in (b), reflecting the effective influence of all remaining degrees of freedom.

Do Bacteriophages Utilize the Protective Polysaccharide Coat of Gram-Negative Bacteria?

Similar questions as for the GPI emerge for certain lipopolysaccharides (LPS). Gram-negative bacteria protect themselves against invaders through a dense polysaccharide coat, which is also a target for the immune response of higher organisms invaded by these bacteria. The coat is formed by an LPS brush, the carbohydrate part of which (the O-Antigen) consists of repeating units (RU) of a tetrasaccharide building block (Fig. 3)

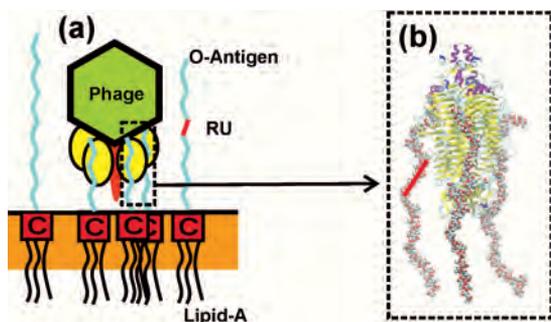


Fig. 3. (a) Schematic representation of a phage penetrating the lipopolysaccharide coat on the membrane of gram-negative bacteria. (b) snapshot of an MD simulation where three O-Antigens simultaneously attach to one tail spike protein.

A bacteriophage must, prior to infection, overcome the polysaccharide barrier before its DNA can be injected into the cell. It does so by recognizing a 2 RU epitope (an octasaccharide) with its so-called tail spike proteins (TSP), and cleaving the O-Antigen by hydrolysis at an active site on the corresponding protein scaffold. Little is known about important further aspects of the cleavage process e.g., whether it occurs continuously, is used as a means to orient the phage or to generate a force in order to push it against the membrane and initiate the DNA injection process.

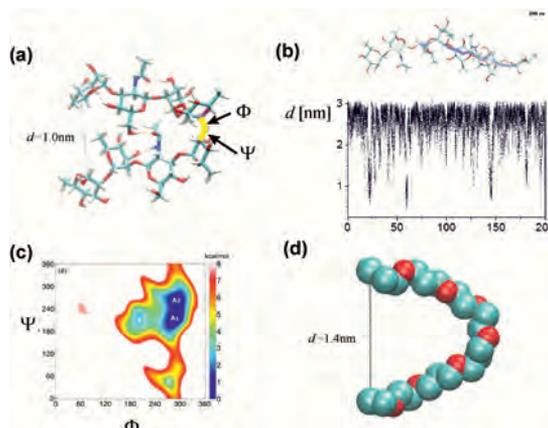


Fig. 4. (a) Hairpin-like extreme conformation of two repeat units of a serotype Y *Shigella flexneri* O-Antigen, the end-to-end distance of the octasaccharide can become as small as 1 nm, but this event is relatively rare as shown in (b). Most of the time the molecule resided in an extended conformation as depicted above. The formation of the hairpin can be attributed to the metastable state B in the free energy landscape of the glycosidic angles, see contour plot in (c). (d) The same conformation is also observed in a reduced model similar to that in Fig. 2 (only backbone atoms are displayed).

A first clue to these questions is given by a comprehensive simulation study of short fragments (a few RU long) of the O-Antigens, see Fig. 4. They show the formation of hairpin-like conformations that can lead to significant temporal coiling of the otherwise stiff polysaccharide. This suggests a rich variety of carbohydrate-protein interactions, such as conformational selection of the O-Antigen by the TSP. Here we have an analogy to the interaction of a GPI anchor with a membrane. The time scales needed to characterize the problem appropriately, e.g., as transitions between many possible intermediate states, exceed the scope of atomistic simulations, and the mapping to reduced models is called for.

M. Santer, M. Wehle, Yu Kang
mark.santer@mpikg.mpg.de.

References:

- [1] A. Varki et al., *Essentials of Glycobiology*. CSH Press, Cold Spring Harbor NY (2009).
- [2] Subgel Phase Structure in Monolayers of Glycosylphosphatidylinositol Glycolipids. C. Stefaniu, I. Vilotijevic, M. Santer, D. Varon Silva, G. Brezesinski, and P. H. Seeberger, *Angew. Chem. Int. Ed.* <http://dx.doi.org/10.1002/anie.201205825>
- [3] Mechanical Compressibility of the Glycosylphosphatidylinositol(GPI) Anchor Backbone Governed by Independent Glycosidic linkages. Wehle, M.; Vilotijevic, I.; Lipowsky, R.; Seeberger, P. H.; Varon Silva, D.; Santer, M.: *J. Am. Chem. Soc.* <http://pubs.acs.org/doi/full/10.1021/ja30280r>
- [4] Y. Kang, S. Barbirz, R. Lipowsky and M. Santer (in preparation).

Conformational Changes in Protein Function



Thomas Weikl 01.04.1970

1996: Diploma, Physics

(Freie Universität Berlin)

Thesis: Interactions of rigid

membrane inclusions

1999: PhD, Physics

(Max Planck Institute of Colloids

and Interfaces, Potsdam)

Thesis: Adhesion of

multicomponent membranes

2000-2002: Postdoc

(University of California,

San Francisco)

Since 2002: Group Leader

(Max Planck Institute of Colloids

and Interfaces, Potsdam)

2008: Habilitation, Physics

(University Potsdam)

Thesis: Transition states and loop-

closure principles in protein folding

Conformational Selection and Induced Changes

Protein binding and function often involves conformational changes. The changes between different protein conformations occur during binding or unbinding of ligands, or during chemical reactions of ligands that are catalysed by a protein. A central question is how the conformational changes of a protein are coupled to these binding and catalytic processes. In some cases, a conformational change has been proposed to occur predominantly prior to a binding process, an unbinding process, or a catalytic process, which has been termed 'conformational selection' since the ligand appears to select a conformation for binding, unbinding, or catalysis. In other cases, the conformational change seems to occur predominantly after a binding, unbinding, or catalytic process. The conformational change then appears to be 'induced' by this process. Binding via conformational selection implies induced-change unbinding, and vice versa, since the ordering of events is reversed in the binding and unbinding direction. The ordering of events has no effect on the binding equilibrium, but affects the binding kinetics and, thus, may be revealed by mutations that change the kinetics [1]. Our group has suggested a general kinetic framework that can be used (i) to identify the ordering of events in the coupling of conformational changes, binding

and catalysis from mutational data and (ii) to determine the rates of the substeps of coupled processes from a combined analysis of enzyme kinetics measurements and dynamic NMR experiments that inform on the conformational exchange [2].

Mutational Analysis of Binding Mechanism

Our mutational analysis of the binding and unbinding kinetics focuses on mutations distal to the binding site that mainly affect the conformational equilibrium of a protein. We find that conformational-selection processes are sensitive to such distal mutations because these processes involve a change to a low-populated, excited-state conformation prior to a binding, unbinding, or catalytic event, and because the equilibrium probability and excitation rate of this conformation depend on the conformational free-energy differences. In contrast, induced-change processes involve a conformational relaxation into a new ground state after a binding, unbinding, or catalytic event, which is rather insensitive to changes in conformational free-energy differences, provided (i) the conformational relaxation is fast [1], or (ii) the transition-state for the conformational exchange is close in free energy and structure to the excited protein conformation [2]. The analysis of the effect of distal mutations thus can provide the basis for a simple diagnostic to identify conformational-selection versus induced-change processes.

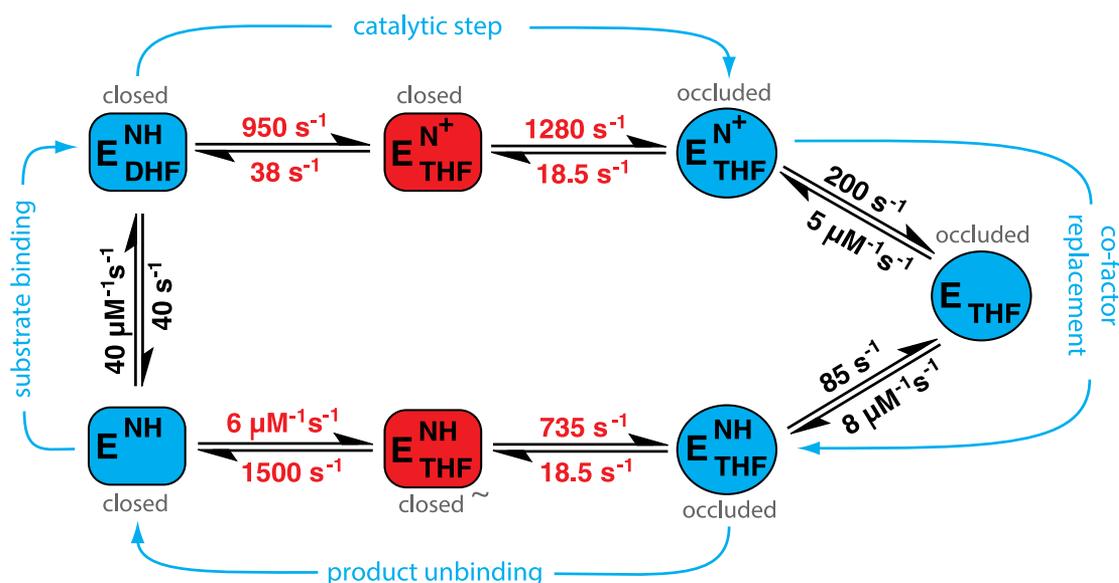


Fig. 2: Extended catalytic cycle of the enzyme DHFR from *E. coli*. The enzyme (E) catalyzes the reduction of dihydrofolate (DHF) to tetrahydrofolate (THF), using NADPH (NH) as a co-factor. Excited-state conformations are shown in red, ground-state conformations in blue. On our extended cycle, the catalytic step is decomposed into the actual chemical substep in the closed conformation of the enzyme required for catalysis and a physical substep in which the enzyme conformation changes from closed to occluded. Our analysis of the product-unbinding kinetics and NMR relaxation experiments indicate that the conformational change from the occluded to the closed conformation occurs largely prior to the unbinding of the product THF. Along our extended cycle, the product unbinds from an excited state with a conformation similar to the closed conformation (denoted as 'closed~').

Conformational Changes Along the Catalytic Cycle of the Enzyme DHFR

The enzyme dihydrofolate reductase (DHFR) is an important model system for investigating the interplay of conformational dynamics, binding and catalysis. DHFR from *E. coli* exhibits characteristic changes between a 'closed' and an 'occluded' conformation of the active-site loop along its catalytic cycle (Fig. 1). The change from the closed to the occluded conformation occurs during the catalytic step. Since the catalysed reaction can only occur in the closed conformation, we have suggested an induced-change mechanism in which the chemical reaction precedes the conformational change during the catalytic step (Fig. 2). We have determined the rates of these two substeps from experimental data for the overall rates of the catalytic step and for the rates of the conformational exchange. Our analysis of mutational data indicates that the conformational change during product unbinding follows a conformational-selection mechanism, i.e. the conformational change occurs predominantly prior to unbinding [2].

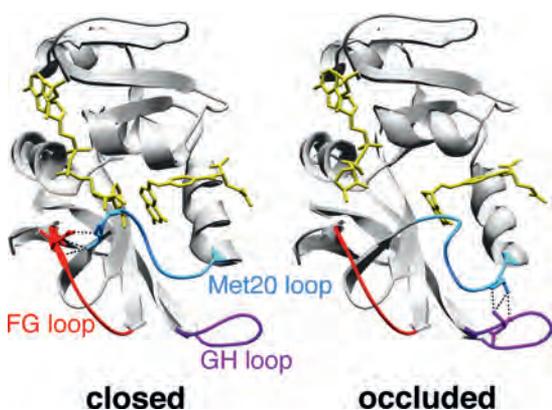


Fig. 1: DHFR from *E. coli* exhibits changes between a closed and occluded conformation along its catalytic cycle. In these conformations, the Met20 loop either closes over the active site, or protrudes into it. The different conformations are stabilized by different hydrogen bonds to adjacent loops. The bound substrate and co-factor here are shown in yellow.

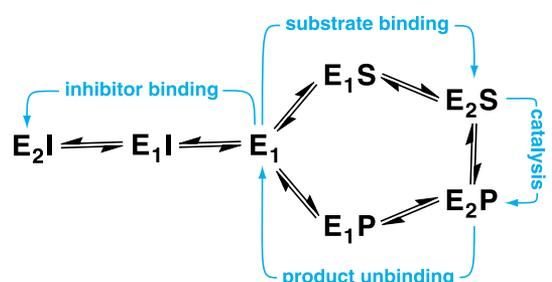


Fig. 3: 7-state model for catalysis and inhibition of an enzyme with induced-fit binding mechanism. In this model, substrate molecules *S* and inhibitor molecules *I* first bind in conformation E_1 of the enzyme. These binding events induce changes into conformation E_2 in which the substrate *S* is converted into the product *P*.

Catalysis, Inhibition and Drug Resistance of Enzymes with Induced-fit Binding Mechanism

We have extended classical models of enzyme catalysis and inhibition by including a conformational change during the binding and unbinding of substrate, product, or inhibitor molecules (Fig. 3). Our focus was on enzymes with induced-change binding mechanism since many enzymes close rather tightly over substrate or inhibitor molecules during binding. Binding via an induced-change mechanism, i.e. prior to the change from the 'open' to the 'closed' conformation of these enzymes, is required if the entry and exit of the ligand molecules is sterically obstructed in the closed conformation. The role of the conformational changes for catalysis and inhibition can be revealed by distal, non-active-site mutations that slightly shift the conformational equilibrium, but do not interfere directly with binding and catalysis in the active site of the enzymes. Several groups have suggested that such shifts in the conformational equilibrium might explain why non-active-site mutations can contribute to multi-drug resistance, i.e. to an increase of catalytic rates in the presence of different inhibitory drugs. Based on our extended model for enzymes with induced-change binding mechanism shown in Fig. 1, we have investigated how these mutations affect catalysis and inhibition [3]. Two cases can be distinguished: In case 1, the maximum catalytic rate of the enzyme is limited by the unbinding of the product. We find that the catalytic rate in the presence of inhibitors depends exponentially on the mutation-induced change $\Delta\Delta G_c$ of the free-energy difference between the two conformations of the enzyme in this case. Non-active-site mutations with $\Delta\Delta G_c > 0$ that slightly destabilize the closed conformation 2 relative to the open conformation 1 of the enzyme lead to an increase in the catalytic rate, irrespective of the inhibitor. Such non-active-site mutations thus contribute to a multi-drug-resistance of the enzyme. In case 2, the maximum catalytic rate of the enzyme is limited by the forward rate of the catalytic step. In this case, mutation-induced changes of the conformational equilibrium have no effect on the catalytic rate in the presence of inhibitors. A comparison with experimental data for the non-active-site mutation L90M of the HIV-1 protease indicates that this enzyme appears to follow case 1, which implies that non-active-site mutations that slightly destabilize the closed conformation contribute to multi-drug resistance.

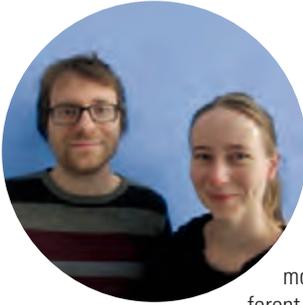
T. Weikl, B. Hemmateenejad, F. Paul
thomas.weikl@mpikg.mpg.de

References:

- [1] Weikl, T. R., and von Deuster, C.: Selected-fit versus induced-fit protein binding: Kinetic differences and mutational analysis. *Proteins* **75**, 104-110 (2009).
- [2] Weikl, T. R., and Boehr, D. D.: Conformational selection and induced changes along the catalytic cycle of *E. coli* DHFR. *Proteins* **80**, 2369-2383 (2012).
- [3] Weikl, T. R., and Hemmateenejad, B.: How conformational changes can affect catalysis, inhibition and drug resistance of enzymes with induced-fit binding mechanism such as the HIV-1 protease. *Biochim. Biophys. Acta* (2013).

MOLECULAR MOTORS AND FILAMENTS

Cargo Transport by Teams of Molecular Motors: Elastic Coupling and Interference Regimes



Florian Berger 06.11.1981

2008: Diploma, Physics,
(University of Stuttgart)

Thesis: Optimization in Driven Systems

2012: PhD, Physics, (MPI of Colloids and
Interfaces, Potsdam) Thesis: Different
Modes of Cooperative Transport by
Molecular Motors

Since 2012: Postdoc

(MPI of Colloids and Interfaces,
Potsdam)

Corina Keller 27.10.1977

2009: Diploma, Physics,

(Humboldt University Berlin)

Thesis: Coupled Molecular Motors

2013: PhD, Physics, (MPI of Colloids and
Interfaces, Potsdam) Thesis: Coupled
Molecular Motors: Network Representa-
tion and Dynamics of Kinesin Motor Pairs

Since 2013: Postdoc

(MPI of Colloids and Interfaces,
Potsdam)

Active transport by molecular motors is ubiquitous in all eukaryotic cells. These motor proteins convert chemical energy into mechanical work which enables them to transport cargoes such as RNAs, protein complexes or organelles. Such intracellular transport is often driven cooperatively by several molecular motors, which may belong to the same or to different motor species like kinesin, dynein or myosin.

These motors step stochastically along filaments, from which they unbind after a finite run length. Understanding how these motors interact and how their movements are coordinated and regulated is a central and challenging problem of cellular transport [1]. To establish a general theoretical framework for elucidating and analysing such transport processes, we recently introduced two complementary approaches: (i) a detailed enzymatic chemo-mechanical description that starts from the nucleotide states of the single motors [2] and (ii) a coarse-grained description considering the single motor as a stochastic stepper [3,4]. Such theoretical approaches integrate the well-established properties of individual motors into a predictive theory for cooperative transport.

Network Representation of Motor Pairs

Cargo transport by two coupled molecular motors is studied using a chemomechanical network for the complete transport system and analyzing the trajectories generated by this network. The theoretical description starts from the different nucleotide states of a single motor supplemented by chemical and mechanical transitions between these states. As an instructive example, we focus on kinesin-1, for which a detailed chemomechanical network has been developed previously [5]. The motor pair system considered here consists of two kinesin motors, a leading and a trailing motor, which are attached to the same cargo and walk on the same filament. Each motor can unbind from and rebind to the filament individually. As a consequence, the cargo is actively pulled by either one or two motors. A mechanical step of one of the motors during a 2-motor run leads to an elastic interaction force between the two motors described by the extension of a linear spring. The state space of the elastically coupled motor pair is characterized by three variables, the chemical states i_{le} and i_{lr} of the leading and trailing motor and of the extension ΔL of the motor-motor separation [2]. The resulting network has a layer structure as shown in Fig. 1, where each layer corresponds to a constant value of ΔL . Any 1-motor run occurs on one of the boundary lines of the network and may be terminated either by unbinding of the active motor which

leads to the unbound motor pair state, or by the rebinding of the inactive motor and a subsequent 2-motor run. Mechanical steps during 2-motor runs lead to transitions between neighbouring ΔL -layers. Even though this motor pair network has a complex structure, it involves, apart from the single motor parameters, only two additional parameters, the coupling parameter K and the single motor rebinding rate π_{si} .

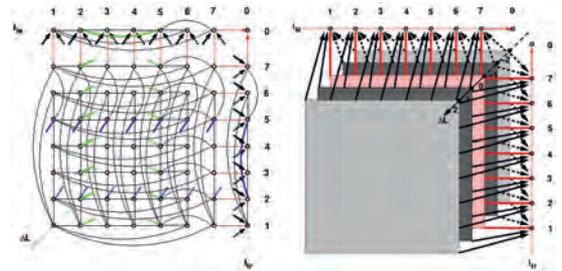


Fig. 1: State space of a motor pair described by the individual motor states i_{le} and i_{lr} and the extension ΔL of the motor-motor separation. (left) Detailed description of the layer with $\Delta L=0$ and (right) stack of five ΔL -layers.

Activity States and Motor Pair Parameters

In stochastic simulations, we studied the trajectories generated from the chemomechanical network of the motor pair as a function of the single motor rebinding rate π_{si} and the elastic coupling parameter K [2]. In experimental studies, the values of these two parameters are usually not known but have to be determined in a consistent manner. Our theory shows that one can determine these two parameters by measuring the average run times during 1- and 2-motor runs of cargo trajectories. Alternatively, individual motor trajectories and the properties of the ΔL -distribution can be used to deduce the two unknown parameters. Which activity state is dominant during a motor pair walk also depends on these two parameters. The corresponding activity diagram in Fig. 2 shows the crossover line which separates the parameter regime, in which 1-motor runs dominate the cargo run, from the regime, in which 2-motor runs are more likely. From individual motor trajectories, one can deduce the distribution of the extension ΔL of the motor-motor separation during 2-motor runs as shown in Fig. 2. Within the studied range for the coupling parameter, the number of accessible ΔL values varies by one order of magnitude. The maximal values of ΔL observed in the simulations determines the size of the network in Fig. 1.

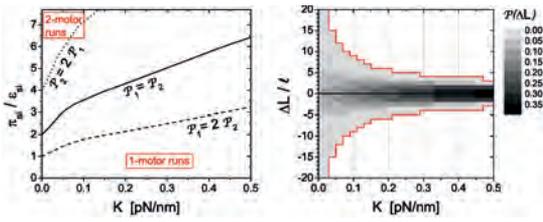


Fig. 2: (left) Activity regimes of a motor pair as a function of elastic coupling parameter K and single motor rebinding rate π_{on} . (right) Probability distribution $P(\Delta L)$ for the extension ΔL of the motor-motor separation as a function of the coupling parameter K .

Distinct Transport Regimes for Elastically Coupled Motors

The case of cargo transport by two identical motors involves an elastic coupling between the motors that can reduce the motors' velocity and/or the binding time to the filament. We show that this elastic coupling leads, in general, to four distinct transport regimes characterized by the motor pair's average velocity v_2 and its average binding time t_2 , during which the two motors remain simultaneously bound to the filament [3]. Both quantities depend on the single motor dynamics and on the strength K of their elastic coupling. Thus, strongly coupled and/or fast motors can quickly build up a large strain force that pulls one of the motors from the filament, while weakly coupled and/or slow motors may unbind spontaneously before reaching such a large force. The motor pair dynamics are governed by the interplay of three different forces: the stall force F_s , which corresponds to the maximal force that a single motor can generate, the detachment force F_d , which is the typical force that one motor can sustain for an extended period of time, and the scale F_K for the elastic strain forces between the two motors.

Using a continuous-time Markov process to describe the single motors as stochastic steppers, we calculate the average binding time t_2 and the velocity v_2 for two active motors and identify four different transport regimes, see Fig. 3. We estimate the crossover lines between these regimes from time scale arguments for the strain force generation which, in addition, allows us to obtain an intuitive understanding of the mutual motor-motor interference.

We apply our framework to predict the behavior of different pairs of molecular motors based on typical parameters from single motor experiments. In addition to a weak coupling regime, kinesin and dynein motors are found to exhibit a strong coupling and an enhanced unbinding regime, whereas myosin motors are predicted to attain a reduced velocity regime. All of these regimes can be explored experimentally by varying the elastic coupling parameter K . Our theory is consistent with the available experimental data for a kinesin-1 and myosin V.

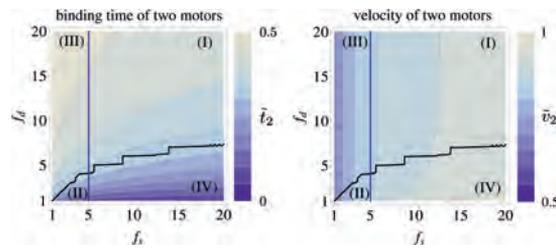


Fig. 3: (left) Average binding time and (right) velocity of a cargo pulled by two active motors in units of the single motor binding time and single motor velocity, respectively. Both quantities are displayed in a colored contour plot as functions of the rescaled single motor stall force $f_s = F_s/F_K$ and the rescaled detachment force $f_d = F_d/F_K$, where the force scale $F_K = K/2l$ is the elastic strain force between the motors per motor step with step size l . The solid blue line separates the region with and without a reduced velocity, whereas the solid black line separates the region of spontaneous and force-induced unbinding. These lines define four distinct transport regimes: (I) weak coupling with essentially unchanged velocity and binding time; (II) strong coupling with both reduced binding time and reduced velocity; (III) reduced velocity with no effect on the binding time and (IV) enhanced unbinding with no effect on the velocity.

F. Berger, C. Keller, S. Klumpp, R. Lipowsky
 florian.berger@mpikg.mpg.de
 corina.keller@mpikg.mpg.de

References:

- [1] Berger, F., Keller, C., Müller, M. J. I., Klumpp, S., Lipowsky, R., Co-operative transport molecular motors, *Biochem. Soc. Trans.*, **39**, 1211-1215 (2011).
- [2] Keller, C., Berger, F., Liepelt, S., Lipowsky, R., Network complexity and parametric simplicity for cargo transport by two molecular motors, *J. Stat. Phys.*, **150**, 205-234 (2013).
- [3] Berger, F., Keller, C., Klumpp, S., Lipowsky, R., Distinct transport regimes of two elastically coupled molecular motors, *Phys. Rev. Lett.*, **108**, 208101 (2012).
- [4] Berger, F., Keller, C., Lipowsky, R., Klumpp, S., Elastic coupling effects in cooperative transport by a pair of molecular motors, *Cell. Mol. Bioeng.*, **6**, 48-64 (2013).
- [5] Liepelt, S., Lipowsky, R., Kinesin's network of chemomechanical motor cycles, *Phys. Rev. Lett.*, **98**, 258102 (2007).

Depolymerization of Actin Filaments



Thomas Niedermayer 18.12.1981
2008: Diploma, Physics (University of Marburg); Thesis: Synchronization, phase-locking, and metachronal wave formation in ciliary chains
2012: PhD, Physics (MPI of Colloids and Interfaces, Potsdam); Thesis: On the depolymerization of actin filaments
Since 2012: Postdoc (MPI of Colloids and Interfaces, Potsdam)

Actin is one of the most abundant and highly conserved proteins in eukaryotic cells. The globular protein assembles into long filaments, which form a variety of different networks within the cytoskeleton. The dynamic reorganization of these networks – which is pivotal for cell motility, cell adhesion, and cell division – is based on cycles of polymerization (assembly) and depolymerization (disassembly) of actin filaments. Actin binds adenosine triphosphate (ATP), and within the filament the actin-bound ATP is hydrolyzed into adenosine diphosphate (ADP) on a time scale of a few minutes.

Because ADP-actin dissociates faster from the filament ends than ATP-actin, it was thought that the filament becomes less stable as it grows older. However, recent depolymerization experiments with single filaments suggested the opposite behavior. Abrupt dynamic changes during filament depolymerization have been observed in buffers containing no free monomers, and indicate that the actin filaments become increasingly stable with time. Several mechanisms for this stabilization have been proposed. The most prominent hypothesis correlates the stabilization with structural transitions of the whole filament helix [1].

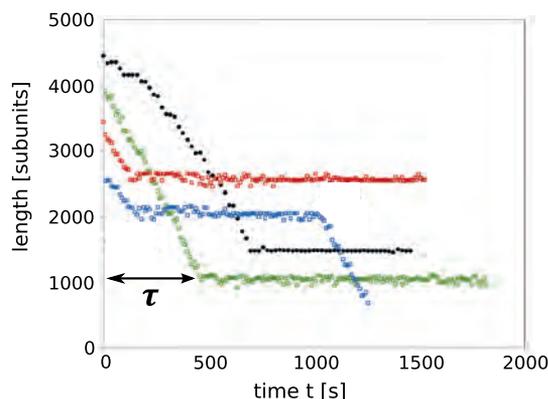


Fig. 1: Length of four actin filaments as a function of time. The filaments depolymerize in buffers containing no free monomers. The shrinkage is suddenly interrupted at a certain interruption time τ , which differs from filament to filament and represents a stochastic variable.

Interruptions of Depolymerization

In order to study the interruptions of depolymerization, we collaborated with the experimental lab of Marie-France Carlier in Gif-sur-Yvette (France). A combination of single filament microscopy and stochastic modeling allowed us to discover the surprising mechanism of filament stabilization [2,3]. In depolymerization experiments on filaments having one end blocked, we confirmed that filaments abruptly cease to

shrink and determined the time from the initiation of depolymerization until the occurrence of the first interruption, see Fig. 1. This duration time τ differs from filament to filament and represents a stochastic variable.

We considered various hypothetical mechanisms that may cause the observed interruptions. These mechanisms cannot be observed directly, but they lead to distinct distributions of the duration τ and these distributions can be compared with those obtained from single filament experiments. By modeling the underlying stochastic processes – such as the association and dissociation of filament subunits and putative transformations of these subunits – we computed the cumulative distribution functions $P(t) = \text{prob}(\tau \leq t)$ of the stochastic variable τ for all transformation mechanisms in question. For global filament transformations, which were implicitly considered in [1], or transitions that only occur at the depolymerizing filament end, the duration τ is exponentially distributed. Furthermore, many other mechanisms – for instance the copolymerization of actin with already transformed subunits – give rise to an approximately exponential distribution of τ . Successive transformations of subunits starting from a single seed cause the duration τ to have a very narrow Gaussian distribution, and thus result in a sharp rise of $P(t)$ at $t = \langle \tau \rangle$. For the experimentally relevant range of parameters, local transformations of random subunits within the filament lead to a cumulative distribution that is well described by the expression

$$P(t) = 1 - \exp(-\alpha\omega t^2), \quad (1)$$

where the parameter α is fixed by both the polymerization and depolymerization velocities, and the free parameter ω is the rate of the putative subunit transformations. A comparison of our analytical expressions with the measured distribution, see Fig. 2, revealed that the sudden truncation of the shrinkage process does neither arise from blocking of the ends nor from a collective transition of the whole filament. Instead, we have predicted a novel, local transition process occurring at random sites within the filament.

The combination of additional single filament experiments with our theoretical approach – and in particular with a generalization of the distribution in equation (1) – confirmed the notion of a local transition mechanism and identified the postulated transition as the photo-induced formation of an actin dimer within the filaments. Furthermore, we showed that only fluorescently labeled filament subunits may exhibit a transition and that unlabeled actin filaments do not exhibit pauses. This implies that, *in vivo*, older filaments become destabilized by ATP hydrolysis, in contrast to the view expressed in [1].

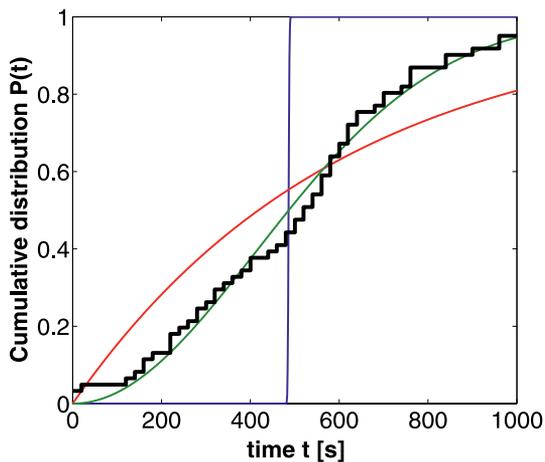


Fig. 2: The cumulative distribution $P(t) = \text{prob}(\tau \leq t)$ of the duration τ , i.e., the probability that the interruption occurs at any time prior to time t , provides a fingerprint of the mechanism that causes the interruption. The exponential distribution (shown in red) is implied by many possible mechanisms such as transformations that may occur only at the shrinking filament end. The step-like function (shown in blue) is caused by sequential transformations of the filament subunits. Local transformations of random subunits lead to a cumulative distribution given by equation (1) and displayed in green. Experimental data are shown in black. The red, blue, and green curves corresponding to theoretical distributions were obtained by least-square-fitting of the respective distributions to the experimental distribution. Each fitting procedure involves only one fit parameter provided by the transition rate ω . Since the data can only be described by the green curve, we conclude that the interruptions arise from local transitions of random subunits within the filament. As soon as such a transformed subunit arrives at the shrinking end, it causes the interruption of depolymerization.

Mechanism of ATP Hydrolysis

The filament destabilization by ATP hydrolysis becomes apparent as an acceleration of the depolymerization prior to the interruption: In Fig. 1, the black data, corresponding to a filament grown from ATP-actin, exhibit an increase of the depolymerization velocity, whereas the red, green and blue data points, obtained for three filaments grown from ADP-actin, exhibit shrinkage with constant velocity. The mechanism of ATP hydrolysis has remained elusive for many years: Both the so called “random model”, where ATP is hydrolyzed at each subunit with the same rate, as well as the “vectorial model”, where ATP hydrolysis exclusively takes place at a subunit neighboring an ADP-actin subunit, have been proposed in the literature. The measurement of the time-dependent depolymerization velocity using fluorescence microscopy in conjunction with a theoretical description of the depolymerization process and a careful data analysis

reveals that the rate of ATP hydrolysis is constant within the filament, corresponding to a random hydrolysis mechanism [3,4]. This method also provided novel insight into the function of profilin, a protein that accelerates actin depolymerization in cells, thus demonstrating the method’s potential in the functional analysis of actin regulators.

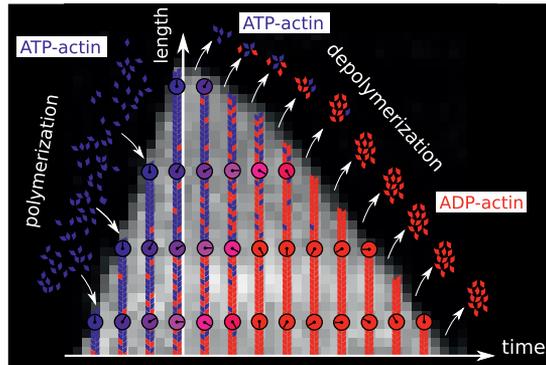


Fig. 3: The time-dependent extension of an actin filament is shown in light gray. Left of length axis: During polymerization, ATP-actin is incorporated into the filament. The subsequent hydrolysis of the bound ATP gives rise to ADP-actin. Right of length axis: The velocity of depolymerization increases over time, since ADP-actin dissociates more rapidly from the filament end than ATP-actin. The local composition of the filament (i.e. the fraction of ATP-actin) can be inferred from the time-dependence of the depolymerization velocity and is indicated by the coloring of the small clocks. These clocks measure the ‘age’ of the subunit at the respective position within the filament, that is the time that has elapsed since the incorporation of the respective filament segment. The correspondence between the color of the clocks and the local time indicates that the rate of ATP hydrolysis is constant along the filament.

Thomas Niedermayer, Reinhard Lipowsky
 thomas.niedermayer@mpikg.mpg.de

References:

- [1] Kueh, H. Y. and Mitchison, T. J. Structural plasticity in actin and tubulin polymer dynamics. *Science* **325**, 960-963 (2009).
- [2] Niedermayer, T., Jégou, A., Chièze, L., Guichard, B., Helfer, E., Romet-Lemonne, G., Carlier, M.-F. and Lipowsky, R. Intermittent depolymerization of actin filaments is caused by photo-induced dimerization of actin protomers. *Proc. Natl. Acad. Sci. USA* **109**, 10769-10774 (2012).
- [3] Niedermayer, T. PhD Thesis: On the depolymerization of actin filaments (2012).
- [4] Jégou, A., Niedermayer, T., Orbán, J., Didry, D., Lipowsky, R., Carlier, M. and Romet-Lemonne, G. Individual actin filaments in a microfluidic flow reveal the mechanism of ATP hydrolysis and give insight into the properties of profilin. *PLoS Biology* **9**, e1001161 (2011).

Stability of Lipids and Lipid Bilayers



Lipid bilayers belong to the most important structural elements of biological cells. For biological function, a flexible and dynamic internal structure and membrane composition is required. Thus, despite their great inherent stability, the lipid membranes constantly undergo remodeling processes, involving membrane fusion, pore formation and various means of lipid exchange between membranes.

Understanding the molecular mechanisms and energetics that govern such remodeling processes presents a great challenge for both experiments and molecular modeling. This challenge arises from the disparate length and time scales involved. Bilayer membranes have lateral sizes of 100 nm to over 100 μm , yet are only a few nanometers in thickness. The processes of interest take place or are initiated at the scale of one or at most a couple of lipids molecules, i.e. a few nanometers. At the same time, they take place on time scales too fast for high resolution experiments, yet are non-equilibrium processes, and out of reach for most molecular simulations.

Strategies to overcome these difficulties involve either the use of simplified coarse-grained models, with fewer degrees of freedom as used in [1-3] to study membrane fusion, or enhanced sampling methods, such as umbrella sampling, which forces the system out of equilibrium, along a chosen reaction coordinate. Here we describe the application of the latter strategy to two membrane related processes.

Energetics of Nano-Pore Formation

Pore formation plays an important role in many cellular processes that require membrane remodeling, as well as for biomedical applications.

Theories of pore formation are often based on classical nucleation theory as a balance between the edge energy and the membrane tension Σ . When the pore radius is close to the molecular scale however, this continuum description is unlikely to hold, because the creation and closure of the hydrophobic pore requires considerable rearrangement of the lipid molecules at the pore edge.

Simulation studies of pore formation are limited to small length and time scales, and thus require artificially large membrane tensions. Alternatively, the free energy required to create a nm sized hydrophilic pore can be calculated with umbrella sampling. Here, the chosen reaction coordinate was the distance z of a certain lipid head group from the bilayer's center of mass.

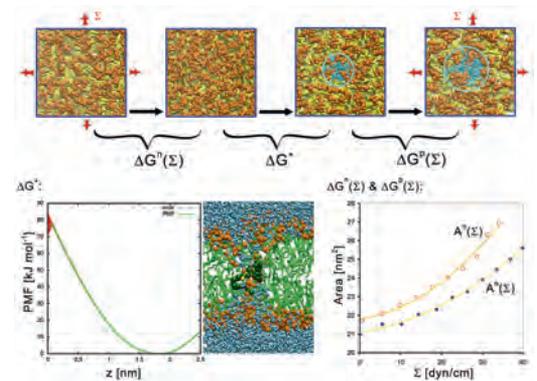


Fig. 1: Scheme for calculating the free energy of pore formation as a function of membrane tension in simulated lipid bilayers.

When the headgroup is close to the center of the bilayer a pore forms spontaneously and the corresponding potential of mean force (PMF) can be calculated. This method is however computationally expensive and limited to individual values of membrane tension. A scheme to estimate the pore formation free energy as a function of tension Σ is outlined in Fig. 1. In this scheme the process of creating a pore in a bilayer at a given Σ is divided into three steps: 1) reducing the bilayer tension from Σ to zero, 2) creating a nano-pore and 3) stretching the bilayer containing a pore back to Σ .

Using this scheme, the free energy of pore formation has been calculated as a function of Σ . The validity of the results can be tested by comparing the results to a second PMF calculation at a high lateral pressure of ~ 40 bar, which finds the pore formation free energy to be $61.7 \pm 3 \text{ kJ mol}^{-1}$. In comparison, the integration scheme leads to a value of $64 \pm 4 \text{ kJ mol}^{-1}$, demonstrating, that this method gives reliable results, over a large range of membrane tensions.

The results can be used to estimate the probability of finding a nanopore in a membrane as a function of membrane tension and size. The tensions for which this probability reaches finite values of $\sim 10\%$ correlate well with the order of magnitude of rupture tensions observed for simulated membrane patches and typical vesicle sizes, despite the different timescales. A fit of the pore free energy as a function of Σ for the line tension gives a value of 7.2 pN , which is close to experimental estimates ranging from 8 to 21 pN [4].

As the restrained lipid influences the pathway of pore formation, it is not a priori clear that unrestrained conditions lead to the same intermediate transition states for pore formation. It is not possible to observe the formation of nanopores in unrestrained simulations, but simulations of nanopore closing can give insights to the intermediate con-

formations. The two, very similar closing pathways are shown in Fig. 2. The first proceeds via a half-pore, spanning one of the monolayers only and is the same as the one observed in the pore formation pathway of the restrained simulations. In the second case, instead of a half-pore in one monolayer, two smaller hydrophilic indentations are present in both monolayers. A full hydrophobic pore spanning the entire bilayer is never seen.



Fig 2: Two possible intermediate states observed in pore closing simulations. (a) a 'half-pore' spanning one monolayer (b) two smaller hydrophilic indentations, one in each monolayer.

Lipid Exchange and Local Geometry

Similar PMF calculations, restraining the lipid head-group at a range of distances outside the bilayer membrane can be used to estimate the desorption free energy [5].

For a tension-free membrane the desorption free energy is found to be 63 ± 2 kJ mol⁻¹. Using the same protocol to determine the free energy change upon desorption of a lipid from a tense bilayer with a lateral pressure of -40 bar, we find a desorption free energy of 80 ± 2 kJ mol⁻¹, 17 kJ mol⁻¹ larger than for the desorption from the relaxed bilayer. To understand this difference, the different contributions to the free energy change have to be considered. The major contribution will be the energy cost of exposing the hydrophobic tails to the water. However, when the lipid is pulled into solution, its tails, which are extended within a conical region in the bilayer, become disordered with random orientations, as in Fig. 3c, increasing their conformational entropy. This represents a favorable contribution to lipid desorption and partially compensates the hydrophobic interactions. In the tense bilayer, the lipids are more disordered and therefore gain less entropy in solution. To investigate this effect of the local structure further, the free energy of desorption of a lipid from a spherical micelle has also been calculated. Due to the high local curvature the lipid tails in the micelle are even more disordered than in the tense bilayer. As expected, the desorption free energy for the micelle is also higher than for the tension-free bilayer, with 73 ± 1.3 kJ mol⁻¹.

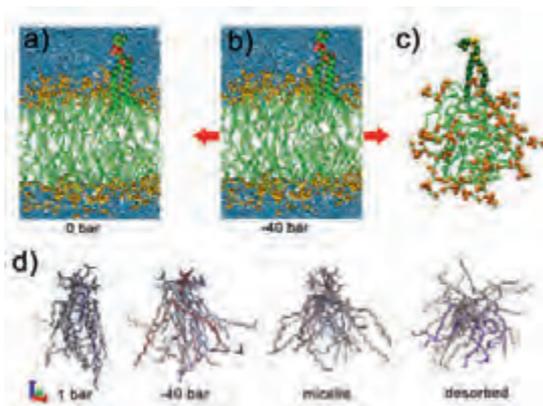


Fig.3: Three different aggregates, for which the desorption free energy has been calculated (a-c). (d) The conformational space of individual lipids within the three aggregates and in solution.

For a more quantitative assessment, the average conformational entropy of lipid tails in the different aggregates has been estimated with the quasi-harmonic (QH) approximation. The results are summarized in Table 1. In the tense membrane, the change in conformational entropy of 14 ± 5 kJ mol⁻¹ provides a quantitative explanation for the difference in desorption free energy. The difference in conformational free energies, which only differ by ~ 10 kJ mol⁻¹. Therefore, the large lipid entropy change is to a large part compensated by other free energy contributions. This result is consistent with the observation, that the number of tail-water contacts for a lipid chain in the micelle is approximately 5 times as high as in the membrane aggregates, leading to a reduced contribution of water-chain interactions.

What has become clear from studying these three systems is that the local structure has a strong influence on the free energy of lipids in the aggregates.

	ΔG^{des} (kJ/mol)	$\Delta \Delta G^{\text{des}}$ (kJ/mol)	$T\Delta \Delta S$ (kJ/mol)
Bilayer $P_{\text{II}} = 0$ bar	63 ± 2	0	0
Bilayer $P_{\text{II}} = 40$ bar	80 ± 2	17 ± 3	14 ± 5
Micelle	73 ± 1.3	10 ± 3	55 ± 5

Table 1: The free energy for lipid desorption, ΔG^{des} for the transfer of a DPPC lipid from an aggregate into water, the difference from the bilayer at zero tension, $\Delta \Delta G^{\text{des}}$ and the change in lipid entropy in the aggregates relative to the bilayer at zero tension, $-T\Delta \Delta S$

A. Grafmüller, V. Knecht, R. Lipowsky
gmueller@mpikg.mpg.de.

References:

- [1] Grafmüller, A., J. Shillcock, and R. Lipowsky, *Physical Review Letters*, . **98**(21) (2007).
- [2] Grafmüller, A., J. Shillcock, and R. Lipowsky, *Biophysical Journal*, **96**(7): p. 2658-2675 (2009).
- [3] Grafmüller, A., J. Shillcock, and R. Lipowsky, *Molecular Simulation*, **35**(7): p. 554-560 (2009).
- [4] Portet, T. and R. Dimova, *Biophysical Journal*, **99**: p. 3264-3273 (2010).
- [5] Grafmüller, A., R. Lipowsky, and V. Knecht, *Physical Chemistry Chemical Physics*, **15**(3): p. 876-881 (2013).

Lipid Membranes in Contact with Aqueous Phases of Polymer Solutions



Rumiana Dimova 06.04.1971

1991-1995: Master of Science majoring in Theoretical Chemistry and Chemical Physics (Sofia University, Bulgaria)

1996-1997: Second Master of Science majoring in Physical Chemistry (Sofia University, Bulgaria)

1997-1999: Doctoral Thesis: Hydrodynamic properties of model lipid membranes: study by means of optical trapping manipulation of particles. (Bordeaux University, Centre de Recherche Paul Pascal, Bordeaux, France)

2000-2001: Postdoctoral Scientist, Theory Department, Max Planck Institute of Colloids and Interfaces

Since 2001: Research Group Leader, Department of Theory and BioSystems, Max Planck Institute of Colloids and Interfaces

The interior of living cells is crowded with macromolecules and organelles. The weight fraction of proteins, RNAs and polysaccharides is on the order of 20–30 %. Interactions between macromolecules in water can lead to the formation of coexisting aqueous phases. Thus, in the concentrated interior of the cell, local phase separation may occur, involving microcompartmentation, which in turn can affect, e.g., cell functioning and the performance of cytoplasmic proteins.

The phenomenon of phase separation is often observed in solutions of two polymer species. The most well studied aqueous two-phase system (ATPS) formed by macromolecules is the one of poly(ethylene glycol) (PEG) and dextran. We studied the phase separation of this system in the closed compartment of lipid vesicles as a model for biological microcompartmentation. Giant lipid vesicles loaded with polymer solutions typically contain two droplets with different polymer compositions, formed by phase separation within the vesicle interior [1]. We employed these cell-sized biomimetic systems to study the wetting behavior of the polymer phases on the membrane [2, 3], the reorganization of the lipid bilayer arising from molecular crowding [4] and the resulting morphological shapes adopted by vesicles loaded with ATPS [5].

Aqueous Two-Phase Polymer Solutions of Dextran and PEG

Above a total polymer weight fraction of a few weight percent, aqueous solutions of PEG and dextran demix. The corresponding two-phase region is bounded by the binodal line within the phase diagram of the system (Fig. 1). At concentrations below the binodal the polymer solution is homogeneous. Above the binodal, the solution undergoes phase separation and the compositions of the coexisting phases are given by the tie lines in the phase diagram. A variety of methods for tie-line determination has been explored in the literature based on the use of different experimental techniques. Recently, we proposed a relatively simple approach based on density measurements of the phases [6].

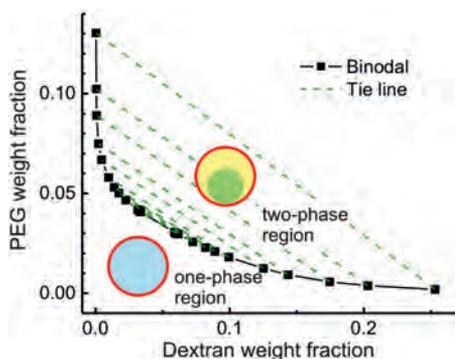


Fig. 1: Binodal and tie lines of the aqueous solution of dextran (molecular weight 400-500 kg/mol) and PEG (molecular weight 8 kg/mol) measured at 24 °C [6]. Below the binodal the polymer solution is homogeneous; above the binodal it undergoes phase separation. The insets schematically illustrate the vesicle membrane (red) enclosing the homogeneous solution (blue) or the two liquid droplets consisting of dextran-rich (green) and PEG-rich (yellow) phases.

Membrane Wetting and Wetting Transition

Liquid droplets at interfaces may exhibit zero or nonzero contact angles corresponding to complete or partial wetting, respectively. As one varies the liquid composition, the system may undergo a transition from complete to partial wetting. Such a transition can also occur for an aqueous solution enclosed within a vesicle [2]. In this case, the substrate is the lipid membrane.

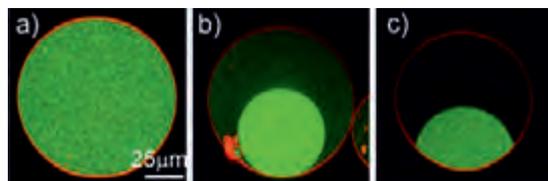


Fig. 2: Phase separation inside a vesicle (confocal vertical cross-sections). The membrane is labelled in red; a small fraction of dextran is labelled in green. As the external osmolarity is increased in a stepwise manner, phase separation occurs (a, b) and the dextran-rich drop (green) undergoes a wetting transition (b, c).

We used giant vesicles encapsulating PEG-dextran solutions in the one-phase state (Fig. 2a). In order to obtain vesicles containing two phases, we raise the interior polymer concentration above the binodal by exposing the vesicles to a hypertonic medium, i.e., by osmotic deflation. The polymer concentration inside increases, leading to phase separation (Fig. 2a, b). The dextran-rich phase is heavier and thus, the dextran-rich droplet is always located at the bottom of the vesicle. When the external osmolarity is further increased, the dextran-rich phase starts to wet the membrane (Fig. 2c). The morphology change of the dextran-rich droplet indicates a wetting transition from complete wetting of the PEG-rich phase in Fig. 2b to partial wetting in Fig. 2c.

Wetting-Induced Budding

When both phases wet the membrane, the smaller one may bud out of the vesicle upon further deflation (Fig. 3a-c). Initially, for weak deflation, the vesicle is approximately spherical (Figs. 2c and 3b). Upon further deflation, the dextran-rich phase starts to form a bud away from the PEG-rich phase (Fig. 3c). The excess area arising from deflation is utilized by the vesicle to undergo morphological changes and a budding transition [5]. The direction of budding can be reversed if the phase separation occurs in the vesicle exterior [5].

In mechanical equilibrium, the two membrane tensions $\hat{\Sigma}_{pe}$ and $\hat{\Sigma}_{de}$ must be balanced along the contact line (where the external medium, the PEG-rich phase and the dextran-rich phase are in close proximity) by the interfacial tension Σ_{pd} between the two liquid phases (Fig. 3d). The interfacial tension Σ_{pd} pulls on the membrane towards the vesicle interior. When Σ_{pd} is small, the membrane tensions can easily balance this pulling force in the normal direction and the contact angle θ_e remains close to 180 degrees. As the interfacial tension Σ_{pd} increases and the vesicle is deflated further, the membrane tension can no longer sustain the quasi-spherical vesicle shape, the membrane bends along the contact line and the dextran-rich phase buds out. The budding event sig-

nificantly reduces the interfacial energy by decreasing the interfacial area between the two liquid phases.

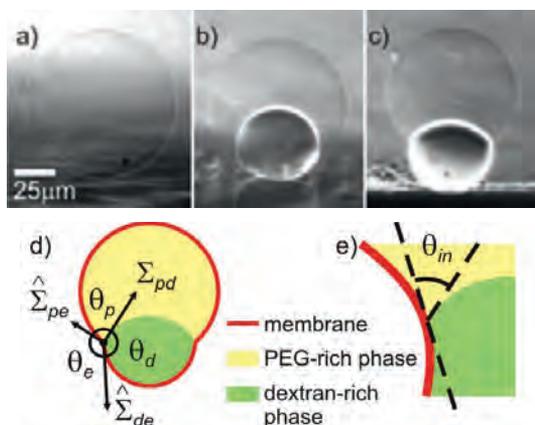


Fig. 3: (a-c) Side-view phase contrast images of a budding vesicle. After phase separation (a, b), the interior solution consists of PEG-rich (lighter) and dextran-rich (heavier) droplets. Further deflation of the vesicle causes the dextran-rich droplet to bud out as shown in (c). In the sketch in (d), the three effective contact angles as observed with optical microscopy are indicated as well as the two membrane tensions and the interfacial tension Σ_{pd} . The intrinsic contact angle θ_m , which characterizes the wetting properties of the membrane by the PEG-rich phase at the nanometer scale is sketched in (e).

The kink in the vesicle membrane shown in **Fig. 3c, d** is observed by optical microscopy but cannot persist to small length scales, since such a kink would imply an infinite bending energy of the membrane. Therefore, when viewed with suboptical resolution, the membrane must be smoothly curved as in **Fig. 3e**, which implies the existence of an intrinsic contact angle θ_m . In contrast to the three contact angles shown in **Fig. 3d**, the intrinsic contact angle represents a material parameter that is independent of the vesicle geometry [3].

Formation of Membrane Nanotubes

Upon vesicle deflation, excess area is created. Depending on the membrane tension and spontaneous curvature, the area created during deflation may lead to vesicle budding as shown above, and/or may be involved in creating membrane nanotubes [4], which have a diameter below optical resolution and become visible when fluorescently labelled (**Fig. 4**). The tubes form during the phase separation process and are stable after this process has been completed. They are always in contact with the PEG-rich phase and adsorb onto the two-phase interface forming a layer or meshwork of tubes (**Fig. 4b**). When the interface becomes overcrowded, hundreds of tubes protrude into the PEG-rich phase (**Fig. 4c**).

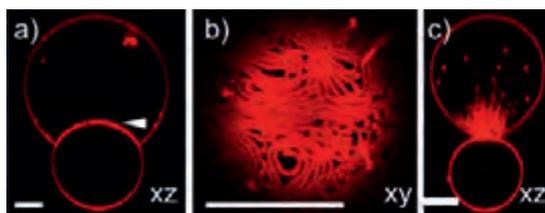


Fig. 4: Tube formation in vesicles with internal phase separation. (a) Vertical xz-section showing adsorption of tubes onto the two-phase interface (arrowhead). (b) Horizontal xy-section at the z-position of the arrowhead in (a) showing tubes at the two-phase interface. (c) Vertical xz-section of a vesicle with overcrowded two-phase interface; the tubes protrude into the upper PEG-rich phase. The scale bars correspond to 15 μm .

A theoretical analysis of the deflated vesicles reveals that these membrane tubes are stabilized by negative spontaneous curvature [4, 7]. Using the large separation of length scales between the tube diameter and the overall size of the vesicles, the spontaneous curvature can be calculated and is found to be about $-1/(240 \text{ nm})$ for a certain range of polymer concentrations. The nanotubes can also be retracted back into the mother vesicle by increasing the membrane tension via micropipette aspiration of the vesicle.

R. Dimova, H. Kusumaatmaja, Y. Li, R. Lipowsky, Y. Liu
dimova@mpikg.mpg.de.

References:

- [1] Dimova R. and Lipowsky R., *Soft Matter*, **8**, 6409-6415 (2012).
- [2] Li Y., Lipowsky R. and Dimova R., *J. Am. Chem. Soc.*, **130**, 12252-12253 (2008).
- [3] Kusumaatmaja H., Li Y., Dimova R. and Lipowsky R., *Phys. Rev. Lett.*, **103**, 238103 (2009).
- [4] Li Y., Lipowsky R. and Dimova R., *Proc. Natl. Acad. Sci. U.S.A.*, **108**, 4731-4736 (2011).
- [5] Li Y., Kusumaatmaja H., Lipowsky R. and Dimova R., *J. Phys. Chem. B*, **116**, 1819-1823 (2012).
- [6] Liu Y., Lipowsky R. and Dimova R., *Langmuir*, **28**, 3831-3839 (2012).
- [7] Lipowsky R., *Faraday Discussions*, **161**, 305-331 (2013).

Interplay of Curvature and Composition in Membranes



Thomas Weikl 01.04.1970

1996: Diploma, Physics
(Freie Universität Berlin)

Thesis: Interactions of rigid
membrane inclusions

1999: PhD, Physics
(Max Planck Institute of Colloids
and Interfaces, Potsdam)

Thesis: Adhesion of
multicomponent membranes

2000-2002: Postdoc
(University of California,
San Francisco)

Since 2002: Group Leader
(Max Planck Institute of Colloids
and Interfaces, Potsdam)

2008: Habilitation, Physics
(University Potsdam)

Thesis: Transition states and loop-
closure principles in protein folding

Biological membranes are the 'skin' of our cells and cell organelles. They consist of a large variety of different lipids and proteins, and are highly flexible and fluid, which allows drastic changes in membrane shape and curvature. The interplay of molecular composition and curvature of the membranes is crucial for their biological function. Our group investigates this interplay during the encapsulation of nanoparticles [1], in the formation of membrane domains [2], and upon membrane adhesion [3].

Cooperative Wrapping of Nanoparticles

Recent advances in nanotechnology have led to an increasing interest in how nanoparticles interact with biological matter. While biomedically designed nanoparticles are promising carriers for drug delivery, the wide application of industrial nanoparticles has also led to concerns about their safety. To enter the cells or cell organelles of living organisms, nanoparticles have to cross biomembranes. The membranes deform and wrap around nanoparticles if the adhesive interaction between the nanoparticles and membranes is sufficiently strong to compensate for the cost of membrane bending. While the wrapping of single nanoparticles by membranes has been studied intensively in theory and simulations, relatively little is known about the organization and elastic, membrane-mediated interactions of multiple nanoparticles adsorbed on membranes. These interactions arise because the elastic deformations of membranes depend on the distance between the adsorbed particles.

Our group has recently found strongly attractive elastic interactions between spherical nanoparticles adsorbed on vesicles [1]. These attractive interactions lead to bound states of the particles with a morphology that depends on the ratio of the area and volume of the vesicles, which is typically characterized by the reduced volume $v \leq 1$. The maximal value $v = 1$ of the reduced volume corresponds to the area to volume ratio of a sphere. For large values of v , nanoparticles are only partially wrapped by the vesicle since the area to volume ratio does not allow full wrapping. For such values of v , we

have found bound states in which two particles are equally wrapped by the vesicle (Fig. 1a). For smaller values of v , we have found strongly bound states in which two or more particles are cooperatively wrapped by a membrane tube that protrudes into the vesicle (Fig. 1b and c). This tubular confinement of several nanoparticles constitutes a novel route to encapsulate nanoparticles reversibly in vesicle membranes. In experiments, the amount of confined nanoparticles as well as their release may be controlled by changes in the osmotic conditions, which lead to changes in the reduced volume of the vesicles.

The wrapping and membrane-mediated interactions of the nanoparticles arise from the interplay of membrane bending and adhesion. The total energy is the sum of the bending energy of the vesicle and the overall adhesion energy of the particles. We have determined the minimum total energy of the vesicle and particles with simulated annealing Monte Carlo simulations of triangulated vesicles in contact with particles. In Fig. 2, the minimal total energy E of a vesicle with two adsorbed particles is displayed as a function of the particle distance r . At the reduced volume $v = 0.96$, the total energy $E(r)$ exhibits local minima at the contact distance $r = 2R_p$ of the particles and at a distance r between $6R_p$ and $9R_p$, separated by an energy barrier. The local minimum of E at the contact distance $r = 2R_p$ corresponds to the bound state of the particles shown in Fig. 1a in which both particles are symmetrically wrapped by the vesicle membrane. At $v = 0.92$ and 0.94 , we find additional branches of low-energy conformations with negative values of E at distances $r < 3R_p$ of the particles. In these low-energy conformations, the particles are jointly but asymmetrically wrapped by a membrane tube that invaginates into the vesicles (Fig. 1b and snapshot at bottom left of Fig. 2). In these conformations, the wrapping of the particles is asymmetric since the particle at the tip of the invagination is more strongly wrapped. Besides these low-energy conformations, we have found branches of higher-energy conformations with positive values of E in which the particles are symmetrically wrapped as in Fig. 1a. In addition, we have investigated the adhesion of membranes via adsorbed nanoparticles [4].

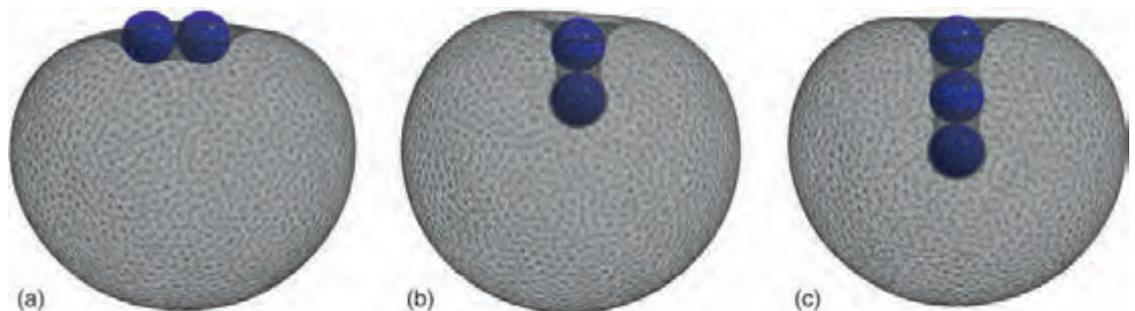


Fig. 1: (a) Bound state of two particles for the reduced volume $v = 0.96$ of the vesicle and the rescaled adhesion energy $u = U R_p^2 / \kappa$ of the particle where U is the adhesion energy per area, R_p is the particle radius, and κ is the bending rigidity of the vesicle membrane. - (b) Strongly bound state of two particles for $v=0.92$ and $u=2.33$. - (c) Strongly bound state of three particles for $v = 0.88$ and $u = 2$. In (b) and (c), the particles are jointly wrapped by a membrane tube that protrudes into the vesicle.

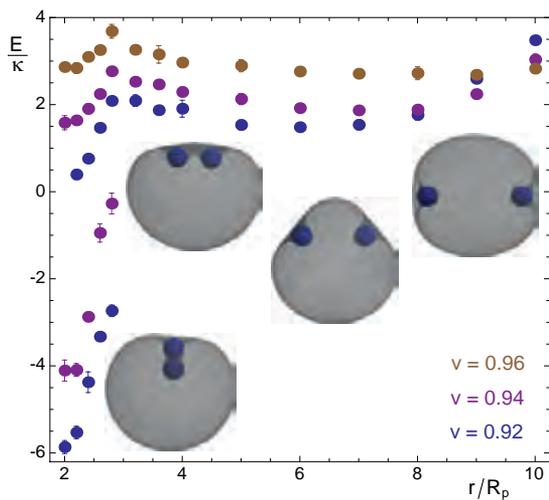


Fig. 2: Minimal total energy E of a vesicle with two adsorbed particles as a function of the particle distance r for the rescaled adhesion energy $\nu=2.33$ and the values $\nu=0.92, 0.94$, and 0.96 of the reduced volume. The minimal total energy E is given in units of the bending rigidity κ of the membrane. The particles with radius R_p are in contact at the distance $r=2R_p$. The four snapshots represent minimum energy conformations for the reduced volume $\nu=0.92$ at particle distances with $r/R_p = 2, 3.2, 6$ and 9 .

Vesicles with Multiple Lipid Domains

Multicomponent lipid vesicles with coexisting liquid-ordered and liquid-disordered domains are widely used as model system for the lipid bilayers of cells. The liquid-ordered domains have a significantly higher bending rigidity than the liquid-disordered domains. Our group has investigated the coupling of curvature and composition of vesicles that contain such domains [2]. We have modeled these vesicles as triangulated surfaces, and have determined their equilibrium morphologies with Monte Carlo simulations. The total energy of the vesicles is the sum of the overall bending energy of the vesicle and the line energy of the domains. We have found that the interplay between the bending energies of the domains and the line energy of the domain boundaries can lead to multi-domain morphologies in which the flexible liquid-disordered domains are located in more strongly curved sections of the vesicles (Fig. 3).

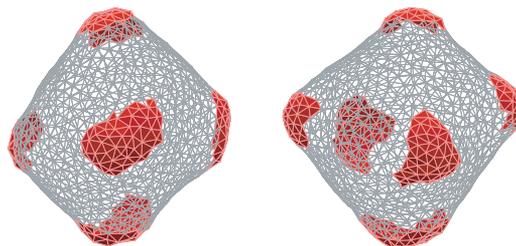


Fig. 3: Stable multi-domain morphologies of vesicles with coexisting liquid-ordered (grey) and liquid-disordered domains (red). In these morphologies, the more flexible liquid-disordered domains are located at more strongly curved 'edges' of the vesicle.

Protein Domains in Cell Adhesion Zones

Submicron scale domains of membrane-anchored receptor proteins play an important role in cell signaling. Central questions concern the stability of these microdomains, and the mechanisms leading to the domain formation. In immune-cell adhesion zones, microdomains of short receptor-ligand complexes form next to domains of significantly longer receptor-ligand complexes. The length mismatch between the receptor-ligand complexes leads to membrane deformations and has been suggested as a possible cause of the domain formation. The domain formation is a nucleation and growth process that depends on the line tension and free energy of the domains. Our group has derived general expressions for the line tension between domains of long and short receptor-ligand complexes and for the adhesion free energy of the domains with a combination of analytical calculations and Monte Carlo simulations [3]. We have found that the length mismatch of receptor-ligand complexes alone is sufficient to drive the domain formation, and have obtained submicron-scale minimum sizes for stable domains that are consistent with the domain sizes observed during immune-cell adhesion.

T. Weikl, A. H. Bahrami, J. Hu, H. Krobath, T. Stieger, G. Xu
 thomas.weikl@mpikg.mpg.de.

References:

- [1] Bahrami, A. H., Lipowsky, R., and Weikl, T. R.: Tubulation and aggregation of spherical nanoparticles adsorbed on vesicles. *Phys. Rev. Lett.* **109**, 188102 (2012).
- [2] Hu, J., Weikl, T. R., and Lipowsky, R.: Vesicles with multiple membrane domains. *Soft Matter* **7**, 6092-6102 (2011).
- [3] Krobath, H., Rozycki, B., Lipowsky, R., and Weikl, T. R.: Line tension and stability of domains in cell-adhesion zones mediated by long and short receptor-ligand complexes. *PLoS ONE* **6**, e23284 (2011).
- [4] Stieger, T., Schoen, M., and Weikl, T. R.: Adhesion of surfaces mediated by adsorbed particles: Monte Carlo simulations and a general relationship between adsorption isotherms and effective adhesion energies. *Soft Matter* **8**, 11737 (2012).

Anchored Polymers – Self-Organization & Response to Perturbations



Assembly of Nano-Particles at AB Diblock Copolymer Brushes

Polymer brushes, i.e., polymers densely anchored to an interface have received much interest because of their scientific and technological importance. Brushes consisting of incompatible components are of special interest because they exhibit phase separation on nanometer scales. Lateral segregation can lead to stable surface nano-patterns that can be used to control the organization of nano-particles (NP) into larger aggregates.

To study both the morphology of diblock copolymer brushes (DCB) and the organization of nanoparticles we use dissipative particle dynamics (DPD) simulation [1, 2]. In our model, there are five different types of DPD beads: polymer A and B blocks (A, B), solvent (S), nanoparticles (P), and wall (W). The interaction strength between these beads is set by the DPD parameters a_{ij} . Polymer chains are anchored via the ends of soluble A blocks while the solvent is poor for B blocks. Under such conditions, A blocks form stretched brushes whereas insoluble B blocks exhibit different morphologies, which depend both on solvent quality and chain composition $f_B = N_B / (N_A + N_B)$, where $N_{A,B}$ are the lengths of A and B blocks, respectively.

We performed an extensive simulation study of the morphology diagram of such polymer brushes, where the AB immiscibility and solvent selectivity are treated independently and on an equal footing [1]. Such an approach, which is a natural extension of the standard model of DCBs, seems to be necessary to obtain results that are consistent with experimental data of, e.g., polystyrene-polymethylmethacrylate brushes.

Morphological Changes Caused by B-like Nano-particles

B-like nano-particles (e.g., core particles covered by a polymer B shell) exhibit high affinity to polymer B domains. At low NP load, particles follow the various brush pattern and form ordered spherical aggregates or extended chains depending on both polymer composition f_B and NP concentration φ . With increasing φ , we observe morphological transitions of the microphase-separated DCB resulting in a shift towards structures appearing in pure DCBs only at larger f_B values (Fig. 1). Such a behavior is very similar to that previously obtained for diblock copolymer melts.

Spreading of Nano-droplets along Polymer Stripes

Considering B-unlike nano-particles we observe a strong tendency that NPs aggregate into a single, large droplet, which is mostly located on the top of a B domain. Hexagonally ordered many-droplet morphologies are only obtained for relatively weak incompatibility between nano-particles and polymer B. On the other hand, we demonstrated that spreading along B stripes can be realized if (i) the surface tension at the droplet-solvent interface is reduced and (ii) the contrast between polymer B affinities of NPs and solvent is sufficiently strong (Fig. 2) [2]. The observation of two different spreading regimes, i.e., complete spreading of NPs along B stripes

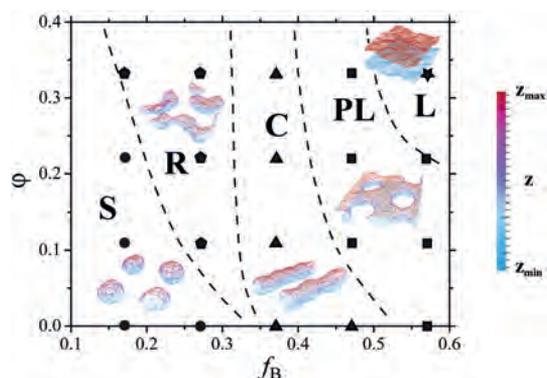


Fig. 1: Morphology diagram of AB diblock copolymer brushes mixed with B-like nano-particles in the (f_B, φ) -parameter space. The five different phases of B domains, i.e., spherical (S) and cylindrical (C) micelles, ripple-like (R), perforated (PL) and complete (L) lamella, are illustrated by characteristic snapshots where the color-coding indicates the distance from the grafting plane. Symbols indicate simulation points.

or localization into one large droplet, agrees qualitatively quite well with theoretical predictions about wetting morphologies on substrates with striped surface domains [3].

Furthermore, our study suggests a new mechanism to move nano-objects on the surface of diblock copolymer brushes. A slight change of the NP's solvophobicity can alter the equilibrium position of the droplet from the top of a B domain (Fig. 2B, g) to the valley between two neighboring domains (Fig. 2B, h). Performing additional simulations we have shown that the particular process is reversible. The new mechanism relies only on a switching of the solvophobicity of nano-particles, which, in principle, can be realized by covering them with appropriate pH-sensitive ligands.

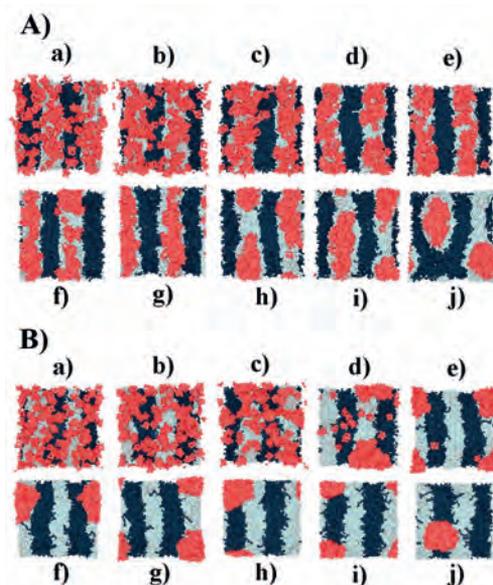


Fig. 2: Spreading of B-unlike nano-particle along B stripes for increasing insoluble NPs from $a_{PS} = 26$ (a) to 37 (j) ($f_B = 0.37$, $\varphi = 0.224$, $a_{AB} = a_{PA} = 40$). Anchored A blocks are colored dark blue, B blocks light blue and nano-particles red. A) $a_{PB} = 27$, B) $a_{PB} = 35$.

Field-regulated Force by Grafted Polyelectrolytes

During the past couple of decades, investigations of the response of charged polymers, so-called polyelectrolytes, to external electric field attracted much scientific attention. If the free end of a grafted polyelectrolyte is under load, while the chain itself is exposed to electric field that favors its adsorption, both field strength and force determine the configuration of the chain. In particular, a restoring force may arise if the chain is mechanically coupled to a deformable, nano-sized object such as another polymer chain or a colloidal particle. In that case, force and length of the bulk polymer segment pulled off from the adsorption layer are determined in a self-regulated manner.

We study the response of grafted polyelectrolytes to electrostatic fields both theoretically and by means of molecular dynamics simulations. Two strictly different setups are considered. First, we apply a constant force and analyze the length of the bulk part of the chain as a function of varying electric field (Fig. 3) [4]. Note that force is measured in units of $k_B T/b \approx k_B T/l_B \approx 6$ pN and electric field in units of $k_B T/(be) \approx k_B T/(l_B e) \approx 4 \times 10^7$ V/m, with b being the distance between charges. l_B is the Bjerrum length and e the elementary charge. Our theory is based on a detailed description of both adsorbed and bulk parts of the chain and goes beyond previous studies. Fig. 3 demonstrates quite clearly the agreement between simulation data and theory without any fitting parameter. In addition, we observe that the length of the bulk part may be fairly well estimated by a purely mechanical theory, which accounts only for force balance and yields $f = NEe$ (inset of Fig. 3). Using our theory we are able to explain the surprising accuracy of the simple mechanical approach.

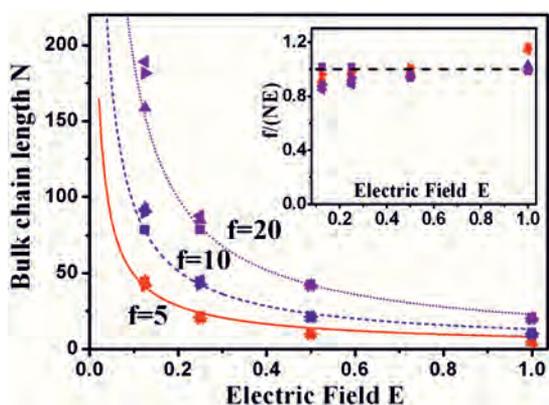


Fig. 3: Size N of the desorbed bulk part of the chain as a function of electric field E at constant pulling force $f = 5, 10,$ and 20 . (Lines – theory, symbols – simulation data.) Inset: Rescaled force $f/(NE)$ as a function of E .

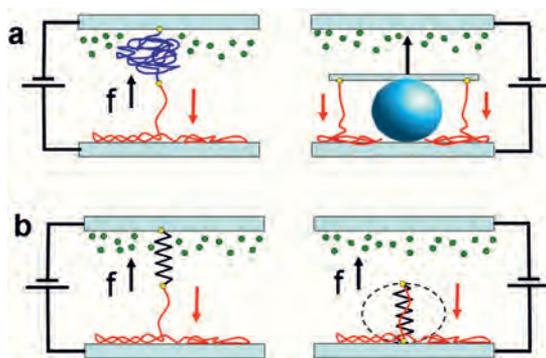


Fig. 4: (a) Two possible setups to explore field-regulated force generation. Red down arrows indicate the force generated by an electric field that favors polyelectrolyte adsorption. Black arrows show the counteracting force caused by the deformation of the linker/body. (b) The simulation setups used to model the „experimental“ ones shown in the upper panel. The free chain end is linked to linear or nonlinear springs, respectively.

In the second setup, the free end of a grafted polyelectrolyte is linked to a target body. Two different models are schematically shown in Fig. 4. The right panel demonstrates also the working principle of a possible nano-device. We consider a few target bodies with different force-deformation relations both linear and nonlinear ones [5]. Among the latter we focus on the so-called Hertzian force, which mimics the behavior of a squeezed colloidal particle. The predictions of our theory agree quantitatively with the results of the numerical simulations, while a zero-order approximation that corresponds to the purely mechanical approach yields substantial deviations (Fig. 5).

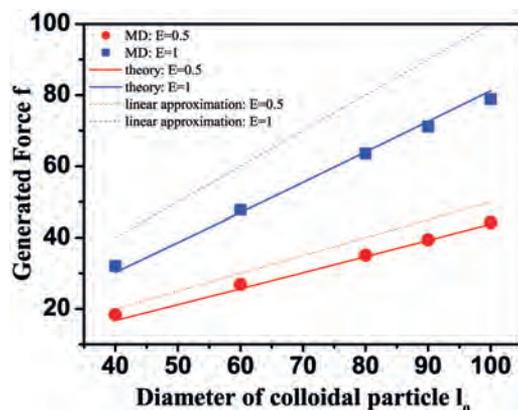


Fig. 5: The dependence of generated force f on equilibrium Hertzian spring length l_0 (size of colloidal particle). Solid lines give theoretical predictions; symbols represent simulation data while dashed lines show the results of a zero-order approximation that corresponds to the simple mechanical theory.

The project is done in collaboration with Prof. N. V. Brilliantov, University of Leicester.

C. Seidel, O. A. Guskova¹⁾
seidel@mpikg.mpg.de.

¹⁾ present address: Leibniz-Institut für Polymerforschung Dresden

References:

- [1] Guskova, O. A., Seidel, C.: Mesoscopic Simulations of Morphological Transitions of Stimuli-Responsive Diblock Copolymer Brushes. *Macromolecules* **44**, 671 (2011).
- [2] Guskova, O. A., Seidel, C.: Assembly of nano-particles on diblock copolymer brushes: toward laterally nano-structured composites. *Soft Matter* **8**, 2833 (2012).
- [3] Brinkmann, M., Lipowsky, R.: Wetting morphologies on substrates with striped surface domains. *J. Appl. Phys.* **92**, 4296 (2002).
- [4] Brilliantov, N. V., Seidel, C.: Grafted polyelectrolyte in strong electric field under load: Field-regulated force and chain contraction. *Europhys. Lett.* **97**, 28006 (2012).
- [5] Seidel, C., Budkov, Yu. A., Brilliantov, N. V.: Field-regulated force by grafted polyelectrolytes. *J. Nanoeng. Nanosyst., to appear.*

Stochastic Processes in Complex Bio-Systems



Degradation of mRNA and Translational Control

Degradation of mRNA is one of the key processes that control gene expression in the cells. Traditionally, this process has been thought to be governed by a decay rate constant. Biochemists, however, have unveiled a large number of complex mechanisms underlying mRNA degradation. In addition, several measurements of mRNA turnover have shown that mRNA decay is rarely simple. The turnover of mRNA molecules introduces new timescales that interact with the timescales of translation and of cell division. In [1] we have considered the interaction of the lifetime distribution of an mRNA species with the timescale needed by ribosomes to build a stable polysome (Fig. 1). The latter timescale is proportional to the length of the mRNA. We have found out that for very long mRNAs with a high turnover, the transient time until protein synthesis begins may be comparable with the lifetime of the mRNA thus affecting both the protein synthesis rate and the size of the polysome.

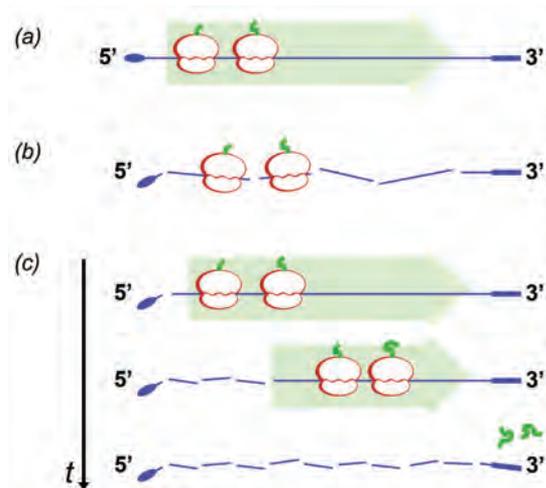


Fig. 1: Translation and degradation of mRNA. (a) Prokaryotic mRNA and (b) the effect of endonucleolytic degradation on the polysome. (c) Eukaryotic mRNA. Degradation occurs in the 5' to the 3' direction.

The analysis of experimental data from *E. coli* shows that longer mRNA produce, in general, fewer proteins than shorter mRNA if the lifetime distribution of the mRNA is short and exponential (Fig. 2).

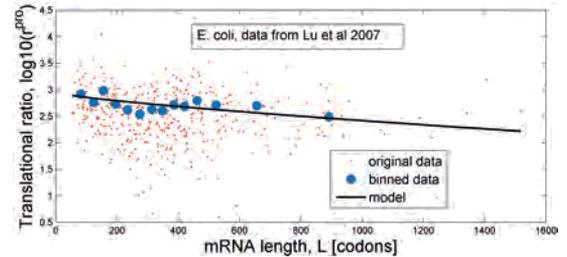


Fig. 2: The interplay between degradation and loading of the polysome can produce a negative correlation between the number of proteins per mRNA and its length.

There is also an indication that mRNA degradation may affect the spatial distribution of the ribosomes on the mRNA. This point was investigated in [2] using flux balance equations and stochastic simulations. Since the lifetime distribution of the mRNA is not exponential, in [3] we have looked at the interplay between the shape of the lifetime distribution and the timescales necessary to reach a steady state expression level (Fig. 3).

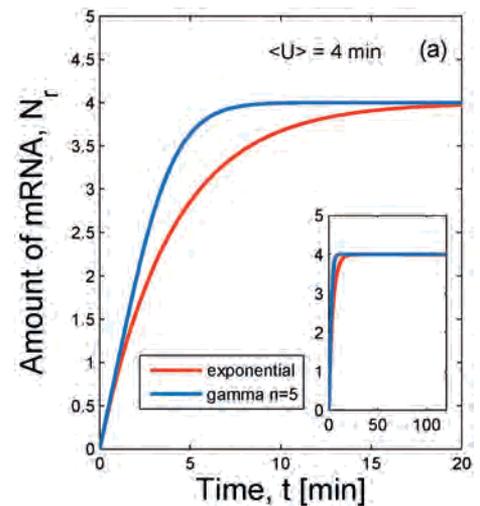


Fig. 3: Two assumptions for the mRNA lifetime distributions lead to different transient times. In *E. coli* the average mRNA lifetime is about four minutes and its cell cycle has duration of twenty minutes.

We found that mRNA characterized by broadly distributed lifetimes take longer to reach a steady state copy number so that especially in bacteria certain mRNAs may never reach a steady state copy number before cell division. In [3] we did not investigate the origin of the different lifetime distributions, a topic that was left for further investigations published in [4].

Ribosomal profiling is a new experimental technique that provides an *in vivo* picture of the translational state of the cell. With this technique one can investigate the various mechanisms of translational control, which include the initiation rate by ribosomes and the codon dependent elongation rate. One important question that we wanted to address concerns the differential translational state of organisms under different growth or stress conditions. To address this ques-

tion, in the framework of the Marie-Curie ITN “NICHE” Prof Zoya Ignatova and her lab at the University of Potsdam have worked on the ribosomal profiles of *E. coli* cell cultures under four different growth conditions. The analysis of the data produced with advanced bioinformatics tools [5], will be further statistically analyzed in a manuscript in preparation [6] to provide the most complete picture of the differential gene expression in *E. coli* so far. This data will then become a useful benchmark for modelling the interaction of ribosome with the mRNA.

Heterogeneity of Chlamy Cell Populations

Chlamydomonas reinhardtii (chlamy) is a unicellular photosynthetic alga. The cells of this organism have the special property to remain in the growth phase for a random amount of time and attain, at a population level, a relatively broad distribution of cell sizes. One consequence is that each mother cell can produce a number of daughter cells that is roughly proportional to the logarithm of its size (Fig. 4). Since cell volume is often considered as a proxy for the cellular metabolic state, one first objective has been to develop a model for the cell size distribution under time-independent conditions such as those created in some bioreactors. The model can be used to calculate and compare stationary distributions for the common binary and the multiple division processes [7]. The model has left many questions open. One biologically important question is whether the experimentally observed diversity is solely given by the stochastic nature of cell growth and division or to the heterogeneous mixture over the phases of the cell cycle. Furthermore, we wanted to investigate if the volume of the mother cells is the only determinant of the number of daughter cells.

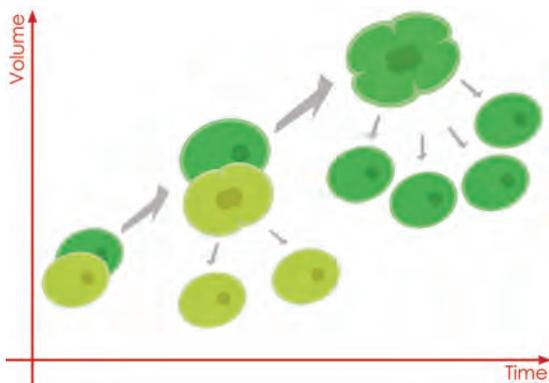


Fig. 4: Two chlamy daughter cells (bottom left) grow in time but divide at two different time points. Although the number of daughter cells is different, their sizes are very similar.

To investigate these points, Prof. Martin Steup and his lab at the University of Potsdam have performed a set of experiments with synchronized chlamy cells. The synchronization is obtained by cultivating the cells with fixed periods of light and darkness, in a growth medium that does not allow for cell growth in the darkness. Synchronization relies on the fact that, under certain general conditions, all cells would

divide after the start of the dark period and the daughter cells would start to grow only when light is turned on again. Clearly, at the beginning of each light period all the cells are in the same point of the cell cycle. The experiments showed us that DNA replication occurs stochastically during the light period according to relatively simple rules that we have been able to cast in a stochastic model of cell growth and division. The conclusion of this study [8], is that DNA replication is one major determinant of the number of daughter cells and that its stochastic nature maintains the population heterogeneous even under synchronization conditions.

Markov Chains in Biological Processes

Markov chains are a very common tool to mathematically model biological processes.

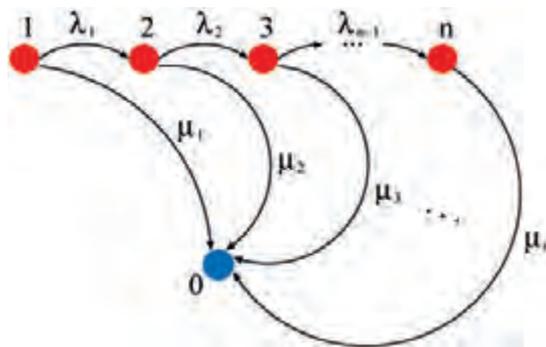


Fig. 5: The stochastic life of a single mRNA molecule is made of specific biochemical states. At each state, a transition to the next state or to absorption is possible.

The recent application of this tool in our group covers modelling the complex life time of mRNA, where each molecule undergoes several biochemical transitions until degradation takes place (Fig. 5, from Ref. [4]), and the stochastic lifetime of trabecular bones [9], within a project led by Dr. Richard Weinkamer in the Biomaterials department. We have considered also mathematical models of molecular motors. In one particularly instructive work [10], we have considered a simple model of molecular motors interacting with the fuel substrate. When the amount of fuel molecules is not constant, due to its stochastic consumption and replacement, the rate by which a motor receives the fuel varies stochastically in time. We could derive an analytical expression of the distribution of the time that a motor has to wait for a fuel molecule and found that it is not exponential. This implies that at low molecule number the law of mass action does not hold. Models of molecular motors like Kinesin have also inspired several problems in the mathematical theory of Markov chains that we have investigated in collaboration with Prof Sylvie Røelly at the Institute of Mathematics of the University of Potsdam and are going to be submitted soon [11,12].

A. Valleriani, C. Deneke, P. Keller, A. Nagar, M. Rading, S. Rudorf, C. Sin

References:

- [1] Valleriani, A., Zhang, G., Nagar, A., Ignatova, Z., Lipowsky, R. Length-dependent Translation of Messenger RNA by Ribosomes, *Phys. Rev. E* **83**, 042903 (2011).
- [2] Nagar, A., Valleriani, A., Lipowsky, R., Translation by Ribosomes with mRNA Degradation: Exclusion Processes on Aging Tracks, *J. Stat. Phys.* **145**, 1385-1404 (2011).
- [3] Deneke, C., Rudorf, S., Valleriani, A., Transient Phenomena in Gene Expression after Induction of Transcription, *PLoS ONE* **7**, e35044 (2012).
- [4] Deneke, C., Lipowsky, R., Valleriani, A., Complex degradation processes lead to non-exponential decay patterns and age-dependent decay rates of messenger RNA, *PLoS ONE* **8**, e55442 (2013).
- [5] Zhang, G., Fedyunin, I., Kirchner, S., Xiao, C., Valleriani, A., Ignatova, Z., FANSe: an accurate algorithm for quantitative mapping of large scale sequencing reads, *Nucl Acid Res* **40**, e83 (2012).
- [6] Fedyunin I., et al, „Global quantification of stress-response programs in bacteria with nucleotide resolution” in preparation
- [7] Rading, M.M., Engel, T.A., Lipowsky, R., Valleriani, A., Stationary Size Distribution of Growing Cells with Binary and Multiple Cell Division, *J Stat Phys* **145**, 1-22 (2011).
- [8] Sandmann, M., Rading, M.M., et al, Single Cell Analyses and Modelling of Growth and Division of two Synchronized *Chlamydomonas* strains, in preparation
- [9] Rusconi, M., Valleriani, A., Dunlop, J.W.C., Kurths, J., Weinkamer, R., Quantitative approach to the stochasticity of bone remodeling, *EPL* **97**, 28009 (2011).
- [10] Keller, P., Valleriani, A., Single-molecule stochastic times in a reversible bimolecular reaction, *J Chem Phys* **127**, 084106 (2012).
- [11] Keller, P., Røelly, S., Valleriani, A., A Quasi-Random-Walk to model a biological transport process, submitted for publication
- [12] Keller, P., Røelly, S., Valleriani, A., On Time Duality for a Quasi-Birth-and-Death-Processes, in preparation

Regulation of Bio-Processes



Stefan Klumpp 29.09.1973

1999: Diploma, Physics
(University of Heidelberg)

Thesis: Noise-induced transport of two coupled particles.

2003: PhD, Physics (University of Potsdam/MPI of Colloids and Interfaces, Potsdam)

Thesis: Movements of molecular motors: Diffusion and directed walks

2004-2005: Research associate
(MPI of Colloids and Interfaces, Potsdam)

2006-2009: Postdoc

(University of California, San Diego)

since 2009: Group leader
(MPI of Colloids and Interfaces, Potsdam)

Physical processes and interactions constrain the space of possible designs of biological systems. In addition, however, biological processes also underlie functional requirements and are the result of evolutionary selection. Our group is interested in the interplay of physical and biological forces in complex living systems, with a focus on regulatory processes, mostly in bacterial systems. We address these issues in three interrelated areas of research: (i) Molecular machines, (ii) genetic circuits, and (iii) cellular dynamics. Our main interest is in characterizing how generic physical processes enable, constrain and shape biological systems and how biological systems make use of these processes or circumvent them towards specific functions. Understanding these issues is also expected to provide theoretical guidance for applications in bioengineering and synthetic biology.

Molecular Machines

Cells contain billions of molecular machines that perform a huge variety of functions from catalysis in metabolism to processing the genetic information. Complex behaviour of such machines can arise both at the level of the properties of individual molecules and at the level of assemblies of multiple molecules [1]. Currently, we focus on the machines that read out the genetic information, RNA polymerases and ribosomes. Important features of these machines are proofreading mechanisms to increase their accuracy. For individual molecules, there is typically a trade-off between accuracy and speed of the read-out. Additional issues arise when many such machines process the same gene. For example, RNA polymerases have to move backward for proofreading. A trailing RNA polymerase can block this backward movement and may thus interfere with the proofreading process. If the negative effect is to be contained below a certain threshold, proofreading has to be faster than the arrival of a trailing RNA polymerase. This requirement provides a constraint on the dynamics not present for individual molecules [2].

In addition to studying the mechanisms of these machines, we are interested in the economic principles that underlie their use in cells. This line of research addresses aspects such as the number of these machines present in the cell,

their distribution in space, their allocation to different functions, as well as their costs and benefits for the cell. An intriguing observation in this respect is that ribosomes seem to be far more costly to the cell than RNA polymerases. The cost of ribosomes reflects the intimate coupling of the cell's ribosome content and cell growth (synthesis of biomass and proliferation), which in turn is one of the main determinants of fitness. A consequence of the fact that ribosomes represent costly investments for the cell is that using them efficiently represents a fitness advantage. One mechanism to achieve this is the usage of 'fast codons': The genetic code encodes most amino acids by several nucleotide triplets (codons), but synonymous codons may not be read out with the same rate. The use of a codon that is read out slowly incurs a fitness cost to the cell through the inefficient use of ribosomes. This fitness cost depends on how frequently the particular codon is read out. As a consequence, sequences of abundant proteins are more biased towards fast codons. We have analysed a quantitative evolution model based on this 'ribosome load' idea and derived a simple relation between the frequency of slow codons in a sequence and the abundance (copy number in the cell) of the corresponding protein [3]. This relation provides a simple quantitative estimate of protein abundance from sequence data alone (Fig. 1).

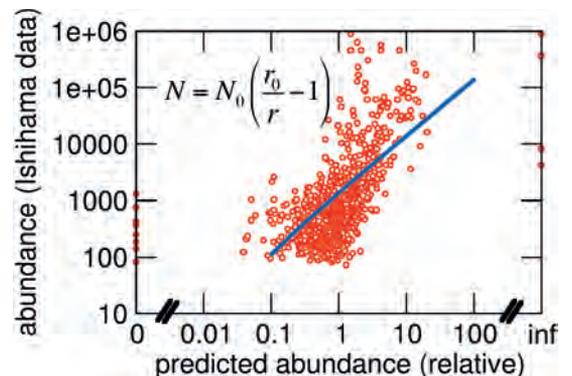


Fig. 1: Protein abundance predicted from genomic sequences: Relation between fraction of slow codons (r) and protein abundance (N) and correlation between predicted and measured abundance for *E. coli* [3].

Gene Regulation and Genetic Circuits

The readout of individual genes is tightly regulated in response to intracellular and external signals. Networks of genes regulating each other (via their protein products) are often compared to electronic circuits where complex functions arise from combinatorics with a limited set of basic components. This analogy is the basis for the design of synthetic gene circuits, which are then implemented on a cellular 'chassis'. However, unlike in electronics, the chassis here (the host cell) is itself a dynamic and adaptive object and the circuits are not isolated from the chassis to which they are coupled through sharing of metabolites and molecular machinery. As a consequence, changes in the state of the cell as a whole may affect individual circuits that are nominally unrelated to host cell functions. One specific example, which we have analysed recently, is the dependence of plasmid copy number on the growth rate of the host cell (Fig. 2). Such dependence affects the expression of all genes on the plasmid including those controlling plasmid replication, and thus its copy number. We have shown that information on such growth-rate dependencies can be used to obtain information about the design of the control system of plasmid replication [4]. A related issue is the systematic variation of protein concentrations that arises from the division cycle of the host cell. This variation provides a deterministic contribution to the observed 'noise' in protein synthesis [5].

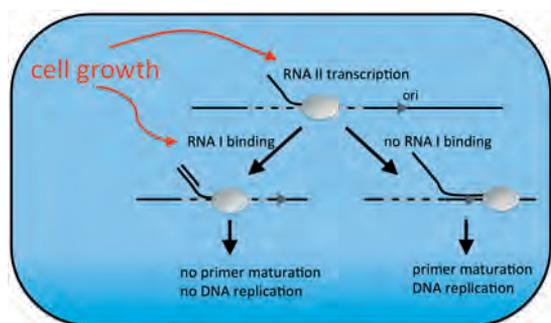


Fig. 2: Control systems of plasmid replication: Whether or not a plasmid is replicated depends on binding of a regulatory RNA (RNA I) to the replication primer (RNA II). The growth state of the host cell affects the concentrations of both RNAs.

Cellular Dynamics

In our third research area, we study the dynamics of structure formation in cells and the movements of cells. Recently we have focused on magnetotactic bacteria, in collaboration with the group of D. Faivre (Department Biomaterials). Magnetotactic bacteria orient in a magnetic field based on a chain of organelles called magnetosomes that contain magnetic nanoparticles. The magnetosome chain acts as a cellular compass needle. Magnetotactic bacteria provide an excellent model system to study what role generic physical interactions (magnetic attraction and repulsion) have in a specific biological context and how they are integrated with more specific biological mechanism. In a first project, we have studied the formation of the magnetosome chain. We developed a computer simulation based on experimental data for chain formation in iron-starved cells (Fig. 3). Our main question was whether the magnetic interactions between the magnetosomes are sufficient to induce chain formation. Simulations allow us to study 'in-silico mutants' defective not in individual genes, but in entire physical processes (i.e. non-magnetic mutants), which may be hard or impossible to obtain by experimental mutagenesis. The results of these simulation show that the magnetic interactions alone are not sufficient to explain the experimental observations. Rather we find that robust chain formation requires the interplay of magnetic interactions and controlled active transport [6]. Other topics we are currently addressing are the interactions of these bacteria with external magnetic fields and various modes of bacterial motility.

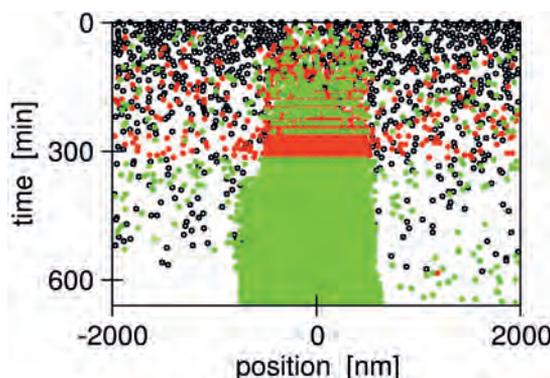


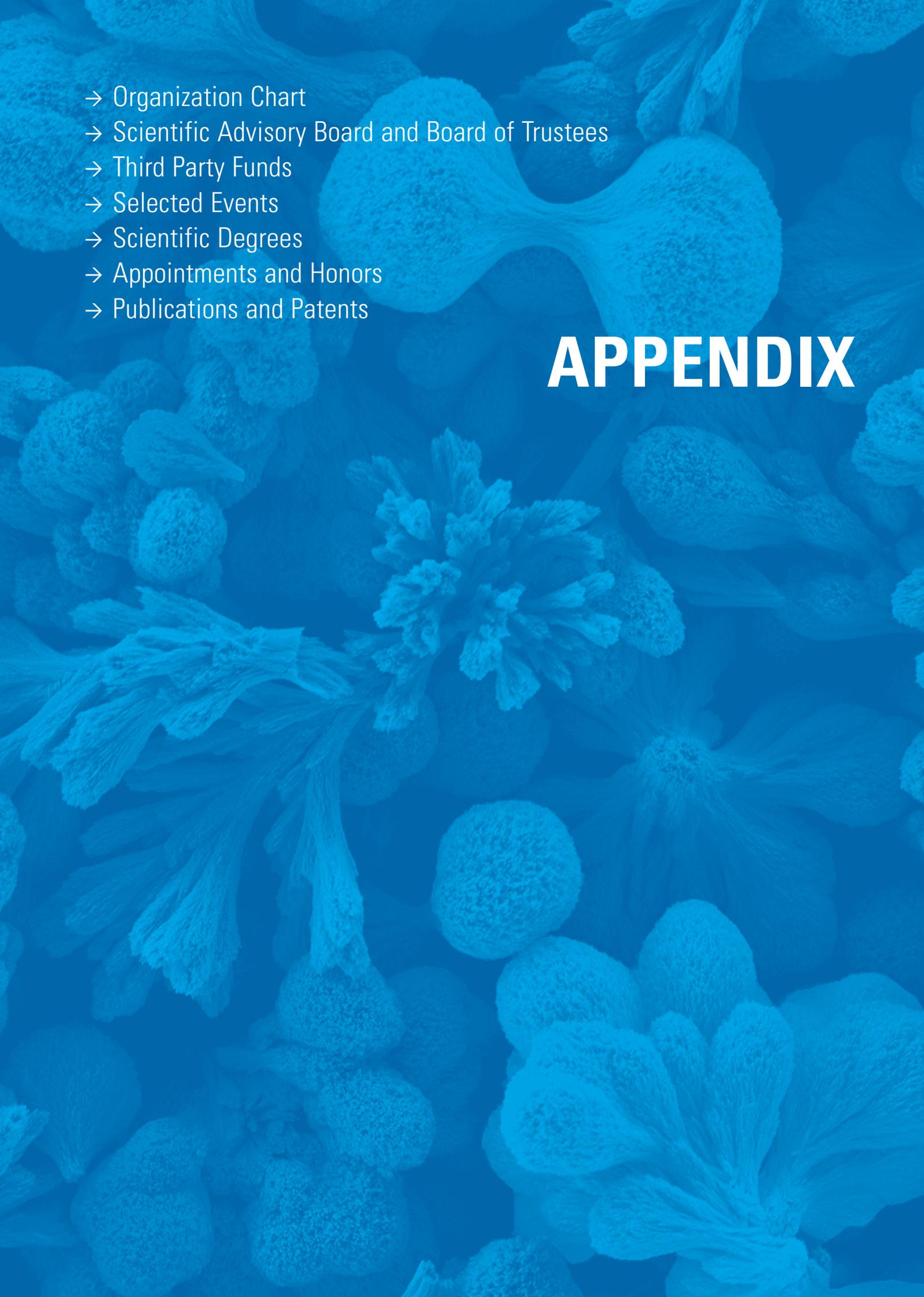
Fig. 3: Simulation of the formation of a magnetosome chain [6]: Initially non-magnetic magnetosomes (black) develop a magnetic nanoparticle (red or green indicate different directions of the magnetic moment) and align in the center of the cell with uniform magnetization.

References:

- [1] Klumpp, S., Mechanisms and economy of molecular machines, *Phys. Scr.* **T151**, 014066 (2012).
- [2] Sahoo, M., Klumpp, S., Transcriptional proofreading in dense RNA polymerase traffic, *EPL* **96**, 60004 (2011).
- [3] Klumpp, S., Dong, J. J., Hwa, T., On ribosome load, codon usage and protein abundance, *PLoS One* **7**, e48542 (2012).
- [4] Klumpp, S., Growth-rate dependence reveals design principles of plasmid copy number control, *PLoS One* **6**, e20403 (2011).
- [5] Marathe, R., Bierbaum, V., Gomez, D., Klumpp, S., Deterministic and stochastic descriptions of gene expression dynamics, *J. Stat. Phys.* **148**, 607-626 (2012).
- [6] Klumpp, S., Faivre, D., Interplay of magnetic interactions and active movements in the formation of magnetosome chains, *PLoS One* **7**, e33562 (2012).

S. Klumpp, V. Bierbaum, M. Faber, D. Gomez, M. Hintsche, R. Marathe, M. Mauri, M. Sahoo, P. Patra
klumpp@mpikg.mpg.de



- 
- Organization Chart
 - Scientific Advisory Board and Board of Trustees
 - Third Party Funds
 - Selected Events
 - Scientific Degrees
 - Appointments and Honors
 - Publications and Patents

APPENDIX

Organigramm

Organization Chart

Biomaterials Director: Prof. Dr. Dr.h.c. Peter Fratzl · Personal Assistant: Kerstin Gabbe

- Biomimetic Actuation and Tissue Growth/Dr. John Dunlop
- Plant Material Adaptation/Dr. Michaela Eder
- Molecular Biomimetics and Magnet Biomineralization/Dr. Damien Faivre
- Biochemical Strategies in Load-Bearing Natural Materials/ Dr. Matthew Harrington
- Biological Chitin-Based Tools and Sensors/Dr. Yael Politi
- Hierarchical structure of biological and biomimetic materials/Dr. Wolfgang Wagermaier
- Mechanobiology/Dr. Richard Weinkamer

- Independent Researchers**
- Water Interactions in Complex Biological Materials/Dr. Luca Bertinetti
 - Evolutionary Perspectives on Vertebrate Hard Tissues/Dr. Mason Dean
 - Synthesis and Thermodynamic Stability of Amorphous Minerals/Dr. Wouter Habraken
 - Advanced Raman Spectroscopic Imaging of Biological Tissues/Dr. Admir Masic
 - In-Situ Mechanical Characterization of Internal Interfaces in Biomaterials/Dr. Igor Zlotnikov

Biomolecular Systems Director: Prof. Dr. Peter H. Seeberger · Personal Assistant: Dorothee Böhme

- Carbohydrate Chemistry**
- Synthetic Vaccines/Prof. Peter H. Seeberger
 - Glycosaminoglycans/Prof. Peter H. Seeberger
 - GPI and Glycoproteins/Dr. Daniel Varón Silva
 - Automated Systems/Prof. Peter H. Seeberger

- Glycobiology**
- Glycobiology of Infection Diseases /Prof. Peter H. Seeberger
 - Glycobiology of Microbe/Host Interaction/Dr. Chakkumkal Anish
 - Polymeric Biomimetics (Emmy Noether Nachwuchsgruppe)/Dr. Laura Hartmann
 - Glycoproteomics/Dr. Daniel Kolarich
 - Glycoimmunology/Dr. Bernd Lepenies
 - Microreactors as Tools for Organic Chemistry/Prof. D. Tyler McQuade
 - Structural Glycobiology/Dr. Christoph Rademacher
 - Nanoparticles and Colloidal Polymers/Prof. Peter H. Seeberger

- Vaccine Development**
- Synthetic Carbohydrates Vaccines/Dr. Claneley L. Pereira, Prof. Peter H. Seeberger

Colloid Chemistry Director: Prof. Dr. Dr. h.c. Markus Antonietti · Personal Assistants: Annette Pape and Carolin Nuglich

- Heterophase Polymerization**
- Heterophase Polymerizations/Dr. Klaus Tauer

- Self-organizing Polymers**
- Bioinspired Polymers und Block Copolymers/Dr. Helmut Schlaad
 - Porous Polymers: Sustainable Synthesis and Advanced Characterization/Dr. Jens Weber
 - Biorefinery/Dr. Davide Esposito

- Mesoporous Materials and Nanoparticles**
- Sustainable Materials for Energy Storage, Catalysis and Separation Science /Dr. Maria-Magdalena Titirici
Since January 2013 Reader in Materials Science at the Queen Mary University of London
 - De Novo Nanoparticles: Novel synthetic routes for nanoparticle production/Dr. Christina Giordano/Dr. Tristan Corbiere
 - Organic Energy Polymers/Dr. Filipe Vilela

- Modern Techniques of Colloid Analysis**
- Electron Microscopic Studies of Colloidal Systems and Biomaterials/Dr. Jürgen Hartmann
 - Poly(ionic liquid)s: Synthesis and Materials Application/Dr. Jiayin Yuan
 - Electrochemical Energy Materials/Dr. Tim-Patrick Fellingner
 - Artificial Photosynthesis/Dr. Dariya Dontsova

Managing Director (2011-2012)

Prof. Dr. Peter H. Seeberger

Interfaces Director: Prof. Dr. Dr. h.c. Helmut Möhwald · Personal Assistant: Stefanie Riedel

- (Quasi) Planar Interfaces - Fluid Interfaces**
 - Interactions in Complex Monolayers/Dr. Gerald Brezesinski
 - Thermodynamics, Kinetics and Rheology of Interfacial Layers/Dr. Reinhard Müller
- Solid Interfaces**
 - Phase Transitions and Transport Phenomena at Solid/Air Interfaces/Dr. Hans Riegler
- Non-Planar Interfaces**
 - Functional Supramolecular Organizes/Prof. Helmut Möhwald
 - Active Interfaces and Coatings/Dr. Dmitry Shchukin
Since May 2013 Professor at the Stephenson Institute for Renewable Energy at the University Liverpool
 - Optical Manipulation of Capsules and Films/Dr. Andre Skirtach
Since October 2012 Professor at the Faculty of Bioscience Engineering, Universiteit Gent
- International Joint Laboratories**
 - Laboratoire Européen Associé (LEA) on Sonochemistry/Dr. Dmitry Shchukin, Prof. Helmut Möhwald

Theory & Bio-Systems Director: Prof. Dr. Reinhard Lipowsky · Personal Assistant: Susann Weber

- Biophysics Lab/Dr. Rumiana Dimova
- Molecular Dynamics/Dr. Volker Knecht
Since November 2012 Akademischer Rat with Gerhard Stock in Biomolecular Dynamics Group, Institute of Physics, Albert Ludwigs University, Freiburg
- Multiscale Modelling/Dr. Andrea Grafmüller
- Proteins and Membranes/Dr. Thomas Weikl
- Carbohydrates and Polysaccharides/Dr. Mark Santer
- Polymers and Polyelectrolytes/Dr. Christian Seidel
- Stochastic Processes in Complex and Biological Systems/Dr. Angelo Valleriani
- Regulation of Bio-Processes/Dr. Stephan Klumpp

Administration/Other Services

Head: Andreas Stockhaus
Personal Assistant: Angelina Schneider

Operating Technology (Campus)

Head: Heiko Jung

Budgeting/Accountancy

Head: Karin Schönfeld
Thea Dumke, Anke Klein,
Drittmittel: Birgit Gölke, Stefanie Riedel,
Ulrike Schell, Nadine Stolz

Personnel

Head: Heike Kienert
Judith Hoyer, Janice Sommer
Apprentice: Stefanie Ebschner

Procurement/Purchase

Head: Katharina Zesch
Sylvia Ost, Anika Becke

Other Services

Head: Andreas Stockhaus
Olaf Gaida, Bodo Ryschka

Location Manager

Reina Schlender

Works Council

The Equal Opportunities Commissioners

The Ph.D. Students Representatives

IT-Service Group

Head: Roy Pfitzner
Michael Born, Christian Büttner,
Marco Ehlert, Ingo Fiedler, Frank Seidel
Apprentice: David Schetter

Public Relations

Katja Schulze

Library

Head: Dorothea Stscherbina
Silke Niehaus-Weingärtner

Mechanic Workshop

Head: Günter Haseloff
Marco Bott, Andreas Kretzschmar,
Jan von Szada-Borzyzkowski

Electronic Workshop

Klaus Bienert, Henryk Pitas

Glass Blowing Workshop

Cliff Janiszewski

Building Services

Head: Heiko Jung
Hagen Hannemann, Christian Mating, Dirk Nast,
Marco Stetzmann, Thomas Vogt

Caretaker

Head: Olaf Gaida

Fachbeirat Scientific Advisory Board

Name	Institution
Prof. Dr. Colin D. Bain	Department of Chemistry (University of Durham)
Prof. Dr. Kurt Binder	Institut für Physik (Johannes- Gutenberg-Universität Mainz)
Prof. Dr. Matthias Drieß	Institut für Chemie (Technische Universität Berlin)
Prof. Dr. Ruth Duncan	Welsh School of Pharmacy (Cardiff University)
Prof. Dr. Michael Grunze	Physikalisch-Chemisches Institut (Universität Heidelberg)
Prof. Dr. Rüdiger Iden	BASF SE Aktiengesellschaft (Ludwigshafen)
Prof. Dr. George Jeronimidis	School of Construction Management and Engineering (The University of Reading)
Prof. Dr. Michael Klein	Department of Chemistry (University of Pennsylvania)
Prof. Dr. Deborah Leckband	Department of Chemical & Biomolecular Engineering (The University of Illinois at Urbana Champaign)
Prof. Dr. Thisbe K. Lindhorst	Otto Diels-Institut für Organische Chemie (Christian-Albrechts- Universität zu Kiel)
Prof. Dr. Michael Schick	Department of Physics (University of Washington)
Prof. Dr. Viola Vogel	Biologisch-Orientierte Materialwissenschaften (Eidgenössische Technische Hochschule Zürich)
Prof. Dr. Stephen Weiner	Department of Structural Biology (Weizmann Institute of Science)

Kuratorium Board of Trustees

Name	Institution
Prof. Dr. rer. nat. Ulrich Buller	Mitglied des Vorstands der Fraunhofer-Gesellschaft
Prof. Dr. Dr. h. c. Rolf Emmermann	Stellvertretender Kuratoriumsvorsitzender, GeoForschungsZentrum Potsdam (HGF)
Prof. Dr. Detlev Ganten	Kuratoriumsvorsitzender, Vorsitzender des Stiftungsrats der Stiftung Charité und Präsident des World Health Summits, Charité- Universitätsmedizin Berlin
Norbert Glante	Mitglied des Europäischen Parlaments
Jann Jakobs	Oberbürgermeister der Landeshauptstadt Potsdam
Dr. Wilhelm Krull	Generalsekretär der VolkswagenStiftung
Prof. Dr.-Ing. Dr. Sabine Kunst	Ministerin für Wissenschaft, Forschung und Kultur des Landes Brandenburg
Dr. rer. nat. Stefan Marcinowski	ehemaliges Vorstandsmitglied der BASF SE
Dr. Wolfgang Plischke	Vorstandsmitglied der Bayer AG
Prof. Dr. rer. nat. Frieder W. Scheller	Kompetenzzentrum Mentoring, Fraunhofer-Institut für Biomedizinische Technik
Prof. Dr. Robert Seckler	Vizepräsident für Forschung und Wissenschaftlichen Nachwuchs an der Universität Potsdam

Drittmittelprojekte

Third Party Funds

Öffentliche Zuwendungsgeber

Zuwendungs- geber	Thema	Projektleiter	Bewilligungszeitraum	Zusammenarbeit mit
BMBF	Bionik (2): Faserverbundwerkstoffe mit graduellen Matrixübergängen; Teilprojekt 1	Dr. Burgert BM	01.05.2008-30.04.2011	Albert-Ludwigs-Universität Freiburg Universität Bayreuth, Institut für Textil- und Verfahrenstechnik Denkendorf
BMBF	GoFORSYS - Potsdam-Golm BMBF - FORschungs- einrichtung zur SYStembiologie, Photosynthesis and Growth: A Systems Biology-based Approach	Prof. Lipowsky Dr. Valleriani TH	01.06.2006-31.12.2011	MPI für Molekulare Pflanzen- physiologie, Potsdam
BMBF	Nanoskalige Hohlstrukturen mit eingebetteten Gastmolekülen für neue aktive Korrosionsschutz- Systeme	Dr. Shchukin GF	01.05.2007-30.04.2011	Capsulation NanoScience AG Berlin PlasmaChem GmbH, Berlin EADS Deutschland GmbH, München BASF Coatings GmbH, Münster
BMBF	Nachwuchsgruppe Glykobiotechnologie: Malaria- Untersuchung der Erythrozytheninvasion und der schweren Pathologie	Dr. Anish BS	01.04.2009-31.03.2014	
BMBF	Nachwuchsgruppe Glykobiotechnologie: Funktion der C-Typ Lektinrezeptoren (CLRs) bei der Modulation der	Dr. Lepenies BS	01.02.2009-31.12.2013	Bernhard-Nocht-Institut für Tropenmedizin, Hamburg Universität Regensburg Technische Universität München Universität Würzburg
BMBF	Verbundprojekt: Nanostrukturen zur Lichtinduzierten Wasserstoffentwicklung (H ₂ -NanoSolar)	Prof. Antonietti Dr. Thomas KC	01.09.2009-31.08.2012	Helmholtz-Zentrum Berlin für Materialien und Energie GmbH (HZB), Berlin Technische Universität Darmstadt Universität Augsburg Universität Ulm (UU)
BMBF	Verbundvorhaben: Dream Reactions-Stoffliche CO ₂ -Verwertung	Prof. Antonietti KC	01.03.2009-29.02.2012	Bayer Technology Services GmbH, Leverkusen Technische Universität Dortmund Leibniz-Institut für Katalyse e.V. an der Universität Rostock Forschungszentrum Karlsruhe GmbH Rheinisch-Westfälische Technische Hochschule Aachen Technische Universität Darmstadt

BM – Abteilung Biomaterialien/Department of Biomaterials
 BS – Abteilung Biomolekulare Systeme/Department of Biomolecular Systems
 GF – Abteilung Grenzflächen/Department of Interfaces
 KC – Abteilung Kolloidchemie/Department of Colloid Chemistry
 TH – Abteilung Theorie & Bio-Systeme/Department of Theory & Bio-Systems

BMBF

Zuwendungs- geber	Thema	Projektleiter	Bewilligungszeitraum	Zusammenarbeit mit
BMBF	Verbundprojekt: Spitzenforschung und Innovation in den neuen Ländern-Das Taschentuchlabor: Impulszentrum für Integrierte Bioanalyse (IZIB)	Prof. Seeberger BS	01.10.2009-30.09.2014	Fraunhofer-Gesellschaft zur Förderung der angewandten Forschung e.V. (FhG), München Universität Potsdam Charité-Universitätsmedizin Berlin Helmholtz-Zentrum für Infektionsforschung GmbH, Braunschweig Ruhr-Universität Bochum IDM Institut für Dünnschichttechnologie und Mikrosensorik e.V., Teltow Technische Fachhochschule Wildau MicroDiscovery GmbH, Berlin BST Bio Sensor Technologie GmbH, Berlin Congen Biotechnologie GmbH, Berlin Scienion AG, Dortmund Poly-An Gesellschaft zur Herstellung von Polymeren für spezielle Anwendungen und Analytik mbH, Berlin
BMBF	Fortführung der experimentellen und theoretischen Untersuchung zur Bildung und Deformation von Einzeltropfen als Modell für Schäume und Emulsionen sowie Begleitung der FASES-Experimente auf der ISS	Dr. Miller GF	01.07.2009-30.06.2011	IENI, Genua, Italien Université Aix-Marseille Université Compiègne, France Universität Complutense Madrid Universität Florenz IPF, Dresden Aristotele Universität Thessaloniki
BMBF	Verbundprojekt: Spitzenforschung und Innovationen in den neuen Ländern-Light2Hydrogen - Energie für die Zukunft - Photokatalytische Spaltung von Wasser zu Wasserstoff -TP2	Prof. Antonietti KC	01.11.2009-31.10.2014	Leibniz-Institut für Katalyse e.V. an der Universität Rostock Leibniz-Institut für Plasmaforschung und Technologie e.V. (INP), Greifswald Technische Universität Berlin Helmholtz-Zentrum Berlin für Materialien und Energie GmbH (HZB), Berlin Fachhochschule Stralsund Universität Rostock
BMBF	Dynamik und Rheologie komplexer Oberflächenschichten und dünner flüssiger Filme	Prof. Vollhardt GF	01.06.2011-31.05.2013	
A.v.H.	Max-Planck-Forschungspreis 2008: Biological and Biomimetic Materials	Prof. Fratzl BM	01.09.2008-31.08.2013	Ludwig Boltzmann Institute of Osteology, Vienna, Austria Harvard University, Department of Chemistry and Chemical Biology, USA University of California at Santa Barbara, USA Weizmann Institute of Science, Rehovot, Israel Montanuniversität Leoben, Austria Institut National Polytechnique de Grenoble, France Department of Materials Science, Technion, Haifa, Israel

BMBF

Zuwendungs- geber	Thema	Projektleiter	Bewilligungszeitraum	Zusammenarbeit mit
BMBF	SOHyb: Keimbildungsinduzierte Selbstorganisation zur Strukturierung organischer Hybridsolarzellen	Dr. Riegler GF	01.11.2008-30.04.2012	Helmholtz-Zentrum Berlin für Materialien und Energie GmbH Chemtec Leuna Fraunhofer-Institut für Angewandte Polymerforschung, Potsdam Justus-Liebig-Universität, Gießen
BMBF	Verbundprojekt: Molekulare Pathologie der Osteoporose (OsteoPath)	Prof. Fratzl Dr. Wagermaier BM	01.06.2010-31.05.2013	Ludwig Boltzmann Gesellschaft, Ludwig Boltzmann Institut für Osteologie, Wien
BMBF	ForMaT2: Intelligente Nanobehälter für selbstheilende Antikorrosionsbeschichtungen	Dr. Shchukin GF	01.12.2010-31.07.2013	EADS Deutschland GmbH, München Volkswagen AG, Wolfsburg Mankiewicz Gebr & Co. (GmbH & Co. KG), Hamburg BASF Coatings AG, Münster Chemetall GmbH, Frankfurt am Main Lankwitzer Lackfabrik GmbH, Berlin Ludwig Boltzmann Gesellschaft, Ludwig Boltzmann Institut für Osteologie, Wien
BMBF	Tropfen-Schäume-Emulsionen III	Dr. Miller GF	01.06.2011-30.04.2014	Deutsches Zentrum für Luft- und Raumfahrt e.V. (DLR) Raumfahrt Agentur
BMBF	WoodWisdom-Net: WOP-Wood Supply	Dr. Eder BM	01.02.2012-31.01.2015	University of Helsinki, Finnland Swedish University of Agricultural Sciences, Umea, Sweden
BMBF	Zentrales Innovationsprogramm Mittelstand (ZIM)	Dr. Lepenies BS	01.10.2011-30.09.2013	Analyticon Discovery GmbH, Potsdam, Germany

Länder

MWFK / LASA Brandenburg GmbH	Verbundforschung Biokohle Brandenburg - Herstellung und Verwendung von Biokohle aus hydrothermalen Karbonisierung	Prof. Antonietti KC	01.02.2009-05.12.2011	Fachhochschule Eberswalde
------------------------------------	---	------------------------	-----------------------	---------------------------

EU

EU	Novel Nanocomposites for Hydrogen Storage Applications (NanoHy)	Prof. Möhwald Dr. Shchukin GF	01.01.2008-30.09.2011	Forschungszentrum Karlsruhe, Consiglio Nazionale delle Ricerche, Rom, CNRS; ParisFutureCarbon GmbH, Bayreuth Institut for energiteknikk, Norwegen National Center for Scientific Research "Demokritos", Griechenland Universität Oslo
----	---	-------------------------------------	-----------------------	---

EU

Zuwendungs- geber	Thema	Projektleiter	Bewilligungszeitraum	Zusammenarbeit mit
EU	Multi-Level Protection of Materials for Vehicles by "smart" Nanocontainers (MUST)	Prof. Möhwald Dr. Shchukin GF	01.06.2008-30.09.2012	EADS Deutschland GmbH; Universidade de Aveiro, Portugal; Stiftelsen Sintef, Norwegen; Universität Paderborn; Mankiewicz Gebr.&Co. GmbH & Co KG, Hamburg; Bayer Technology Services GmbH, Leverkusen; National Center for Scientific Research "Demokritos", Griechenland; Sika Technology AG, Schweiz; Instytut Katalizy i fizykochemii Powierzchni, Polska Akademia Nauk, Krakau; Steinbeis Advanced Risk Technologies GmbH, Stuttgart; Instituto Superior Tecnico, Lissabon; Centro Recherche Fiat SCPA, Italien; RE-TURN AS, Norwegen; Varnish SRL, Italien Daimler AG, Stuttgart; Chemetall GmbH, Frankfurt/M.; Helsingin Yliopisto, Finnland; European Virtual Institute on Knowledge-based Multifunctional Materials AISBL, Belgien
EU	Carbohydrate Multivalent Systems as tools to study Pathogen interaction with DC-Sign (Carmusys)	Prof. Seeberger BS	01.01.2009-31.12.2012	Agencia Estatal Consejo Superior De Investigaciones Cientificas (CSIC), Spain; Universita Degli Studi Di Milano (UNIMI), Italy; Centre National De La Recherche Scientifique (CNRS), France; Fundación Para La Investigación Biomédica del Hospital Universitario "Doce de Octubre", Spain; The Chancellor, Masters and Scholars of the University of Oxford, United Kingdom; Vysoka Skola Chemicko-Technologicka V Praze, Czech Republic; Vereniging Voor Christelijk Hoger Onderwijs Wetenschappelijk Onderzoek En Patientenzorg, Netherlands; Anterio Consult & research GmbH, Germany; DC4U, Netherlands; Institut National De La Sante Et De La Recherche Medicale, France; Vrije Universiteit Medisch Centrum, Niederlande; Universite Joseph Fourier Grenoble, Frankreich
EU	Probing Molecular Recognition of the Avian and Human Influenza Virus (GlycoFlup)	Prof. Seeberger BS	01.03.2009-30.09.2010	
EU	Vesicle formation driven by ESCRT (endosomal sorting complex required for Transport) (vesicle ESCoRT)	Dr. Valleriani TH	15.10.2009-14.09.2012	National Institute of Diabetes and Digestive and Kidney Diseases, National Institutes of Health, USA

EU

Zuwendungs - geber	Thema	Projektleiter	Bewilligungszeitraum	Zusammenarbeit mit
EU	Development of carbohydrate array technology to systematically explore the functional role of glycans in healthy and diseased states (EuroGlycoArrays)	Prof. Seeberger BS	01.09.2008-31.08.2012	The University of Manchester, United Kingdom; Centre National de la Recherche Scientifique, Paris, France; Universität für Bodenkultur Wien, Austria; Eidgenössische Technische Hochschule Zürich, Switzerland; The University of Reading, United Kingdom; Deutsches Krebsforschungszentrum, Heidelberg, Germany; Stockholms Universitet, Sweden; Centre for Cooperative Research in Biomaterials -CIC biomaGUNE, San Sebastian, Spain; Universität Bayreuth, Germany; Shemyakin & Ovchinnikov Institute of Bioorganic Chemistry, Moscow, Russia; Imperial College of Science, Technology and Medicine, London, United Kingdom; University of Zagreb, Kroatien; University of Copenhagen, Denmark; GALAB Laboratories GmbH, Geesthacht, Germany; Ludger Ltd., Abingdon, United Kingdom; National Institute for Bioprocessing Research and Training Ltd., Dublin, Ireland
EU	Biomimetic and Biomimetic Magnetic Nanoparticles for Magnetic Resonance Imaging (Bio2MaN4MRI)	Prof. Fratzl Dr. Faivre BM	01.09.2011-31.08.2014	Panon Egyetem, Hungary Latvijas Universitate, Riga, Latvia Nanopet Pharma GmbH, Berlin, Germany Ludwig-Maximilian-Universität, München, Germany Ludwig Boltzmann Gesellschaft Österreichische Vereinigung zur Förderung der Wiss. Forschung Eidgenössische Technische Hochschule Zürich, Zürich, Switzerland
EU	Biomimetic Membrane Systems (BIOMIMEM)	Prof. Brezesinski GF	01.03.2011-28.02.2014	Universite Claude Bernard Lyon 1, Villeurbanne, France
EU	Nanoparticle development for molecular imaging and drug delivery (Nanomedicine/Imaging)	Prof. Seeberger BS	01.09.2011-31.08.2013	
EU	Design of Photocontrollable Polyelctrolyte-Based Nanoengineered Container Systems (PHOTOCONTROL)	Prof. Möhwald Dr. Shchukin GF	01.04.2011-30.03.2012	Instytut Katalizy i fizykochemii Powierzchni, Polska Akademia Nauk (ICSC), Krakau Belarusian State Universtiy (BSU), Minsk

EU

Zuwendungs- geber	Thema	Projektleiter	Bewilligungszeitraum	Zusammenarbeit mit
EU	Quantitative Glycomics and Glycoproteomics for Biomarker Discovery (Glycoproteomics)	Dr. Kolarich BS	01.09.2011-31.08.2013	
EU	Diagnostic and prognostic biomarkers for inflammatory bowel disease IBD-BIOM	Dr. Kolarich BS	01.10.2012-30.09.2016	The University of Edinburgh, UK Genos Doo ZA Vjestacenje I Analizu, Osijek, Croatia Ludger Ltd, Abingdon, UK Azienda Ospedaliero-Universitaria Careggi, Firenze, Italy IP Research Consulting Sasu, Noisy Le Grande, France Accademisch Ziekenhuis Leiden - Leids Universitair Medisch Centrum, Netherlands Faculty of Science University of Zagreb, Croatia Cedars-Sinai Medical Center, Los Angeles, USA
EU	Advances European lithium sulphur cells for automotive applications (EUROLIS)	Prof. Antonietti KC	01.10.2012-30.09.2016	Kemijski Institut, Ljubljana, Slovenia Centre National de la Recherche Scientifique, Paris, France Chalmers Tekniska Hoegskola AB, Goeteborg, Sweden Sincrotrone Trieste SCPA, Italy Center Odlicnosti Nizkoogljicne Tehnologije Zavod, Slovenia Renault s.a.s. represented by GIE REGIENOV, France Solvionic SA, Toulouse, France Fraunhofer-Gesellschaft zur Förder- ung der angewandten Forschung e.V., München, Germany SAFT SAS, Bagnolet, France Volvo Technology AB, Goeteborg, Sweden
EU	Nanocontainer-Based Active Coatings for Maritime Applications (NANOMAR)	Prof. Möhwald Dr. Shchukin GF	01.05.2012-30.04.2014	Universidade de Aveiro, Portugal A.V. Shubnikov Institute of Crys- tallography Russian Academy of Sciences, Russia Instituto de Pesquisas Tecnologicas do Estado de Sao Paulo SA, Brazil
EU	Training Network in innovative polyelectrolytes for energy and environment (Renaissance)	Prof. Antonietti KC	01.05.2012-30.04.2016	Universidad Del Pais Vasco Eha Upv, Spain Centre National de la Recherche Scientifique, Paris, France Linkopings Universitet, Sweden Universite de Liege, Belgium Fundacion IMDEA Energia, Spain Kitozyme SA, Belgium Procter & Gamble Italia Spa, Italy

EU

Zuwendungs - geber	Thema	Projektleiter	Bewilligungszeitraum	Zusammenarbeit mit
EU	Hydrothermal and Ionothermal Chemistry for Sustainable Materials (HydraChem)	Prof. Antonietti KC	01.11.2008-31.10.2013	
EU	Automated Synthesis of Heparin and Chondroitin Libraries for the Preparation of Diverse Carbohydrate Arrays (Autoheparin)	Prof. Seeberger BS	01.01.2009-31.12.2013	
EU	Molecular Biomimetics and Magnets Biomineralization: Towards Swimming Nanorobots (MB ²)	Dr. Faivre BM	01.01.2011 - 31.12.2016	
EU	Network for Integrated Cellular Homeostasis (NICHE)	Prof. Lipowsky Dr. Valleriani TH	01.01.2012-31.12.2016	Rijksuniversiteit Groningen, Netherlands Universität Potsdam, Germany The University Court of the University of Aberdeen, UK Agencia Estatal Consejo Superior De Investigaciones Cientificas (CSIC), Madrid, Spain The Chancellor, Masters and Scholars of the University of Oxford, UK DSM Food Specialties BV, Delft, Netherlands AstraZeneca UK Limited, London, UK
EU	Extended shelf-live biopolymers for sustainable and multifunctional food packaging solutions (NanoBarrier)	Prof. Möhwald Dr. Shchukin GF	01.03.2012-28.02.2016	Stiftelsen SINTEF, Norwegen University of Maribor, Slovenien Universidade de Aveiro, Portugal Foundation of Research and Technology (FORTH) Greece ITENE - Packaging, Transport & Logis- tics Research Center (ITENE), Spain Innventia AB, Sweden Logoplaste Innovation LAB LDA (ILAB), Portugal Argo SA Plastic Packaging Materials (Argo), Greece Grace Davison - Materials and Packaging Technologies (Grace), France Plasmachem GmbH, Germany Prado Karton, Portugal Elastopoly Oy, Finland Borregaard Industries Limited, Norway SCA R&D Centre AB, Sweden
EU	Automated Glycosaminoglycan Synthesis to Access Defined Oligosaccharides for Diagnostic and Therapeutic Applications (GAGAUTOSYN)	Prof. Seeberger BS	01.05.2012-30.04.2013	

DFG

DFG	Biomechanics and Biology of Musculoskeletal Regeneration - From Functional Assessment to Guided Tissue Formation; The micro-mechanical and structural properties of callus tissue during bone healing	Prof. Fratzl Dr. Manjubala BM	01.01.2007-31.12.2011	Charité - Universitätsmedizin Berlin Freie Universität Berlin; Max-Planck-Institut für molekulare Genetik; Deutsches Rheuma-Forschungszentrum Berlin; Helmholtz-Gemeinschaft Deutscher Forschungszentren; Institut für Polymerforschung GKSS-Forschungszentrums Geesthacht GmbH, Teltow; Zuse Institut Berlin
DFG	Biomechanics and Biology of Musculoskeletal Regeneration - From Functional Assessment to Guided Tissue Formation; Mechano-biology of bone healing and regeneration	Dr. Weinkamer BM	01.01.2007-31.12.2011	Charité - Universitätsmedizin Berlin Freie Universität Berlin; Max-Planck-Institut für molekulare Genetik; Deutsches Rheuma-Forschungszentrum Berlin; Helmholtz-Gemeinschaft Deutscher Forschungszentren; Institut für Polymerforschung GKSS-Forschungszentrums Geesthacht GmbH, Teltow; Zuse Institut Berlin
DFG	SFB Teilprojekt B08	Prof. Seeberger Dr. Lepenies BS	01.01.2012 - 31.12.2013	FU Berlin
DFG	Fluide Grenzflächen	Dr. Miller GF	01.05.2010-30.04.2013	
DFG	Synthesis and properties of glycopolyptide bio-hybrid materials Theme: Novel Polymer Synthesis and New Supramolecular Polymer Assemblies	Dr. Schlaad KC	20.10.2010	
DFG	„Einfluss von Proteinen auf die Schaumbildung und Schaumstabilität“	Dr. Miller GF	01.06.2011 -	
DFG	SPP 1568 - Schwerpunktprogramm: "Design and Generic Principles of Self-Healing Materials"	Dr. Harrington BM	01.07.2011-	
DFG	SPP Schwerpunktprogramm: "Generation of multi-functional inorganic materials by molecular bionics"	Dr. Faivre BM	14.12.2011	
DFG	Deutsch-Israelische Projektkooperation	Prof. Fratzl BM	01.01.2012 - 31.12.2016	
DFG	„Hygroskopische Eigenschaften von natürlichen Oligosacchariden“	Dr. Grafmüller TH	01.11.2012 -	
DFG	Forschergruppe "Ribosome Dynamics in Regulation of Speed and Accuracy of Translation"	Prof. Lipowsky TH	01.07.2012 -	

DFG

Zuwendungs- geber	Thema	Projektleiter	Bewilligungszeitraum	Zusammenarbeit mit
DFG	gemeinsames DFG/NSF-Programm "Materials World Network"	Dr. Politi BM	01.12.2012-	
DFG	Charakterisierung von Grenzflächen zwischen zwei Flüssigkeiten unter hoch-dynamischen Bedingungen	Dr. Miller GF	01.08.2009-31.07.2011	
DFG	Structural and morphological characterization of ceramide-1-phosphate model membran	Dr. Brezesinski GF	20.09.2007-31.10.2012	
DFG	Dynamics of Interfaces between Drops with Miscible Liquids	Dr. Riegler GF	01.09.2008-31.08.2011	
DFG	Intelligent release systems for anticorrosion self-healing coatings (Deutsch-Russisches Kooperationsprojekt)	Prof. Möhwald GF	17.07.2008-16.07.2011	Dr. V.V. Volkov, Shubnikov Institute of Crystallography, RAN, Moscow
DFG	Generation of nanoparticles with tunable surface wettability and surface functionality to cross hydrophilic/hydrophobic interfaces of biological barriers	Prof. Möhwald Dr. Wang GF	01.07.2009-30.06.2011	
DFG	Thermodynamisch stabile Pickering-Emulsionen	Dr. Wüstneck GF	01.09.2009-31.08.2011	
DFG	Thermodynamisch stabile Pickering-Emulsionen	Dr. Wüstneck GF	01.09.2011-31.08.2013	
DFG	Multiscale Smart Coatings with Sustained Anticorrosive Action – SmartCoat	Prof. Möhwald Dr. Shchukin GF	01.09.2012-31.08.2015	TU Berlin, Germany National Institute for Materials Science (NIMS), Japan Institute for Micromanufacturing, Louisiana Tech University, USA Kazan Federal University, Russia
DFG	Biometric Materials Research: Functionality by Hierarchical Structuring of Materials	Prof. Fratzl Prof. Fratzl Dr. Aichmayer Dr. Zaslansky Dr. Faivre Dr. Burgert Dr. Schlaad Dr. Tauer Dr. Cölfen BM	01.05.2009-	(MPI KOLL ist Koordinator, 7 Teilprojekte am Institut) Institut National Polytechnique; E.N.S.E.E.G./ L.T.P.C.M. Grenoble Foundry Institute of RWTH Aachen Department of Materials Engineering, Technical University Berlin Evolutionary Biomaterials Group, MPI für Metallforschung, Stuttgart Department of Materials Science and Engineering, University Erlangen-Nürnberg Dept. Of Microstructure Physics and Metal Forming, MPI Eisenforschung Düsseldorf Plant Biomechanics Group, Botanic Garden, University of Freiburg

DFG

Zuwendungs- geber	Thema	Projektleiter	Bewilligungszeitraum	Zusammenarbeit mit
DFG	"Chemoselektive Reaktionen für die Synthese und Anwendung funktionaler Proteine"	Dr. Silva BS	01.11.2012 -	
DFG	Emmy-Noether-Programm, 1. Förderabschnitt	Dr. Hartmann BS	04.08.2009-03.08.2012	
DFG	Emmy-Noether-Programm, 2. Förderabschnitt	Dr. Hartmann BS	04.08.2012-03.08.2013	
DFG	Emmy-Noether-Programm, 1. Förderabschnitt	Dr. Rademacher BS	01.06.2012-31.05.2015	
DFG	Gottfried Wilhelm Leibniz-Programm	Prof. Fratzl Dr. Dunlop Dr. Wagermaier BM	01.09.2010-31.08.2017 01.09.2010-31.12.2011 01.01.2011-31.12.2012	2 Subprojekte am Institut
DFG	Exzellenzcluster UniCat: Unifying Concepts in Catalysis	Prof. Antonietti KC	01.01.2011-31.12.2015	Technische Universität Berlin Humboldt-Universität Berlin Freie Universität Berlin Universität Potsdam Fritz-Haber-Institut der Max-Planck-Gesellschaft Berlin

Unteraufträge/Weiterleitungen and deutsche Forschungseinrichtungen

BMBF/ Universität Potsdam	GoForsys Potsdam-Golm BMBF-Forschungs - einrichtung zur Systembiologie. Photosynthesis and Growth: A Systems Biology based Approach	Prof. Lipowsky TH	01.01.2007-31.12.2011	Universität Potsdam MPI für molekulare Pflanzenphysiologie
OOO 'Delta XXI Vek', Saratov	Training in nanotechnology and material science (interface phenomena)	Prof. Brezesinski GF	01.10.2010-31.12.2011	Universität Saratov, Russland
FU Berlin	Initiative: CSI-Center for Supramolecular Interactions	Dr. Hartmann BS	01.08.2011-31.07.2012	Freie Universität Berlin
FU Berlin	Biodistribution and Anti-inflammatory Efficacy of Glycosylated Gold Nanoparticles - NanoScale	Dr. Kennedy BS	01.01.2012-31.10.2012	Freie Universität Berlin

Supranationale Einrichtungen

Zuwendungs - geber	Thema	Projektleiter	Bewilligungszeitraum	Zusammenarbeit mit
ESA/ESTEC	FASES - Fundamental and applied studies of emulsion stability	Dr. Miller GF	01.10.2003-31.07.2013	ENI, Genua, Italien Université Aix-Marseille Université Compiègne, France Universität Complutense Madrid Universität Florenz; IPF, Dresden CNR - Consiglio Nazionale delle Ricerche, Italien; Eni S.p.A., Italien Aristotele Universität Thessaloniki
ESA/ESTEC	Topical Team: Foam and Emulsion Technologies- Concerted Action Team (FETCAT)	Dr. Miller GF	01.10.2003-31.12.2013	CNR, Genua, Italien Universität Florence, Italien Universität Marseille, Frankreich Universität Compiègne, Frankreich Murmansk State Technical University, Russland; Aristotele Universität Thessaloniki, Griechenland Universität Stockholm, Schweden EniTecnologie, Milano, Italien University College Dublin, Irland Nestlé Research Center, Lausanne, Schweiz; Wageningen University, Niederlande; University of Manchester Institute of Science and Technology, Großbritannien Institute of Food Research, Norwich, Großbritannien; Norwegian University of Science and Technology, Trondheim, Norwegen St. Petersburg State University, Russland; Université d'Orsay et CNRS, Frankreich; Université de Marne La Vallée, Frankreich Unilever, Großbritannien Norsk Hydro ASA, Norwegen IPF, Dresden
NATO	Nato-Collobarotive Linkage Grant, as coordinator, for the project "Smart Textile Materials with Inherent Remote Identification Ability"	Prof. Møhwald Dr. Shchukin GF	29.06.2009-28.06.2011	St. Petersburg State University of Technology, Russland
Stiftungen				
Körper-Stiftung	Körper-Preis 2007	Prof. Seeberger BS	01.01.09.2007-	Universität München Internationale Universität Bremen
VW-Stiftung	Formation of bi-functional coatings on metals based on self-locating nano- and microcontainers	Dr. Shchukin GF	01.08.2008-31.07.2011	Universität Paderborn Fraunhofer Institut für Schicht- und Oberflächentechnik, Braunschweig
GIF-German Israeli Foundation	Gene manipulation of amorphous biomineralogy	Dr. Aichmayer BM	01.01.2009-31.12.2011	Ben Gurion University, Israel
GIF-German Israeli Foundation	Exponential Amplification of Diagnostic Signals	Prof. Seeberger BS	01.01.2011 - 31.12.2013	Tel Aviv University

Ausländische Forschungsfinanzierer

Zuwendungs- geber	Thema	Projektleiter	Bewilligungszeitraum	Zusammenarbeit mit
Schweizer Nationalfonds	The Role of Glycosylphosphatidylinositol Oligosaccharides in Malaria	Prof. Seeberger BS	01.01.2009-30.05.2011	
Schweiz. Eid- genossenschaft (Labor Spiez)	Impact of microreactors on the Chemical Weapons Convention's Chemistry-Screening of some basis key-reactions	Prof. Seeberger BS	01.01.2010-31.03.2011	
Industrie				
Beiersdorf AG	Glycomics der Haut	Prof. Seeberger BS	01.12.2009-31.01.2011	
AstraZeneca UK Unlimeted	Synthetic Organic Chemistry in Continuous Flow	Prof. Seeberger BS	01.12.2009-30.11.2011	
Merck	HPLC-Collaboration Agreement	Prof. Seeberger BS	07.10.2010-06.10.2011	
Ancora Pharma	GPI	Dr. Lepenies BS	01.03.2011-29.02.2012	
JSR Corporation	Visiting Scientist Agreement	Prof. Antonietti KC	01.10.2011-30.09.2013	
Lam Research AG	Investigations on the Fundamental of Marangoni Convection with a Focus on it's Application for Wafer Surfaces Cleaning Process	Dr. Riegler GF	01.12.2011-30.11.2013	LAM Research AG, Austria

Zuwendungs- geber	Thema	Projektleiter	Bewilligungszeitraum	Zusammenarbeit mit
----------------------	-------	---------------	----------------------	--------------------

Sonstige deutsche Forschungsfinanzierer

DAAD	Projektbezogener Personenaustausch mit Portugal	Dr. Shchukin GF	2011 und 2012	Universidade de Aveiro, Portugal
DAAD	Projektbezogener Personenaustausch mit Portugal	Dr. Titirici KC	2011 und 2012	University of Evora (Portugal)
DAAD	Projektbezogener Personenaustausch mit Frankreich (PROCOPE)	Dr. Dimova TH	2011 und 2012	Université de Bordeaux 1, Pessac, France
DAAD	Projektbezogener Personenaustausch mit Argentinien	Dr. Wagermaier BM	2012 und 2013	Institute of Materials Science and Technology (INTEMA), University of Mar del Plata–National Research Council (CONICET), J. B. Justo 4302, 7600 Mar del Plata, Argentina

Ausgewählte Veranstaltungen

Selected Events

- **10.-12. March 2011 The 5th Glycan Forum in Berlin**
Harnack-Haus, Berlin
- **22.-23. June 2011 Trends in Colloid & Interface Science TICl**
MPI of Colloids and Interfaces
- **24. Juni 2011 Alumni Meeting**
MPI of Colloids and Interfaces
- **4.-9. September 2011 European Colloid and Interface Society ECIS 2011**
Technical University Berlin
- **10. September 2011 Open Day**
MPI of Colloids and Interfaces
- **11. November 2011 Max-Planck-Tag**
- **19.-21. March 2012 6th Glycan Forum in Berlin**
Harnack-Haus, Berlin
- **02.-04. April 2012 Meeting of the Scientific Advisory Board**
MPI of Colloids and Interfaces
- **26. April 2012 GirlsDay 2012**
MPI of Colloids and Interfaces
- **8. June 2012 Alumni Meeting**
- **18.-20. June 2012 The 509th Wilhelm and Else Heraeus-Seminar on Physics of the Extracellular Matrix**
- **21. June 2012 Kick off Meeting – IMPRS on Multiscale Bio-Systems**
- **19.-21. September 2012 Biomembrane Days in Potsdam**
On the occasion of Wolfgang Helfrich's 80th birthday
- **12. October 2012 1st Biomolecular Systems Day**
- **24.-26. October 2012 Minerva Symposium – The Biophysics of Cells and Tissues**

Wissenschaftliche Abschlüsse

Scientific Degrees

Diploma Theses

Department of Biomaterials:

Reinecke, A.: Exploring Molecular Gradients in Byssal Threads of Mytilus Mussels. Universität Potsdam (2011).

Department of Biomolecular Systems:

Hütter, J.: Functional characterization of various murine antigen-presenting cell subsets and evaluation of their utility for C-type lectin receptor-mediated targeting. Freie Universität Berlin (2011).

Lewandowski, A.: Glycoproteomics investigation of seminal fluid from oligoasthenoteratozoospermia (OAT) patients. Technische Universität Berlin (2011).

Department of Interfaces

Keller, J.: SyntWechselwirkungen des antimikrobiellen Peptids NK-2 mit Lipid Mono- und Bischichten. Universität Potsdam. (2012).

Master Theses

Department of Biomolecular Systems:

Matthies, S.: Synthesis of Sialic Acids via the Macrophomate Synthase-Catalyzed Pyruvate Aldol Reaction. Freie Universität Berlin (2011).

Kozakowski, M.: Synthese von Glykan - GPI Strukturen. Freie Universität Berlin (2011).

Alagesan, K.: Novel methods for monosaccharide identification and quantitation based on Liquid Chromatography-Electrospray Ionisation (LC-ESI) ion trap mass spectrometry. University of Oulu, Finland (2012).

Michel, D.: Synthesis of Peptide- and Glycopeptidethioesters for Semisynthesis of the Prion Protein. Freie Universität Berlin (2012).

Grube, M.: Synthese von galaktosyl-verzweigten Strukturen des Glycosylphosphatidylinositols (GPI) von Trypanosoma brucei. Technische Universität Clausthal (2012).

Oetter, K.-M.: Changes in Antigen-Specific IgG Fc N-Glycosylation upon Vaccination. A Comparison of Mice and Men using LC-ESI-MS/MS. Freie Universität Berlin (2012).

Sinaida, L.: The Two Protecting Group-Approach for the Solid Phase Synthesis of Sequence-Defined Oligomers. Freie Universität Berlin (2012).

Vorreiter, F.: Skin cancer glycomics. Beuth Hochschule Berlin (2012).

Wamhoff, E.: Structure-based in silico design and synthesis of mannose-based ligands for human Langerin. Universität Lübeck (2012).

Department of Colloid Chemistry

Höhne, P.: Zum Einfluss der Gasphase auf die Emulsionspolymerisation von Styrol. Universität Potsdam (2011).

Jeong, S.: Biomass derived N-Doped Porous Carbon Materials. Universität Potsdam (2011).

Yazdankbakhsh, F.: Mesoporous Melamine Formaldehyde Resin of Ab/Adsorption Applications. Universität Potsdam. (2012).

Department of Interfaces

Pinchasik, B.: Gradient Polymer Coatings for Induced Motion of Microcapsules. HU Berlin (2012).

PhD Theses

Department of Biomaterials:

Krauß, S.: Characterization of the relations between structure and deformation behavior in deer antler and turtle shell. Universität Potsdam (2011).

Prass, J.: Verformung hexagonal geordneter, mesoporöser Materialien durch die Wechselwirkung mit Fluiden. Untersuchungen mittels Kleinwinkelröntgenbeugung. Universität Potsdam (2011).

Schenk, S.: On the Structure of Bio-Inspired Calcite-Polymer Hybrid Crystals. Universität Potsdam (2011).

Department of Biomolecular Systems:

- Esposito, D.: Automated Solid-Phase Oligosaccharide Synthesis of Conjugation-Ready Glycans. ETH Zürich (2011).
- Guo, X.: I. Synthetic Bacterial Lipopolysaccharide Core Structures as Vaccine Candidates against *Chlamydia trachomatis* and *Yersinia pestis*. II. Synthesis of a Fungal Galectin Epitope Trisaccharide and the HNK-1 Epitope Trisaccharide. ETH Zürich (2011).
- Laurino, P.: Photochemical Transformations in Continuous Flow Devices. ETH Zürich (2011).
- Tsai, Y.-H.: A General and Convergent Strategy for Synthesis of Glycosylphosphatidylinositols. Freie Universität Berlin (2012).

Department of Colloid Chemistry:

- Brummelhuis, N. ten: Self-Assembly of Cross-Linked Polymer Micelles into Complex Higher-Order Aggregates. Universität Potsdam (2011).
- Chen, X.: Neuartige Synthese magnetischer Nanostrukturen: Metallcarbide und Metallnitride der Übergangsmetalle Fe/Co/Ni. Universität Potsdam (2011).
- Fellinger, T.-P.: Hydrothermal and Ionothermal Carbon Structures: From carbon negative materials to energy applications. Universität Potsdam (2011).
- Kopetzki, D.: Exploring Hydrothermal Reactions - From Prebiotic Synthesis to Green Chemistry. Universität Potsdam (2011).
- Krapner, A.: Neuartige Synthese magnetischer Nanostrukturen: Metallcarbide und Metallnitride der Übergangsmetalle Fe/Co/Ni. Universität Potsdam (2011).
- Kubo, S.: Nanostructured Carbohydrate-Derived Carbonaceous Materials. Universität Potsdam (2011).
- Lange, C.: Mineral deposition and maturation during bone development. Universität Potsdam (2011).
- Popović, J.: Novel lithium iron phosphate materials for lithium-ion batteries. Universität Potsdam (2011).
- Tan, I. S.: Toward Greener Stationary Phases: Thermoresponsive and Carbonaceous Chromatographic Supports. Universität Potsdam (2011).
- Unterlass, M.: From Monomer Salts and their Tectonic Crystals to Aromatic Polyimides - Development of neoteric synthesis routes. Universität Potsdam (2011).
- Valverde Serrano, C.: Self-assembly behavior in hydrophilic block copolymers. Universität Potsdam (2011).
- Weber, N.: Die Synthese schizomorpher Copolymer-Latexteilchen. Universität Potsdam (2011).
- Zhao, L.: Sustainable Approaches towards Novel Nitrogen-Doped Carbonaceous Structures. Universität Potsdam (2011).
- Su, F.: Graphitic Carbon Nitride as a Metal-Free Catalyst for Photosynthesis, Amine Oxidation and Base-Mediated Reactions. Universität Potsdam (2012).
- Falco, C.: Sustainable Biomass-Derived Hydrothermal Carbons for Energy Applications. Universität Potsdam (2012).
- Jeromenok, J.: Polymers from the Natural Product Betulin; A Microstructural Investigation. Universität Potsdam (2012).
- Milke, B.: Synthese von Metallnitrid- und Metalloxinitridnanopartikeln für energierelevante Anwendungen. Universität Potsdam (2012).
- Wilke, A.: Synthese und Charakterisierung von mesoporösen Polymernetzwerken. Universität Potsdam (2012).
- Wohlgemuth, S.: Functional Nanostructured Hydrothermal Carbons for Sustainable Technologies: Heteroatom Doping and Superheated Vapor. Universität Potsdam (2012).

Department of Interfaces

- Berg, J.: Size-dependent Wetting Behavior of Organic Molecules on Solid Surfaces. Universität Potsdam (2011).
- Dittrich, M.: Physical-Chemical Characterization of New Lipids Designed for Non-Viral Gene Transfection. Universität Potsdam (2011).
- Fix, D.: Non-invasive in-situ observation of pitting corrosion on aluminum. Universität Potsdam (2011).
- Früh, J.: Structural Change of Polyelectrolyte Multilayers under Mechanical Stress. Universität Potsdam (2011).
- Haase, M.: Modification of Nanoparticle-Surfaces for Emulsion Stabilization and Encapsulation of Active Molecules for Anti-Corrosive Coatings (2011).
- Kohler, D.: Asymmetric Particles for Pulmonary Drug Delivery. Universität des Saarlandes (2011).
- Wegerich, F.: Engineered human cytochrome c: Investigation of superoxide and protein-protein interaction and application in bioelectronic systems. Universität Potsdam (2011).
- Borisova, D.: Feedback active coatings based on mesoporous silica containers. Universität Potsdam (2012).
- Hörnke, M.: Beta-Sheet Formation of Amyloidogenic Model Peptides at Hydrophobic-Hydrophilic Interfaces. Universität Potsdam (2012).
- Karpitschka, S.: Thin liquid films with compositional gradients: Sessile drop noncoalescence and other effects. Universität Potsdam (2012).
- Latnikova, A.: Polymeric capsules for self-healing anticorrosion coatings. Universität Potsdam (2012).
- Madaboosi Srinivasan, N.: Engineering hyaluronic acid / poly L-lysine films as a platform for controlling cell behavior. Universität Potsdam (2012).
- Music, N.: Thermodynamics, kinetics and rheology of surfactant adsorption layers at water/oil interfaces. Universität Potsdam (2012).
- Schneider, J.: Characterisation of Single- and Multibubble Cavitation through Analysis of Molecular, Atomic and Ionic Line Emissions. Universität Potsdam (2012).
- Weber, C.: Nucleation at nano-structured substrates. TU Berlin (2012).

Department of Theory & Bio-Systems

- Bierbaum, V.: Chemomechanical coupling and motor cycles of the molecular motor myosin V. Universität Potsdam (2011).
- Deuster v., Carola: Simulations on several scales: Studies on protein-ligand binding kinetics and on the antimicrobial peptide NK-2. Universität Potsdam (2011).
- Kittner, M.: Folding and Aggregation of Amyloid Peptides. Universität Potsdam (2011).
- Berger, Florian: Impact of translation kinetics on protein folding and ribosome traffic. Universität Potsdam (2012).
- Bezlyepkina, Natalya: Domain formation in model lipid membranes induced by electrofusion of giant vesicles. Universität Potsdam (2012).
- Deneke, C.: Theory of mRNA degradation. Universität Potsdam (2012).
- Keller, P.: Mathematical Modeling of Molecular Motors. Universität Potsdam (2012).
- Pataria, S.: Partitioning of cytochrome c in multicomponent lipid membranes. TU Berlin (2012).
- Rouhiparkouhi, T.: Adhesion-induced phase behavior of multi-component membranes. TU Berlin (2012).
- Wehle, W.: Entwicklung und Untersuchung eines atomistischen Modells des Glykosylphosphatidylinositol-Ankers. Universität Potsdam (2012).

Personalien

Appointments and Honors

Habilitations

Department of Biomaterials

Weinkamer, R.: Processes in Living Bone and the Resulting Structural Changes - Computational Studies. Humboldt-Universität zu Berlin (2012).

Department of Theory & Bio-Systems

Dimova, R.: Probing the Membrane Nanoregime with Optical Microscopy. Universität Potsdam (2011).

2011

Ehrungen/Mitgliedschaften/Honorarprofessuren

Honors/Memberships/Honorary Professorships

Prof. Dr. Markus Antonietti: Director of the Department of Colloid Chemistry received an honorary doctorate from Stockholm University.

Prof. Dr. Markus Antonietti: Director of the Department of Colloid Chemistry received the Victor Grignard-Georg Wittig Prize of the "Gesellschaft Deutscher Chemiker (GDCh)" and "Societe Chimique de France (SCF)"

Dr. Cristina Giordano: Group Leader in the Department of Colloid Chemistry has been awarded the Richard-Zsigmondy-Scholarship for her excellent scientific qualification.

Prof. Dr. Peter H. Seeberger: Director of the Department of Biomolecular Systems is awarded the Roy L. Whistler Award 2012

2012

Prof. Dr. Peter Fratzl: Director of the Department of Biomaterials has been elected Fellow of the Materials Research Society (MRS).

Prof. Dr. Helmuth Möhwald: Director of the Department of Interfaces has been elected to become a member of the Academia Europaea (The Academy of Europe).

Daniel Kopetzki: Postdoctoral Student in the Department of Biomolecular Systems has been awarded the "Brandenburgischer Nachwuchswissenschaftlerpreis" 2012

2011

Ruf an eine Universität

Appointments

Dr. habil. Ingo Burgert: Group Leader in the Department of Biomaterials accepted a position as Full Professor of Wood-Based Materials at the ETH Zürich.

2012

Dr. Andre Skirtach: Group Leader in the Department of Interfaces accepted a position as professor at the University Gent.

Dr. Dmitry Shchukin: Group Leader in the Department of Interfaces accepted a position as Professor at the Stephenson Institute for Renewable Energy at the University of Liverpool

Dr. Maria-Magdalena Titirici: Group Leader in the Department of Colloid Chemistry accepted a position as Reader in Materials Science at the Queen Mary University London

Wissenschaftliche Veröffentlichungen

Publications

Biomaterials 2011

- Andert, J., E. Wessen, G. Borjesson and S. Hallin: Temporal changes in abundance and composition of ammonia-oxidizing bacterial and archaeal communities in a drained peat soil in relation to N₂O emissions. In: *Journal of Soils and Sediments* 11, 8, 1399-1407 (2011).
- Baumgartner, J. and D. Faivre: Magnetite biomineralization in bacteria. In: *Molecular Biomineralization: Aquatic Organisms Forming Extraordinary Materials*. (Eds.) Müller, W. E. G. Bacterial in progress in molecular and subcellular biology 52. Springer, Heidelberg (2011) 3-27.
- Blunck, U. and P. Zaslansky: Enamel Margin Integrity of Class I One-bottle All-in-one Adhesive-based Restorations. In: *Journal of Adhesive Dentistry* 13, 1, 23-29 (2011).
- Bratashov, D. N., A. Masic, A. M. Yashchenok, M. F. Bedard, O. A. Inozemtseva, D. A. Gorin, T. Basova, T. K. Sievers, G. B. Sukhorukov, M. Winterhalter, H. Möhwalde and A. G. Skirtach: Raman imaging and photodegradation study of phthalocyanine containing microcapsules and coated particles. In: *Journal of Raman Spectroscopy* 42, 10, 1901-1907 (2011).
- Burgert, I. and J. W. C. Dunlop: Micromechanics of cell walls. In: *Mechanical Integration of Plant Cells and Plants*. (Eds.) Wojtaszek, P. Springer, Berlin (2011) 27-52.
- Charilaou, M., K. K. Sahu, D. Faivre, A. Fischer, I. Garcia-Rubio and A. U. Gehring: Evolution of magnetic anisotropy and thermal stability during nanocrystal-chain growth. In: *Applied Physics Letters* 99, 18, Seq. No.: 182504 (2011).
- Claeson, K. M. and M. N. Dean: Cartilaginous fish skeletal anatomy. In: *Encyclopedia of fish physiology: from genome to environment*. (Eds.) Farrell, A. P. Academic Press, San Diego (2011) 419-427.
- Clarke, D. R. and P. Fratzl: Annual Review of Materials Research. Materials science of biological systems. *Annual Reviews*, Palo Alto (2011) 448 S.p.
- Cornelius, T. W., D. Carbone, V. L. R. Jacques, T. U. Schulli and T. H. Metzger: Three-dimensional diffraction mapping by tuning the X-ray energy. In: *Journal of Synchrotron Radiation* 18, 413-417 (2011).
- Dean, M. N.: Cartilaginous fish skeletal tissues. In: *Encyclopedia of fish physiology: from genome to environment*. (Eds.) Farrell, A. P. Academic Press, San Diego (2011) 428-433.
- Fernandes, F. M., I. Manjubala and E. Ruiz-Hitzky: Gelatin renaturation and the interfacial role of fillers in bionanocomposites. In: *Physical Chemistry Chemical Physics* 13, 11, 4901-4910 (2011).
- Fischer, A., M. Schmitz, B. Aichmayer, P. Fratzl and D. Faivre: Structural purity of magnetite nanoparticles in magnetotactic bacteria. In: *Journal of the Royal Society Interface* 8, 60, 1011-1018 (2011).
- Dunlop, J. W. C., R. Weinkamer and P. Fratzl: Artful interfaces within biological materials. In: *Materials Today* 14, 3, 70-78 (2011).
- Gilow, C., E. Zolotoyabko, O. Paris, P. Fratzl and B. Aichmayer: Nanostructure of Biogenic Calcite Crystals: A View by Small-Angle X-Ray Scattering. *Crystal Growth & Design* 11, 6, 2054-2058 (2011).
- Graf, P., A. Manton, A. Haase, A. F. Thünemann, A. Masic, W. Meier, A. Luch and A. Taubert: Silicification of Peptide-Coated Silver Nanoparticles-A Biomimetic Soft Chemistry Approach toward Chiral Hybrid Core-Shell Materials. In: *ACS Nano* 5, 2, 820-833 (2011).
- Haase, A., H. F. Arlinghaus, J. Tentschert, H. Jungnickel, P. Graf, A. Manton, F. Draude, S. Galla, J. Plendl, M. E. Goetz, A. Masic, W. Meier, A. F. Thünemann, A. Taubert and A. Luch: Application of Laser Postionization Secondary Neutral Mass Spectrometry/Time-of-Flight Secondary Ion Mass Spectrometry in Nanotoxicology: Visualization of Nanosilver in Human Macrophages and Cellular Responses. In: *ACS Nano* 5, 4, 3059-3068 (2011).
- Haase, A., J. Tentschert, H. Jungnickel, P. Graf, A. Manton, F. Draude, J. Plendl, M. E. Goetz, A. Galla, A. Masic, A. F. Thünemann, A. Taubert, H. F. Arlinghaus and A. Luch: Toxicity of silver nanoparticles in human macrophages: uptake, intracellular distribution and cellular responses. In: *Journal of Physics: Conference Series* 304, Seq. No.: 012030 (2011).
- Harrington, M. J., K. Razghandi, F. Ditsch, L. Guiducci, M. Rüggeberg, J. W. C. Dunlop, P. Fratzl, C. Neinhuis and I. Burgert: Origami-like unfolding of hydro-actuated ice plant seed capsules. In: *Nature Communications* 2, Seq. No.: 337 (2011).
- Hartmann, M. A., J. W. C. Dunlop, Y. J. M. Brechet, P. Fratzl and R. Weinkamer: Trabecular bone remodelling simulated by a stochastic exchange of discrete bone packets from the surface. In: *Journal of the Mechanical Behavior of Biomedical Materials* 4, 6 Sp. Iss., 879-887 (2011).
- Holten-Andersen, N., M. J. Harrington, H. Birkedal, B. P. Lee, P. B. Messersmith, K. Y. C. Lee and J. H. Waite: pH-induced metal-ligand cross-links inspired by mussel yield self-healing polymer networks with near-covalent elastic moduli. In: *Proceedings of the National Academy of Sciences of the United States of America* 108, 7, 2651-2655 (2011).
- Hoo, R. P., P. Fratzl, J. E. Daniels, J. W. C. Dunlop, V. Honkimaki and M. Hoffman: Cooperation of length scales and orientations in the deformation of bovine bone. In: *Acta Biomaterialia* 7, 7, 2943-2951 (2011).
- Idelevich, A., M. Kerschnitzki, R. Shahar and E. Monsonego-Ornan: 1,25(OH)₂D₃ Alters Growth Plate Maturation and Bone Architecture in Young Rats with Normal Renal Function. In: *PLoS ONE* 6, 6, Seq. No.: e20772 (2011).
- Kerschnitzki, M., W. Wagermaier, Y. F. Liu, P. Roschger, G. N. Duda and P. Fratzl: Poorly Ordered Bone as an Endogenous Scaffold for the Deposition of Highly Oriented Lamellar Tissue in Rapidly Growing Ovine Bone. In: *Cells Tissues Organs* 194, 2-4, 119-123 (2011).
- Kerschnitzki, M., W. Wagermaier, P. Roschger, J. Seto, R. Shahar, G. Duda, S. Mundlos and R. Fratzl: The organization of the osteocyte network in bone and potential mechanisms of passive mineral dissolution. In: *Bone* 48, Suppl. Suppl. 2, S139-S139 (2011).
- Kerschnitzki, M., W. Wagermaier, P. Roschger, J. Seto, R. Shahar, G. N. Duda, S. Mundlos and P. Fratzl: The organization of the osteocyte network mirrors the extracellular matrix orientation in bone. *Journal of Structural Biology* 173, 2, 303-311 (2011).

Publications/Department of Biomaterials

- Kolednik, O., J. Predan, F. D. Fischer and P. Fratzl: Bioinspired Design Criteria for Damage-Resistant Materials with Periodically Varying Microstructure. In: *Advanced Functional Materials* 21, 19, 3634-3641 (2011).
- Kollmannsberger, P., C. M. Bidan, J. W. C. Dunlop and P. Fratzl: The physics of tissue patterning and extracellular matrix organisation: how cells join forces. In: *Soft Matter* 7, 20, 9549-9560 (2011).
- Kollmannsberger, P. and B. Fabry: Linear and Nonlinear Rheology of Living Cells. In: *Annual Review of Materials Research* 41, 75-97 (2011).
- Kollmannsberger, P., C. Lukas, P. Roschger, P. Fratzl and R. Weinkamer: The interplay between calcium homeostasis and bone mineralization – A computational approach. In: *Bone* 48, Suppl. Suppl. 2, S181-S181 (2011).
- Kommareddy, K.P., C. Lange, J. Cui, J. Boergemann, I. Manjubala, M. Rumpler, J. W. C. Dunlop, K. Karl, A. Lendlein, P. Knaus and P. Fratzl: Three-dimensional tissue growth in polymer scaffolds with different stiffness and in-vitro influence of BMP-2 on tissue formation in hydroxyapatite scaffolds. In: *Tissue Engineering Part A* 17, 538-539 (2011).
- Krauss, S., W. Wagermaier, J. A. Estevez, J. D. Currey and P. Fratzl: Tubular frameworks guiding orderly bone formation in the antler of the red deer (*Cervus elaphus*). In: *Journal of Structural Biology* 175, 3, 457-464 (2011).
- Lange, C., C. Li, I. Manjubala, W. Wagermaier, J. Kuhnisch, M. Kolanczyk, S. Mundlos, P. Knaus and P. Fratzl: Fetal and postnatal mouse bone tissue contains more calcium than is present in hydroxyapatite. In: *Journal of Structural Biology* 176, 2, 159-167 (2011).
- Lee, S. M., V. Ischenko, E. Pippel, A. Masic, O. Moutanabbir, P. Fratzl and M. Knez: An Alternative Route Towards Metal-Polymer Hybrid Materials Prepared by Vapor-Phase Processing. In: *Advanced Functional Materials* 21, 16, 3047-3055 (2011).
- Le Norcy, E., S. Y. Kwak, M. Allaire, P. Fratzl, Y. Yamakoshi, J. P. Simmer and H. C. Margolis: Effect of phosphorylation on the interaction of calcium with leucine-rich amelogenin peptide. In: *European Journal of Oral Sciences* 119, Suppl. 1 Sp. Iss. SI, 97-102 (2011).
- Löbbecke, R., M. Chanana, H. Schlaad, C. Pilz-Allen, C. Günter, H. Möhwald and A. Taubert: Polymer Brush Controlled Bioinspired Calcium Phosphate Mineralization and Bone Cell Growth. In: *BIOMACROMOLECULES* 12, 10, 3753-3760 (2011).
- Lukas, C., P. Kollmannsberger, D. Ruffoni, P. Roschger, P. Fratzl and R. Weinkamer: The Heterogeneous Mineral Content of Bone-Using Stochastic Arguments and Simulations to Overcome Experimental Limitations. In: *Journal of Statistical Physics* 144, 2, 316-331 (2011).
- Lukas, C., P. Kollmannsberger, D. Ruffoni, P. Roschger, P. Fratzl and R. Weinkamer: The effect of a disturbed mineralization process on the bone mineralization density distribution (BMDD). In: *Bone* 48, Suppl. Suppl. 2, S181-S182 (2011).
- Lukas, C., F. Lambers, D. Ruffoni, F. A. Schulte, G. A. Kuhn, P. Kollmannsberger, R. Weinkamer and R. Müller: Quantification of the interplay between mineralization and remodeling in trabecular bone assessed by in vivo micro-computed tomography. In: *Bone* 48, Suppl. Suppl. 2, S205-S205 (2011).
- Mantion, A., P. Graf, I. Florea, A. Haase, A. F. Thünemann, A. Masic, O. Ersen, P. Rabu, W. Meier, A. Luch and A. Taubert: Biomimetic synthesis of chiral erbium-doped silver/peptide/silica core-shell nanoparticles (ESPN). In: *Nanoscale* 3, 12, 5168-5179 (2011).
- Masic, A., L. Bertinetti, R. Schuetz, L. Galvis, N. Timofeeva, J. W. C. Dunlop, J. Seto, M. A. Hartmann and P. Fratzl: Observations of Multiscale, Stress-Induced Changes of Collagen Orientation in Tendon by Polarized Raman Spectroscopy. In: *Biomacromolecules* 12, 11, 3989-3996 (2011).
- Minkevich, A. A., E. Fohntung, T. Slobodskyy, M. Riotte, D. Grigoriev, T. Metzger, A. C. Irvine, V. Novak, V. Holy and T. Baumbach: Strain field in (Ga,Mn)As/GaAs periodic wires revealed by coherent X-ray diffraction. In: *EPL* 94, 6, Seq. No.: 66001 (2011).
- Misof, B., P. Roschger and P. Fratzl: Imaging mineralized tissues in vertebrates. In: *Comprehensive biomaterials*. (Eds.) Ducheyne, P.; Healy, K. E.; Huttmacher, D. W.; Grainger, D. W.; Kirkpatrick, C. J. Elsevier, Amsterdam (2011) 407-4126.
- Mochales, C., A. Maerten, A. Rack, P. Cloetens, W. D. Mueller, P. Zaslansky and C. Fleck: Monoclinic phase transformations of zirconia-based dental prostheses, induced by clinically practised surface manipulations. In: *Acta Biomaterialia* 7, 7, 2994-3002 (2011).
- Paris, O., B. Aichmayer, A. Al-Sawalmih, C. H. Li, S. Siegel and P. Fratzl: Mapping Lattice Spacing and Composition in Biological Materials by Means of Microbeam X-Ray Diffraction. In: *Advanced Engineering Materials* 13, 8 Sp. Iss. SI, 784-792 (2011).
- Paschalis, E. P., D. N. Tatakis, S. Robins, P. Fratzl, I. Manjubala, R. Zoehrer, S. Gamsjaeger, B. Buchinger, A. Roschger, R. Phipps, A. L. Boskey, E. Dall'Ara, P. Varga, P. Zysset, K. Klaushofer and P. Roschger: Lathyrism-induced alterations in collagen cross-links influence the mechanical properties of bone material without affecting the mineral. In: *Bone* 49, 6, 1232-1241 (2011).
- Preininger, B., S. Checa, F. L. Molnar, P. Fratzl, G. N. Duda and K. Raum: SPATIAL-TEMPORAL MAPPING OF BONE STRUCTURAL AND ELASTIC PROPERTIES IN A SHEEP MODEL FOLLOWING OSTEOTOMY. In: *Ultrasound in Medicine and Biology* 37, 3, 474-483 (2011).
- Reiche, I., K. Müller, A. Staude, J. Goebbels and H. Riesemeier: Synchrotron radiation and laboratory micro X-ray computed tomography-useful tools for the material identification of prehistoric objects made of ivory, bone or antler. In: *Journal of Analytical Atomic Spectrometry* 26, 9, 1802-1812 (2011).
- Richter, S., J. Mussig and N. Gierlinger: Functional plant cell wall design revealed by the Raman imaging approach. In: *Planta* 233, 4, 763-772 (2011).
- Roth, S. V., G. Herzog, V. Korstgens, A. Buffet, M. Schwartzkopf, J. Perlich, M. M. A. Kashem, R. Dohrmann, R. Gehrke, A. Rothkirch, K. Stassig, W. Wurth, G. Benecke, C. Li, P. Fratzl, M. Rawolle and P. Müller-Buschbaum: In situ observation of cluster formation during nanoparticle solution casting on a colloidal film. In: *Journal of Physics-Condensed Matter* 23, 25, Seq. No.: 254208 (2011).
- Rumpler, M., T. Wuerger, P. Roschger, E. Zwettler, H. Peterlik, P. Fratzl and K. Klaushofer: Microcracks and osteoclast resorption activity in vitro. In: *Bone* 48, Suppl. Suppl. 2, S134-S134 (2011).

Publications/Department of Biomaterials

- Ruprecht, C., M. Mutwil, F. Saxe, M. Eder, Z. Nikoloski and S. Persson: Large-scale co-expression approach to dissect secondary cell wall formation across plant species. In: *Frontiers in Plant Physiology* 2, Seq. No.: 23 (2011).
- Saparin, P., H. Scherf, J. J. Hublin, P. Fratzl and R. Weinkamer: Structural Adaptation of Trabecular Bone Revealed by Position Resolved Analysis of Proximal Femora of Different Primates. In: *Anatomical Record-Advances in Integrative Anatomy and Evolutionary Biology* 294, 1, 55-67 (2011).
- Screen, H. R. C., J. Seto, S. Krauss, P. Boesecke and H. S. Gupta: Extrafibrillar diffusion and intrafibrillar swelling at the nanoscale are associated with stress relaxation in the soft collagenous matrix tissue of tendons. In: *SOFT MATTER* 7, 23, 11243-11251 (2011).
- Shahar, R., C. Lukas, S. Papo, J. W. C. Dunlop and R. Weinkamer: Characterization of the Spatial Arrangement of Secondary Osteons in the Diaphysis of Equine and Canine Long Bones. In: *Anatomical Record-Advances in Integrative Anatomy and Evolutionary Biology* 294, 7, 1093-1102 (2011).
- Shin, T. G., D. Müter, J. Meissner, O. Paris and G. H. Findenegg: Structural Characterization of Surfactant Aggregates Adsorbed in Cylindrical Silica Nanopores. In: *Langmuir* 27, 9, 5252-5263 (2011).
- Speck, T. and I. Burgert: Plant Stems: Functional Design and Mechanics. In: *Annual Review of Materials Research* 41, 169-193 (2011).
- Turcaud, S., L. Guiducci, P. Fratzl, Y. J. M. Brechet and J. W. C. Dunlop: An excursion into the design space of biomimetic architected biphasic actuators. In: *International Journal of Materials Research* 102, 6 Sp. Iss., 607-612 (2011).
- Vetter, A., Y. Liu, F. Witt, I. Manjubala, O. Sander, D. R. Epari, P. Fratzl, G. N. Duda and R. Weinkamer: The mechanical heterogeneity of the hard callus influences local tissue strains during bone healing: A finite element study based on sheep experiments. In: *Journal of Biomechanics* 44, 3, 517-523 (2011).
- Walz, M., S. Gerth, P. Falus, M. Klimczak, T. H. Metzger and A. Magerl: Nanoscale structures and dynamics of a boundary liquid layer. In: *Journal of Physics-Condensed Matter* 23, 32, Seq. No.: 324102 (2011).
- Wang, X. Q., H. Q. Ren, B. Zhang, B. H. Fei and I. Burgert: Cell wall structure and formation of maturing fibres of moso bamboo (*Phyllostachys pubescens*) increase buckling resistance. In: *Journal of the Royal Society Interface*, Seq. No.: 0462 (2011).
- Weinkamer, R. and P. Fratzl: Mechanical adaptation of biological materials - The examples of bone and wood. In: *Materials Science & Engineering C-Materials for Biological Applications* 31, 6 Sp. Iss., 1164-1173 (2011).
- Witt, F., A. Petersen, R. Seidel, A. Vetter, R. Weinkamer and G. N. Duda: Combined In Vivo/In Silico Study of Mechanobiological Mechanisms During Endochondral Ossification in Bone Healing. In: *ANNALS OF BIOMEDICAL ENGINEERING* 39, 10, 2531-2541 (2011).
- Zaslansky, P., P. Fratzl, A. Rack, M. K. Wu, P. R. Wesselink and H. Shemesh: Identification of root filling interfaces by microscopy and tomography methods. In: *International Endodontic Journal* 44, 5, 395-401 (2011).
- Zou, X. Q., K. L. Wong, S. Thomas, T. H. Metzger, V. Valtchev and S. Mintova: Platinum clusters confined in FAU-LTA hierarchical porous composite with a core-shell structure. In: *Catalysis Today* 168, 1, 140-146 (2011).
- Bauer, F., L. Bertinetti, A. Masic and T. Scheibel: Dependence of Mechanical Properties of Lacewing Egg Stalks on Relative Humidity. In: *Biomacromolecules* 13, 11, 3730-3735 (2012).
- Baumgartner, J., P. Lesevic, M. Kumari, K. Halbmaier, M. Bennet, A. Körnig, M. Widdrat, J. Andert, M. Wollgarten, L. Bertinetti, P. Strauch, A. Hirt and D. Faivre: From magnetotactic bacteria to hollow spirilla-shaped silica containing a magnetic chain. In: *Rsc Advances* 2, 21, 8007-8009 (2012).
- Behra, M., S. Schmidt, J. Hartmann, D. V. Volodkin and L. Hartmann: Synthesis of Porous PEG Microgels Using CaCO₃ Microspheres as Hard Templates. In: *Macromolecular Rapid Communications* 33, 12, 1049-1054 (2012).
- Bentov, S., P. Zaslansky, A. Al-Sawalmih, A. Masic, P. Fratzl, A. Sagi, A. Berman and B. Aichmayer: Enamel-like apatite crown covering amorphous mineral in a crayfish mandible. In: *Nature Communications* 3, Seq. No.: 839 (2012).
- Bidan, C. M., K. P. Kommareddy, M. Rumpler, P. Kollmannsberger, Y. J. M. Brechet, P. Fratzl and J. W. C. Dunlop: How Linear Tension Converts to Curvature: Geometric Control of Bone Tissue Growth. In: *PLoS ONE* 7, 5, Seq. No.: e36336 (2012).
- Bikondoa, O., D. Carbone, V. Chamard and T. H. Metzger: Ion beam sputtered surface dynamics investigated with two-time correlation functions: a model study. In: *Journal of Physics-Condensed Matter* 24, 44, Seq. No.: 445006 (2012).
- Cipitria, A., C. Lange, H. Schell, W. Wagermaier, J.C. Reichert, D.W. Hutmacher, P. Fratzl and G.N. Duda: Porous scaffold architecture guides tissue formation. In: *Journal of Bone and Mineral Research* 27, 6, 1275-1288 (2012).
- Cohen, L., M. N. Dean, A. Shipov, A. Atkins, E. Monsonogo-Ornan and R. Shahar: Comparison of structural, architectural and mechanical aspects of cellular and acellular bone in two teleost fish. In: *Journal of Experimental Biology* 215, 11, 1983-1993 (2012).
- Abraham, Y., C. Tamburu, E. Klein, J. W. C. Dunlop, P. Fratzl, U. Raviv and R. Elbaum: Tilted cellulose arrangement as a novel mechanism for hygroscopic coiling in the stork's bill awn. In: *Journal of the Royal Society Interface* 9, 69, 640-647 (2012).
- Amarie, S., P. Zaslansky, Y. Kajihara, E. Griesshaber, W. W. Schmahl and F. Keilmann: Nano-FTIR chemical mapping of minerals in biological materials. In: *Beilstein Journal of Nanotechnology* 3, 312-323 (2012).
- Andert, J., G. Börjesson and S. Hallin: Temporal Changes in Methane Oxidizing and Denitrifying Communities and Their Activities in a Drained Peat Soil. In: *Wetlands* 32, 6, 1047-1055 (2012).
- Andreeva, D. V., D. V. Sviridov, A. Masic, H. Möhwald and E. V. Skorb: Nanoengineered Metal Surface Capsules: Construction of a Metal-Protection System. In: *Small* 8, 6, 820-825 (2012).

Publications/Department of Biomaterials

- Cornelius, T. W., A. Davydok, V. L. R. Jacques, R. Grifone, T. Schüllli, M. I. Richard, G. Beutier, M. Verdier, T. H. Metzger, U. Pietsch and O. Thomas: In situ three-dimensional reciprocal-space mapping during mechanical deformation. In: *Journal of Synchrotron Radiation* 19, 688-694 (2012).
- Dean, M. N. and R. Shahar: The structure-mechanics relationship and the response to load of the acellular bone of neoteleost fish: a review. In: *Journal of Applied Ichthyology* 28, 3 Sp. Iss. SI, 320-329 (2012).
- Dmitrovic, V., G. J. M. Habraken, M. M. R. M. Hendrix, W. J. E. M. Habraken, A. Heise, G. de With and N. A. J. M. Sommerdijk: Random Poly(Amino Acid)s Synthesized by Ring Opening Polymerization as Additives in the Biomimetic Mineralization of CaCO₃. In: *Polymers* 4, 2, 1195-1210 (2012).
- Erko, M., D. Wallacher and O. Paris: Deformation mechanism of nanoporous materials upon water freezing and melting. In: *Applied Physics Letters* 101, 18, Seq. No.: 181905 (2012).
- Ermeidan, M. A., E. Cabane, A. Masic, J. Koetz and I. Burgert: Flavonoid Insertion into Cell Walls Improves Wood Properties. In: *ACS Applied Materials & Interfaces* 4, 11, 5782-5789 (2012).
- Fischer, F. D., J. Predan, P. Fratzl and O. Kolednik: Semi-analytical approaches to assess the crack driving force in periodically heterogeneous elastic materials. In: *International Journal of Fracture* 173, 1, 57-70 (2012).
- Fix, D., S. Puchegger, C. Pilz-Allen, P. Roschger, S. Blouin, P. Fratzl and R. Weinkamer: Functional mapping of bone on the micrometer-scale by scanning acoustic microscopy. In: *Bone* 50, Suppl. 1, S125-S126 (2012).
- Fratzl, P.: A Composite Matter of Alignment. In: *SCIENCE* 335, 6065, 177-178 (2012).
- Fratzl, P. and M.M. Giraud-Guille: Hierarchy in Natural Materials. In: *Hierarchically Structured Porous Materials*. (Eds.) Sanchez, Clément. Wiley-Vch, Weinheim (2012) 29-39.
- Fratzl-Zelman, N., P. Roschger, I. Schmidt, F. H. Glorieux, K. Klaushofer, P. Fratzl, F. Rauch and W. Wagermaier: Mineral particle size in children with dominant osteogenesis imperfecta is not associated with specific collagen mutation: A synchrotron X-ray scattering study. In: *Bone* 50, Suppl. 1, S129-S129 (2012).
- Gal, A., A. Hirsch, S. Siegel, C. H. Li, B. Aichmayer, Y. Politi, P. Fratzl, S. Weiner and L. Addadi: Plant Cystoliths: A Complex Functional Biocomposite of Four Distinct Silica and Amorphous Calcium Carbonate Phases. In: *Chemistry-A European Journal* 18, 33, 10262-10270 (2012).
- Gierlinger, N., T. Keplinger and M. Harrington: Imaging of plant cell walls by confocal Raman microscopy. In: *Nature Protocols* 7, 9, 1694-1708 (2012).
- Guzman, A., M. Zelman-Femiak, J. H. Boergemann, S. Paschkowsky, P. A. Kreuzaler, P. Fratzl, G. S. Harms and P. Knaus: SMAD versus Non-SMAD Signaling Is Determined by Lateral Mobility of Bone Morphogenetic Protein (BMP) Receptors. *Journal of Biological Chemistry* 287, 47, 39492-39504 (2012).
- Habegger, M. L., P. J. Motta, D. R. Huber and M. N. Dean: Feeding Biomechanics in Bull Sharks (*Carcharhinus leucas*) during Ontogeny. In: *Zoology* 115, 6, 354-364 (2012).
- Harrington, M. J., S. S. Wasko, A. Masic, F. D. Fischer, H. S. Gupta and P. Fratzl: Pseudoelastic behaviour of a natural material is achieved via reversible changes in protein backbone conformation. In: *Journal of the Royal Society Interface* 9, 76, 2911-2922 (2012).
- Herzog, G., M. M. Abul Kashem, G. Benecke, A. Buffet, R. Gehrke, J. Perlich, M. Schwartzkopf, V. Körstgens, R. Meier, M. A. Niedermeier, M. Rawolle, M. A. Ruderer, P. Müller-Buschbaum, W. Wurth and S. V. Roth: Influence of Nanoparticle Surface Functionalization on the Thermal Stability of Colloidal Polystyrene Films. In: *Langmuir* 28, 21, 8230-8237 (2012).
- Hoenicka, H., S. Lautner, A. Klingberg, G. Koch, F. El-Sherif, D. Lehnhardt, B. Zhang, I. Burgert, J. Odermatt, S. Melzer, J. Fromm and M. Fladung: Influence of over-expression of the FLOWERING PROMOTING FACTOR 1 gene (FPF1) from *Arabidopsis* on wood formation in hybrid poplar (*Populus tremula* L. x *P. tremuloides* Michx.). In: *Planta* 235, 2, 359-373 (2012).
- Hwang, D. S., M. J. Harrington, Q. Y. Lu, A. Masic, H. B. Zeng and J. H. Waite: Mussel foot protein-1 (mcfp-1) interaction with titania surfaces. In: *Journal of Materials Chemistry* 22, 31, 15530-15533 (2012).
- Klumpp, S. and D. Faivre: Interplay of Magnetic Interactions and Active Movements in the Formation of Magnetosome Chains. In: *PLoS ONE* 7, 3, Seq. No.: e33562 (2012).
- Körnig, A. and D. Faivre: Nanoparticles in magnetotactic bacteria. In: *Nature's Nanostructures*. (Eds.) Barnard, A. S.; Guo, H. Pan Stanford Publ., Singapore (2012) 249-271.
- Kuttner, C., M. Tebbe, H. Schlaad, I. Burgert and A. Fery: Photochemical Synthesis of Polymeric Fiber Coatings and Their Embedding in Matrix Material: Morphology and Nanomechanical Properties at the Fiber-Matrix Interface. In: *ACS Applied Materials & Interfaces* 4, 7, 3484-3492 (2012).
- Lee, K., W. Wagermaier, A. Masic, K.P. Kommareddy, M. Bennet, I. Manjubala, S. W. Lee, S. B. Park, H. Cölfen and P. Fratzl: Self-assembly of amorphous calcium carbonate microlens arrays. In: *Nature Communications* 3, Seq. No.: 725 (2012).
- Lee, S. W., Y. I. Kim, K. Lee, J. H. Bang, C. W. Jun and Y. N. Jang: Effect of Serine and Arginine on the Phase Transition from Amorphous CaCO₃ and CaCO₃.6H₂O to Calcite Film. In: *Materials Transactions* 53, 10, 1732-1738 (2012).
- Marwan, N., G. Beller, D. Felsenberg, P. Saporin and J. Kurths: QUANTIFYING CHANGES IN THE SPATIAL STRUCTURE OF TRABECULAR BONE. In: *International Journal of Bifurcation and Chaos* 22, 2, Seq. No.: 1250027 (2012).
- Masic, A., M. R. Chierotti, R. Gobetto, G. Martra, I. Rabin and S. Coluccia: Solid-state and unilateral NMR study of deterioration of a Dead Sea Scroll fragment. In: *Analytical and Bioanalytical Chemistry* 402, 4, 1551-1557 (2012).
- Murat, D., V. Falahati, L. Bertinetti, R. Csencsits, A. Körnig, K. Downing, D. Faivre and A. Komeili: The magnetosome membrane protein, MmsF, is a major regulator of magnetite biomineralization in *Magnetospirillum magneticum* AMB-1. In: *Molecular Microbiology* 85, 4, 684-699 (2012).

Publications/Department of Biomaterials

- Omelon, S., M. N. Dean, A. Masic, J. Georgiou and P. Fratzl: Evidence of polyphosphates and their distribution in active biological apatite mineralization sites of stingray jaws. In: *Bone* 50, Suppl. 1, S99-S100 (2012).
- Osorio-Madrao, A., M. Eder, M. Rueggeberg, J. K. Pandey, M. J. Harrington, Y. Nishiyama, J. L. Putaux, C. Rochas and I. Burgert: Reorientation of Cellulose Nanowhiskers in Agarose Hydrogels under Tensile Loading. In: *Biomacromolecules* 13, 3, 850-856 (2012).
- Pinzari, F., P. Colaizzi, O. Maggi, A. M. Persiani, R. Schütz and I. Rabin: Fungal bioleaching of mineral components in a twentieth-century illuminated parchment. In: *Analytical and Bioanalytical Chemistry* 402, 4, 1541-1550 (2012).
- Politi, Y., M. Priewasser, E. Pippel, P. Zaslansky, J. Hartmann, S. Siegel, C. H. Li, F. G. Barth and P. Fratzl: A Spider's Fang: How to Design an Injection Needle Using Chitin-Based Composite Material. In: *Advanced Functional Materials* 22, 12, 2519-2528 (2012).
- Potdevin, G., A. Malecki, T. Biernath, M. Bech, T. H. Jensen, R. Feidenhans'l, I. Zanette, T. Weitkamp, J. Kenntner, J. Mohr, P. Roschger, M. Kerschnitzki, W. Wagermaier, K. Klaushofer, P. Fratzl and F. Pfeiffer: X-ray vector radiography for bone micro-architecture diagnostics. In: *Physics in Medicine and Biology* 57, 11, 3451-3461 (2012).
- Prass, J., D. Müter, M. Erko and O. Paris: Apparent lattice expansion in ordered nanoporous silica during capillary condensation of fluids. In: *Journal of Applied Crystallography* 45, 798-806 (2012).
- Rumpler, M., T. Würger, P. Roschger, E. Zwettler, H. Peterlik, P. Fratzl and K. Klaushofer: Microcracks and Osteoclast Resorption Activity In Vitro. In: *Calcified Tissue International* 90, 3, 230-238 (2012).
- Rusconi, M., A. Valleriani, J.W.C. Dunlop, J. Kurths and R. Weinkamer: Quantitative approach to the stochasticity of bone remodeling. In: *EPL* 97, 2, Seq. No.: 28009 (2012).
- Sanchez-Rodriguez, C., S. Bauer, K. Hematy, F. Saxe, A. B. Ibanez, V. Vodermaier, C. Konlechner, A. Sampathkumar, M. Rüggeberg, E. Aichinger, L. Neumetzler, I. Burgert, C. Somerville, M. T. Hauser and S. Persson: CHITINASE-LIKE1/POM-POM1 and Its Homolog CTL2 Are Glucan-Interacting Proteins Important for Cellulose Biosynthesis in Arabidopsis. In: *Plant Cell* 24, 2, 589-607 (2012).
- Schenk, A. S., I. Zlotnikov, B. Pokroy, N. Gierlinger, A. Masic, P. Zaslansky, A. N. Fitch, O. Paris, T. H. Metzger, H. Cölfen, P. Fratzl and B. Aichmayer: Hierarchical Calcite Crystals with Occlusions of a Simple Polyelectrolyte Mimic Complex Biomineral Structures. In: *Advanced Functional Materials* 22, 22, 4668-4676 (2012).
- Schwemmer, T., J. Baumgartner, D. Faivre and H. G. Börner: Peptide-Mediated Nanoengineering of Inorganic Particle Surfaces: A General Route toward Surface Functionalization via Peptide Adhesion Domains. In: *Journal of the American Chemical Society* 134, 4, 2385-2391 (2012).
- Seto, J., B. Busse, H. S. Gupta, C. Schäfer, S. Krauss, J. W. C. Dunlop, A. Masic, M. Kerschnitzki, P. Zaslansky, P. Boesecke, P. Catala-Lehnen, T. Schinke, P. Fratzl and W. Jahnen-Dechent: Accelerated Growth Plate Mineralization and Foreshortened Proximal Limb Bones in Fetuin-A Knockout Mice. In: *PLoS ONE* 7, 10, Seq. No.: e47338 (2012).
- Seto, J., Y. R. Ma, S. A. Davis, F. Meldrum, A. Gourrier, Y. Y. Kim, U. Schilde, M. Sztucki, M. Burghammer, S. Maltsev, C. Jäger and H. Cölfen: Structure-property relationships of a biological mesocrystal in the adult sea urchin spine. In: *Proceedings of the National Academy of Sciences of the United States of America* 109, 10, 3699-3704 (2012).
- Sonkaria, S., G. Fuentes, C. Verma, R. Narang, V. Khare, A. Fischer and D. Faivre: Insight into the Assembly Properties and Functional Organisation of the Magnetotactic Bacterial Actin-like Homolog, MamK. In: *PLoS ONE* 7, 5, Seq. No.: e34189 (2012).
- Stoychev, G., S. Zakharchenko, S. Turcaud, J. W. C. Dunlop and L. Lonov: Shape-Programmed Folding of Stimuli-Responsive Polymer Bilayers. In: *ACS Nano* 6, 5, 3925-3934 (2012).
- Vermolen, F. J., A. Gefen and J. W. C. Dunlop: In Vitro "Wound" Healing: Experimentally Based Phenomenological Modeling. In: *Advanced Engineering Materials* 14, 3, B76-B88 (2012).
- Vetter, A., F. Witt, O. Sander, G. N. Duda and R. Weinkamer: The spatio-temporal arrangement of different tissues during bone healing as a result of simple mechanobiological rules. In: *Biomechanics and Modeling in Mechanobiology* 11, 1-2, 147-160 (2012).
- Wang, X. Q., H. Q. Ren, B. Zhang, B. H. Fei and I. Burgert: Cell wall structure and formation of maturing fibres of moso bamboo (*Phyllostachys pubescens*) increase buckling resistance. In: *Journal of the Royal Society Interface* 9, 70, 988-996 (2012).
- Woodruff, M. A., C. Lange, J. Reichert, A. Berner, F.L. Chen, P. Fratzl, J.T. Schantz and D.W. Huttmacher: Bone tissue engineering: from bench to bedside. In: *Materials Today* 15, 10, 430-435 (2012).
- Yashchenok, A. M., D. Borisova, B. V. Parakhonskiy, A. Masic, B. E. Pinchasik, H. Möhwald and A. G. Skirtach: Nanoplasmonic smooth silica versus porous calcium carbonate bead biosensors for detection of biomarkers. In: *Annalen der Physik* 524, 11, 723-732 (2012).
- Zickler, G. A., D. Ruffoni, J. W. C. Dunlop, R. Elbaum, R. Weinkamer, P. Fratzl and T. Antretter: Finite Element Modeling of the Cyclic Wetting Mechanism in the Active Part of Wheat Awns. In: *Biointerphases* 7, 1-4, Seq. No.: 42 (2012).

Publications/Department of Biomolecular Systems

Biomolecular Systems 2011

- Adibekian, A., P. Stallforth, M. L. Hecht, D. B. Werz, P. Gagneux and P. H. Seeberger: Comparative bioinformatics analysis of the mammalian and bacterial glycomes. In: *Chemical Science* 2, 2, 337-344 (2011).
- Barylyuk, K., R. M. Balabin, D. Grünstein, R. Kikkeri, V. Frankevich, P. H. Seeberger and R. Zenobi: What Happens to Hydrophobic Interactions during Transfer from the Solution to the Gas Phase? The Case of Electrospray-Based Soft Ionization Methods. In: *Journal of the American Society for Mass Spectrometry* 22, 7, 1167-1177 (2011).
- Bou-Hamdan, F. R., F. Levesque, A. G. O'Brien and P. H. Seeberger: Continuous flow photolysis of aryl azides: Preparation of 3H-azepinones. In: *Beilstein Journal of Organic Chemistry* 7, 1124-1129 (2011).
- Campbell, M. P., C. A. Hayes, W. B. Struwe, M. R. Wilkins, K. F. Aoki-Kinoshita, D. J. Harvey, P. M. Rudd, D. Kolarich, F. Lisacek, N. G. Karlsson and N. H. Packer: UniCarbKB: Putting the pieces together for glycomics research. In: *Proteomics* 11, 21, 4117-4121 (2011).
- Castagner, B., D. Esposito and P. H. Seeberger: Automated solid phase oligosaccharide synthesis. In: *Glycosylation in Diverse Cell Systems: Challenges and New Frontiers in Experimental Biology*. (Eds.) Brooks, S. A.; Rudd, P. M.; Appelmiek, B. J. Essential reviews in experimental biology 4. Society for Experimental Biology, London (2011) 237-270.
- Coste, G., T. Horlacher, L. Molina, A. J. Moreno-Vargas, A. T. Carmona, I. Robina, P. H. Seeberger and S. Gerber-Lemaire: Synthesis and Biological Evaluation of Modified 2-Deoxystreptamine Dimers. In: *Synthesis-Stuttgart*, 11, 1759-1770 (2011).
- Dietrich, P. M., T. Horlacher, P. L. Girard-Lauriault, T. Gross, A. Lippitz, H. Min, T. Wirth, R. Castelli, P. H. Seeberger and W. E. S. Unger: Adlayers of Dimannoside Thiols on Gold: Surface Chemical Analysis. In: *Langmuir* 27, 8, 4808-4815 (2011).
- Dietrich, P. M., T. Horlacher, P.-L. Girard-Lauriault, T. Gross, A. Lippitz, H. Min, T. Wirth, A. G. Shard, R. Castelli, P. H. Seeberger and W. E. S. Unger: Multi-method chemical characterization of carbohydrate-functionalised surfaces. In: *Journal of Carbohydrate Chemistry* 30, 361-372 (2011).
- Gruber, K., B. A. Hermann and P. H. Seeberger: Sensing Carbohydrate-Protein Interactions at Picomolar Concentrations Using Cantilever Arrays. In: *Angewandte Chemie-International Edition* 50, 37, A46-A51 (2011).
- Gruber, K., T. Horlacher, R. Castelli, A. Mader, P. H. Seeberger and B. A. Hermann: Cantilever Array Sensors Detect Specific Carbohydrate-Protein Interactions with Picomolar Sensitivity. In: *ACS Nano* 5, 5, 3670-3678 (2011).
- Grünstein, D., M. Magliano, R. Kikkeri, M. Collot, K. Barylyuk, B. Lepenies, F. Kamena, R. Zenobi and P. H. Seeberger: Hexameric Supramolecular Scaffold Orients Carbohydrates To Sense Bacteria. In: *JOURNAL OF THE AMERICAN CHEMICAL SOCIETY* 133, 35, 13957-13966 (2011).
- Hartmann, L.: Polymers for Control Freaks: Sequence-Defined Poly(amidoamine)s and Their Biomedical Applications. In: *Macromolecular Chemistry and Physics* 212, 1, 8-13 (2011).
- Horlacher, T., C. Noti, J. L. de Paz, P. Bindschadler, M. L. Hecht, D. F. Smith, M. N. Fukuda and P. H. Seeberger: Characterization of Annexin A1 Glycan Binding Reveals Binding to Highly Sulfated Glycans with Preference for Highly Sulfated Heparan Sulfate and Heparin. In: *Biochemistry* 50, 13, 2650-2659 (2011).
- Horlacher, T. and P. H. Seeberger: Glycan arrays. In: *Glycosylation in Diverse Cell Systems: Challenges and New Frontiers in Experimental Biology*. (Eds.) Brooks, S. A.; Rudd, P. M.; Appelmiek, B. J. Essential reviews in experimental biology 4. Society for Experimental Biology, London (2011) 197-212.
- Kamena, F., B. Monnanda, D. Makou, S. Capone, K. Patora-Komisarska and D. Seebach: On the Mechanism of Eukaryotic Cell Penetration by α - and β -Oligoarginines – Targeting Infected Erythrocytes. In: *Chemistry & Biodiversity* 8, 1, 1-12 (2011).
- Khil'chenko, S. R., T. S. Zaporozhets, N. M. Shevchenko, T. N. Zvyagintseva, U. Vogel, P. H. Seeberger and B. Lepenies: Immunostimulatory activity of fucoidan from the brown alga *Fucus evaescens*: role of sulfates and acetates. In: *Journal of Carbohydrate Chemistry* 30, 291-305 (2011).
- Kikkeri, R., S. Y. Hong, D. Grünstein, P. Laurino and P. H. Seeberger: Carbohydrate-based nanoscience: metallo-glycodendrimers and quantum dots as multivalent probes. In: *Proceedings of the International Beilstein Symposium on Functional Nanoscience*. (Eds.) Hicks, M. G.; Kettner, C. Logos-Verlag, Berlin (2011) 143-166.
- Laurino, P., R. Kikkeri, N. Azzouz and P. H. Seeberger: Detection of Bacteria Using Glyco-Dendronized Polylysine Prepared by Continuous Flow Photofunctionalization. In: *Nano Letters* 11, 1, 73-78 (2011).
- Laurino, P., R. Kikkeri and P. H. Seeberger: Continuous-flow reactor-based synthesis of carbohydrate and dihydrolipoic acid-capped quantum dots. In: *Nature Protocols* 6, 8, 1209-1220 (2011).
- Levesque, F. and P. H. Seeberger: Highly Efficient Continuous Flow Reactions Using Singlet Oxygen as a "Green" Reagent. In: *ORGANIC LETTERS* 13, 19, 5008-5011 (2011).
- Martin, C. E., M. W. Weishaupt and P. H. Seeberger: Progress toward developing a carbohydrate-conjugate vaccine against *Clostridium difficile* ribotype 027: synthesis of the cell-surface polysaccharide PS-I repeating unit. In: *Chemical Communications* 47, 37, 10260-10262 (2011).
- Merbouh, N., J. R. Brown, F. Wallner, M. Morton, J. D. Esko and P. H. Seeberger: Rapid chemo-enzymatic synthesis of peracetylated GlcNAc β 3Gal β -aglycones. In: *Journal of Carbohydrate Chemistry* 30, 373-390 (2011).
- Mosca, S., F. Wojcik and L. Hartmann: Precise Positioning of Chiral Building Blocks in Monodisperse, Sequence-Defined Polyamides. In: *Macromolecular Rapid Communications* 32, 2 Sp. Iss., 197-202 (2011).
- Oberli, M. A., M. L. Hecht, P. Bindschadler, A. Adibekian, T. Adam and P. H. Seeberger: A Possible Oligosaccharide-Conjugate Vaccine Candidate for *Clostridium difficile* Is Antigenic and Immunogenic. In: *Chemistry & Biology* 18, 5, 580-588 (2011).
- O'Brien, A. G., F. Levesque and P. H. Seeberger: Continuous flow thermolysis of azidoacrylates for the synthesis of heterocycles and pharmaceutical intermediates. In: *Chemical Communications* 47, 9, 2688-2690 (2011).
- O'Brien, A. G., F. Levesque, Y. Suzuki and P. H. Seeberger: Safe use of azides in continuous flow. In: *Chimica Oggi-Chemistry Today* 29, 3, 57-60 (2011).
- Pragani, R. and P. H. Seeberger: Total Synthesis of the *Bacteroides fragilis* Zwitterionic Polysaccharide A1 Repeating Unit. In: *Journal of the American Chemical Society* 133, 1, 102-107 (2011).
- Schlegel, M. K., J. Hütter, M. Eriksson, B. Lepenies and P. H. Seeberger: Defined presentation of carbohydrates on a duplex DNA scaffold. In: *ChemBioChem* 12, 18, 2791-2800 (2011).
- Seeberger, P. H. and D. B. Werz: Glycochemistry and glycobiology: a web themed issue. In: *CHEMICAL COMMUNICATIONS* 47, 45, 12259-12259 (2011).

Publications/Department of Biomolecular Systems

- Tamborrini, M., M. Bauer, M. Bolz, A. Maho, M. A. Oberli, D. B. Werz, E. Schelling, J. Zinsstag, P. H. Seeberger, J. Frey and G. Pluschke: Identification of an African *Bacillus anthracis* Lineage That Lacks Expression of the Spore Surface-Associated Anthrose-Containing Oligosaccharide. In: *Journal of Bacteriology* 193, 14, 3506-3511 (2011).
- Tsai, Y. H., S. Götze, N. Azzouz, H. S. Hahm, P. H. Seeberger and D. V. Silva: A General Method for Synthesis of GPI Anchors Illustrated by the Total Synthesis of the Low-Molecular-Weight Antigen from *Toxoplasma gondii*. In: *ANGEWANDTE CHEMIE-INTERNATIONAL EDITION* 50, 42, 9961-9964 (2011).
- Weber, A., H. Butterweck, U. Mais-Paul, W. Teschner, L. Lei, E. M. Muchitsch, D. Kolarich, F. Altmann, H. J. Ehrlich and H. P. Schwarz: Biochemical, molecular and preclinical characterization of a double-virus-reduced human butyrylcholinesterase preparation designed for clinical use. In: *Vox Sanguinis* 100, 3, 285-297 (2011).
-
- Biomolecular Systems 2012**
- Bellapadrona, G., A. B. Tesler, D. Grünstein, L. H. Hossain, R. Kikkeri, P. H. Seeberger, A. Vaskevich and I. Rubinstein: Optimization of Localized Surface Plasmon Resonance Transducers for Studying Carbohydrate-Protein Interactions. In: *Analytical Chemistry* 84, 1, 232-240 (2012).
- Bou-Hamdan, F. R. and P. H. Seeberger: Visible-light-mediated photochemistry: accelerating Ru(bpy)₃(2+)-catalyzed reactions in continuous flow. In: *Chemical Science* 3, 5, 1612-1616 (2012).
- Broecker, F. and K. Moelling: Short hairpin-looped oligodeoxynucleotides reduce hepatitis C virus replication. In: *Virology Journal* 9, Seq. No.: 134 (2012).
- Cahn, O., R. Pragani and P. H. Seeberger: De Novo Synthesis of L-Colitose and L-Rhodinose Building Blocks. In: *Journal of Organic Chemistry* 77, 2, 870-877 (2012).
- Esposito, D., M. Hurevich, B. Castagner, C. C. Wang and P. H. Seeberger: Automated synthesis of sialylated oligosaccharides. In: *Beilstein Journal of Organic Chemistry* 8, 1601-1609 (2012).
- Kolarich, D., B. Lepenies and P. H. Seeberger: Glycomics, glycoproteomics and the immune system. In: *Current Opinion in Chemical Biology* 16, 1-2, 214-220 (2012).
- Kopetzki, D. and P. H. Seeberger: Photochemistry in Fight against Malaria. In: *Nachrichten aus der Chemie* 60, 7-8, 714-717 (2012).
- Kröck, L., D. Esposito, B. Castagner, C. C. Wang, P. Bindschädler and P. H. Seeberger: Streamlined access to conjugation-ready glycans by automated synthesis. In: *Chemical Science* 3, 5, 1617-1622 (2012).
- Laurino, P., H. F. Hernandez, J. Bräuer, K. Krüger, H. Grützmaker, K. Tauer and P. H. Seeberger: Snowballing Radical Generation Leads to Ultrahigh Molecular Weight Polymers. In: *Macromolecular Rapid Communications* 33, 20, 1770-1774 (2012).
- Leonori, D. and P. H. Seeberger: De Novo Synthesis of the Bacterial 2-Amino-2,6-Dideoxy Sugar Building Blocks D-Fucosamine, D-Bacillofucosamine, and D-Xylo-6-deoxy-4-ketohexosamine. In: *Organic Letters* 14, 18, 4954-4957 (2012).
- Levesque, F. and P. H. Seeberger: Continuous-Flow Synthesis of the Anti-Malaria Drug Artemisinin. In: *Angewandte Chemie-International Edition* 51, 7, 1706-1709 (2012).
- Mader, A., K. Gruber, R. Castelli, B. A. Hermann, P. H. Seeberger, J. O. Rädler and M. Leisner: Discrimination of *Escherichia coli* Strains using Glycan Cantilever Array Sensors. In: *Nano Letters* 12, 1, 420-423 (2012).
- O'Brien, A. G., Z. Horvath, F. Levesque, J. W. Lee, A. Seidel-Morgenstern and P. H. Seeberger: Continuous Synthesis and Purification by Direct Coupling of a Flow Reactor with Simulated Moving-Bed Chromatography. In: *Angewandte Chemie-International Edition* 51, 28, 7028-7030 (2012).
- Ponader, D., F. Wojcik, F. Beceren-Braun, J. Dernedde and L. Hartmann: Sequence-Defined Glycopolymer Segments Presenting Mannose: Synthesis and Lectin Binding Affinity. In: *Biomacromolecules* 13, 6, 1845-1852 (2012).
- Pussak, D., M. Behra, S. Schmidt and L. Hartmann: Synthesis and functionalization of poly(ethylene glycol) microparticles as soft colloidal probes for adhesion energy measurements. In: *Soft Matter* 8, 5, 1664-1672 (2012).
- Rademacher, C. and J. C. Paulson: Glycan Fingerprints: Calculating Diversity in Glycan Libraries. In: *ACS Chemical Biology* 7, 5, 829-834 (2012).
- Shibata, T. K., F. Matsumura, P. Wang, S. Y. Yu, C. C. Chou, K. H. Khoo, K. Kitayama, T. O. Akama, K. Sugihara, N. Kanayama, K. Kojima-Aikawa, P. H. Seeberger, M. Fukuda, A. Suzuki, D. Aoki and M. N. Fukuda: Identification of Mono- and Disulfated N-Acetyl-lactosaminyl Oligosaccharide Structures as Epitopes Specifically Recognized by Humanized Monoclonal Antibody HMOCC-1 Raised against Ovarian Cancer. In: *Journal of Biological Chemistry* 287, 9, 6592-6602 (2012).
- Stallforth, P., S. Matthies, A. Adibekian, D. Hilvert and P. H. Seeberger: De novo chemoenzymatic synthesis of sialic acid. In: *Chemical Communications* 48, 98, 11987-11989 (2012).
- Suzuki, Y., P. Laurino, D. T. McQuade and P. H. Seeberger: A Capture-and-Release Catalytic Flow System. In: *Helvetica Chimica Acta* 95, 12, 2578-2588 (2012).
- Tsai, Y.-H., M. Grube, P. H. Seeberger and D. Varon Silva: Glycosylphosphatidylinositols of protozoan parasites. In: *Trends in Glycoscience and Glycotechnology* 24, 140, 231-243 (2012).
- Tsai, Y.-H., X. Liu and P. H. Seeberger: Chemical biology of glycosylphosphatidylinositol anchors. In: *Angewandte Chemie International Edition* 51, 11438-11456 (2012).
- Walvoort, M. T. C., H. van den Elst, O. J. Plante, L. Krock, P. H. Seeberger, H. S. Overkleeft, G. A. van der Marel and J. D. C. Codee: Automated Solid-Phase Synthesis of beta-Mannuronic Acid Alginates. In: *Angewandte Chemie-International Edition* 51, 18, 4393-4396 (2012).
- Williams, C. C., S. H. Thang, T. Hantke, U. Vogel, P. H. Seeberger, J. Tsanaktisidis and B. Lepenies: RAFT-Derived Polymer-Drug Conjugates: Poly(hydroxypropyl methacrylamide) (HPMA)-7-Ethyl-10-hydroxycamptothecin (SN-38) Conjugates. In: *ChemMedChem* 7, 2, 281-291 (2012).
- Williams, C. F., D. Lloyd, D. Kolarich, K. Alagesan, M. Duchene, J. Cable, D. Williams and D. Leitsch: Disrupted intracellular redox balance of the diplomonad fish parasite *Spironucleus vortens* by 5-nitroimidazoles and garlic-derived compounds. In: *Veterinary Parasitology* 190, 1-2, 62-73 (2012).
- Yang, Y., C. E. Martin and P. H. Seeberger: Total synthesis of the core tetrasaccharide of *Neisseria meningitidis* lipopolysaccharide, a potential vaccine candidate for meningococcal diseases. In: *Chemical Science* 3, 3, 896-899 (2012).
- Yin, J., S. Eller, M. Collot and P. H. Seeberger: Acylsulfonamide safety-catch linker: promise and limitations for solid-phase oligosaccharide synthesis. In: *Beilstein Journal of Organic Chemistry* 8, 2067-2071 (2012).

Publications/Department of Colloid Chemistry

Colloid Chemistry 2011

- Ahmad, H., M. K. Hasan, M. A. J. Miah, A. M. I. Ali and K. Tauer: Solvent effect on the emulsion copolymerization of methyl methacrylate and lauryl methacrylate in aqueous media. In: *Polymer* 52, 18, 3925-3932 (2011).
- Antonietti, M.: The wiser choice. In: *Nachrichten aus der Chemie* 59, 11, 1027-1027 (2011).
- Baccile, N., G. Laurent, C. Coelho, F. Babonneau, L. Zhao and M. M. Titirici: Structural Insights on Nitrogen-Containing Hydrothermal Carbon Using Solid-State Magic Angle Spinning ^{13}C and ^{15}N Nuclear Magnetic Resonance. In: *Journal of Physical Chemistry C* 115, 18, 8976-8982 (2011).
- Barner-Kowollik, C., F. E. Du Prez, P. Espeel, C. J. Hawker, T. Junkers, H. Schlaad and W. Van Camp: "Clicking" Polymers or Just Efficient Linking: What Is the Difference?. In: *Angewandte Chemie-International Edition* 50, 1, 60-62 (2011).
- Botiz, I., H. Schlaad and G. Reiter: Processes of ordered structure formation in polypeptide thin film solutions. In: *Advances in Polymer Science* 242, 117-149 (2011).
- Brandt, J., J. Schmidt, A. Thomas, J. D. Epping and J. Weber: Tunable absorption and emission wavelength in conjugated microporous polymers by copolymerization. In: *Polymer Chemistry* 2, 9, 1950-1952 (2011).
- Cui, Y. J., J. S. Zhang, G. G. Zhang, J. H. Huang, P. Liu, M. Antonietti and X. C. Wang: Synthesis of bulk and nanoporous carbon nitride polymers from ammonium thiocyanate for photocatalytic hydrogen evolution. In: *Journal of Materials Chemistry* 21, 34, 13032-13039 (2011).
- de Espinosa, L. M. and M. A. R. Meier: Synthesis of star- and block-copolymers using ADMET: head-to-tail selectivity during step-growth polymerization. In: *Chemical Communications* 47, 6, 1908-1910 (2011).
- Delahaye, E., Z. L. Xie, A. Schaefer, L. Douce, G. Rogez, P. Rabu, C. Gunter, J. S. Gutmann and A. Taubert: Intercalation synthesis of functional hybrid materials based on layered simple hydroxide hosts and ionic liquid guests - a pathway towards multifunctional ionogels without a silica matrix?. In: *DALTON TRANSACTIONS* 40, 39, 9977-9988 (2011).
- Diehl, C., I. Dambowsky, R. Hoogenboom and H. Schlaad: Self-Assembly of Poly(2-alkyl-2-oxazoline)s by Crystallization in Ethanol-Water Mixtures Below the Upper Critical Solution Temperature. In: *Macromolecular Rapid Communications* 32, 21, 1753-1758 (2011).
- Ding, Z. X., X.F. Chen, M. Antonietti and X.C. Wang: Synthesis of Transition Metal-Modified Carbon Nitride Polymers for Selective Hydrocarbon Oxidation. In: *ChemSusChem* 4, 2 Sp. Iss., 274-281 (2011).
- Egli, S., H. Schlaad, N. Bruns and W. Meier: Functionalization of block copolymer vesicle surfaces. In: *Polymers* 3, 1, 252-280 (2011).
- Erel, I., H. Schlaad and A. L. Demirel: Effect of structural isomerism and polymer end group on the pH-stability of hydrogen-bonded multilayers. In: *Journal of Colloid and Interface Science* 361, 2, 477-482 (2011).
- Essawy, H. and K. Tauer: Polyamide capsules via soft templating with oil drops-2. Subsequent radical polymerization of styrene. In: *Colloid and Polymer Science* 289, 2, 121-132 (2011).
- Falco, C., N. Baccile and M. M. Titirici: Morphological and structural differences between glucose, cellulose and lignocellulosic biomass derived hydrothermal carbons. In: *GREEN CHEMISTRY* 13, 11, 3273-3281 (2011).
- Falco, C., F. P. Caballero, F. Babonneau, C. Gervais, G. Laurent, M. M. Titirici and N. Baccile: Hydrothermal Carbon from Biomass: Structural Differences between Hydrothermal and Pyrolyzed Carbons via ^{13}C Solid State NMR. In: *Langmuir* 27, 23, 14460-14471 (2011).
- Farra, R., K. Thiel, A. Winter, T. Klamroth, A. Pöpl, A. Kelling, U. Schilde, A. Taubert and P. Strauch: Tetrahalidocuprates(II)-structure and EPR spectroscopy. Part 1: Tetrabromidocuprates(II). In: *NEW JOURNAL OF CHEMISTRY* 35, 12, 2793-2803 (2011).
- Fukasawa, Y., K. Takanabe, A. Shimojima, M. Antonietti, K. Domen and T. Okubo: Synthesis of Ordered Porous Graphitic- C_3N_4 and Regularly Arranged Ta_3N_5 Nanoparticles by Using Self-Assembled Silica Nanospheres as a Primary Template. In: *Chemistry-an Asian Journal* 6, 1, 103-109 (2011).
- Gao, Q. S., C. Giordano and M. Antonietti: Controlled Synthesis of Tantalum Oxynitride and Nitride Nanoparticles. In: *Small* 7, 23, 3334-3340 (2011).
- Garcia-Marquez, A., D. Portehault and C. Giordano: Chromium nitride and carbide nanofibers: from composites to mesostructures. In: *Journal of Materials Chemistry* 21, 7, 2136-2143 (2011).
- Gentsch, R. and H. G. Börner: Designing Three-Dimensional Materials at the Interface to Biology. In: *Advances in Polymer Science* 240, 163-192 (2011).
- Gentsch, R., F. Pippig, S. Schmidt, P. Cernoch, J. Polleux and H. G. Börner: Single-Step Electrospinning to Bioactive Polymer Nanofibers. In: *Macromolecules* 44, 3, 453-461 (2011).
- Giordano, C. and M. Antonietti: Synthesis of crystalline metal nitride and metal carbide nanostructures by sol-gel chemistry. In: *Nano Today* 6, 4, 366-380 (2011).
- Giordano, C., A. Kraupner, I. Fleischer, C. Henrich, G. Klingelhöfer and M. Antonietti: Non-conventional Fe_3C -based nanostructures. In: *Journal of Materials Chemistry* 21, 42, 16963-16967 (2011).
- Giordano, C., W. Yang, A. Lindemann, R. Crombez and J. Texter: Waterborne WC nanodispersions. In: *Colloids and Surfaces A-Physicochemical and Engineering Aspects* 374, 1-3, 84-87 (2011).
- Graf, P., A. Manton, A. Haase, A. F. Thünemann, A. Masic, W. Meier, A. Luch and A. Taubert: Silicification of Peptide-Coated Silver Nanoparticles-A Biomimetic Soft Chemistry Approach toward Chiral Hybrid Core-Shell Materials. In: *ACS Nano* 5, 2, 820-833 (2011).
- Haase, A., H. F. Arlinghaus, J. Tentschert, H. Jungnickel, P. Graf, A. Manton, F. Draude, S. Galla, J. Plendl, M. E. Goetz, A. Masic, W. Meier, A. F. Thünemann, A. Taubert and A. Luch: Application of Laser Postionization Secondary Neutral Mass Spectrometry/Time-of-Flight Secondary Ion Mass Spectrometry in Nanotoxicology: Visualization of Nanosilver in Human Macrophages and Cellular Responses. In: *ACS Nano* 5, 4, 3059-3068 (2011).

Publications/Department of Colloid Chemistry

- Haase, A., J. Tentschert, H. Jungnickel, P. Graf, A. Mantion, F. Draude, J. Plendl, M. E. Goetz, A. Galla, A. Masic, A. F. Thünemann, A. Taubert, H. F. Arlinghaus and A. Luch: Toxicity of silver nanoparticles in human macrophages: uptake, intracellular distribution and cellular responses. In: *Journal of Physics: Conference Series* 304, Seq. No.: 012030 (2011).
- Hermes, F., K. Otte, J. Brandt, M. Gräwert, H. G. Börner and H. Schlaad: Polypeptide-Based Organogelators: Effects of Secondary Structure. In: *Macromolecules* 44, 18, 7489-7492 (2011).
- Hoogenboom, R. and H. Schlaad: Bioinspired poly(2-oxazoline)s. In: *Polymers* 3, 1, 467-488 (2011).
- Jeromenok, J., W. Böhlmann, M. Antonietti and J. Weber: Intrinsically Microporous Polyesters From Betulin - Toward Renewable Materials for Gas Separation Made From Birch Bark. In: *Macromolecular Rapid Communications* 32, 22, 1846-1851 (2011).
- Jiang, Y., H. F. Gong, D. Volkmer, L. Gower and H. Cölfen: Preparation of Hierarchical Mesocrystalline DL-Lysine . HCl-Poly(acrylic acid) Hybrid Thin Films. In: *Advanced Materials* 23, 31, 3548-3552 (2011).
- Jiang, Y., L. Gower, D. Volkmer and H. Cölfen: Hierarchical DL-Glutamic Acid Microspheres from Polymer-Induced Liquid Precursors. In: *Crystal Growth & Design* 11, 7, 3243-3249 (2011).
- Kita-Tokarczyk, K., M. Junginger, S. Belegriou and A. Taubert: Amphiphilic Polymers at Interfaces. In: *Advances in Polymer Science* 242, 151-201 (2011).
- Kopetzki, D. and M. Antonietti: Hydrothermal formose reaction. In: *New Journal of Chemistry* 35, 9, 1787-1794 (2011).
- Krüger, K., K. Tauer, Y. Yagci and N. Moszner: Photoinitiated Bulk and Emulsion Polymerization of Styrene - Evidence for Photo-Controlled Radical Polymerization. In: *MACROMOLECULES* 44, 24, 9539-9549 (2011).
- Kubo, S., R. J. White, N. Yoshizawa, M. Antonietti and M. M. Titirici: Ordered Carbohydrate-Derived Porous Carbons. In: *Chemistry of Materials* 23, 22, 4882-4885 (2011).
- Latnikova, A., D. O. Grigoriev, J. Hartmann, H. Möhwald and D. G. Shchukin: Polyfunctional active coatings with damage-triggered water-repelling effect. In: *Soft Matter* 7, 2, 369-372 (2011).
- Lausser, C., D. Zahn and H. Cölfen: Barium titanate nanoparticle self-organization in an external electric field. In: *JOURNAL OF MATERIALS CHEMISTRY* 21, 42, 16978-16982 (2011).
- Lei, W., D. Portehault, R. Dimova and M. Antonietti: Boron Carbon Nitride Nanostructures from Salt Melts: Tunable Water-Soluble Phosphors. In: *Journal of the American Chemical Society* 133, 18, 7121-7127 (2011).
- Li, X. H., J. S. Chen, X. C. Wang, J. H. Sun and M. Antonietti: Metal-Free Activation of Dioxide by Graphene/g-C₃N₄ Nanocomposites: Functional Dyads for Selective Oxidation of Saturated Hydrocarbons. In: *Journal of the American Chemical Society* 133, 21, 8074-8077 (2011).
- Li, X. H., J. S. Zhang, X. F. Chen, A. Fischer, A. Thomas, M. Antonietti and X. C. Wang: Condensed Graphitic Carbon Nitride Nanorods by Nanoconfinement: Promotion of Crystallinity on Photocatalytic Conversion. In: *Chemistry of Materials* 23, 19, 4344-4348 (2011).
- Löbbecke, R., M. Chanana, H. Schlaad, C. Pilz-Allen, C. Günter, H. Möhwald and A. Taubert: Polymer Brush Controlled Bioinspired Calcium Phosphate Mineralization and Bone Cell Growth. In: *BIOMACROMOLECULES* 12, 10, 3753-3760 (2011).
- Madaan, N., A. Terry, J. Harb, R. C. Davis, H. Schlaad and M. R. Linford: Thiol-Ene-Thiol Photofunctionalization of Thiolated Monolayers with Polybutadiene and Functional Thiols, Including Thiolated DNA. In: *Journal of Physical Chemistry C* 115, 46, 22931-22938 (2011).
- Mantion, A., P. Graf, I. Florea, A. Haase, A. F. Thünemann, A. Masic, O. Ersen, P. Rabu, W. Meier, A. Luch and A. Taubert: Biomimetic synthesis of chiral erbium-doped silver/peptide/silica core-shell nanoparticles (ESPN). In: *Nanoscale* 3, 12, 5168-5179 (2011).
- Marquardt, D., Z. L. Xie, A. Taubert, R. Thomann and C. Janiak: Microwave synthesis and inherent stabilization of metal nanoparticles in 1-methyl-3-(3-carboxyethyl)-imidazolium tetrafluoroborate. In: *Dalton Transactions* 40, 33, 8290-8293 (2011).
- Mutlu, H., L. M. de Espinosa and M. A. R. Meier: Acyclic diene metathesis: a versatile tool for the construction of defined polymer architectures. In: *Chemical Society Reviews* 40, 3, 1404-1445 (2011).
- Popovic, J., R. Demir-Cakan, J. Tomow, M. Morcrette, D. S. Su, R. Schlogl, M. Antonietti and M. M. Titirici: LiFePO₄ Mesocrystals for Lithium-Ion Batteries. In: *Small* 7, 8, 1127-1135 (2011).
- Portehault, D., S. Devi, P. Beaunier, C. Gervais, C. Giordano, C. Sanchez and M. Antonietti: A General Solution Route toward Metal Boride Nanocrystals. In: *Angewandte Chemie-International Edition* 50, 14, 3262-3265 (2011).
- Portehault, D., V. Maneeratana, C. Candolfi, N. Deschler, I. Veremchuk, Y. Grin, C. Sanchez and M. Antonietti: Facile General Route toward Tunable Magneli Nanostructures and Their Use As Thermoelectric Metal Oxide/Carbon Nanocomposites. In: *ACS Nano* 5, 11, 9052-9061 (2011).
- Prieto, S., A. Shkilnyy, C. Rumlach, A. Ribeiro, F. J. Arias, J. C. Rodriguez-Cabello and A. Taubert: Biomimetic Calcium Phosphate Mineralization with Multifunctional Elastin-Like Recombinamers. In: *Biomacromolecules* 12, 5, 1480-1486 (2011).
- Ritter, N., I. Senkovska, S. Kaskel and J. Weber: Intrinsically Microporous Poly(imide)s: Structure-Porosity Relationship Studied by Gas Sorption and X-ray Scattering. In: *Macromolecules* 44, 7, 2025-2033 (2011).
- Ritter, N., I. Senkovska, S. Kaskel and J. Weber: Towards Chiral Microporous Soluble Polymers - Binaphthalene-Based Polyimides. In: *Macromolecular Rapid Communications* 32, 5, 438-443 (2011).
- Schnepp, Z., M. Thomas, S. Glatzel, K. Schlichte, R. Palkovits and C. Giordano: One pot route to sponge-like Fe₃N nanostructures. In: *Journal of Materials Chemistry* 21, 44, 17760-17764 (2011).
- Sevilla, M., A. B. Fuertes and R. Mokaya: Preparation and hydrogen storage capacity of highly porous activated carbon materials derived from polythiophene. In: *International Journal of Hydrogen Energy* 36, 24, 15658-15663 (2011).

Publications/Department of Colloid Chemistry

- Shkilnyy, A., S. Schone, C. Rumpel, A. Uhlmann, A. Hedderich, C. Gunter and A. Taubert: Calcium phosphate mineralization with linear poly(ethylene imine): a time-resolved study. In: *Colloid and Polymer Science* 289, 8, 881-888 (2011).
- Stocco, A., T. Mokhtari, G. Haseloff, A. Erbe and R. Sigel: Evanescent-wave dynamic light scattering at an oil-water interface: Diffusion of interface-adsorbed colloids. In: *Physical Review E* 83, 1, Seq. No.: 011601 (2011).
- Stocco, A., K. Tauer, S. Pispas and R. Sigel: Dynamics of amphiphilic diblock copolymers at the air-water interface. In: *Journal of Colloid and Interface Science* 355, 1, 172-178 (2011).
- Su, F. Z. and M. Antonietti: Carbon nitride-photocatalyzed aerobic oxygenation of tertiary amines via activation of sp(3) C-H bond with visible light. In: *Abstracts of Papers of the American Chemical Society* 241, (2011).
- Su, F. Z., S. C. Mathew, L. Mohlmann, M. Antonietti, X. C. Wang and S. Blechert: Aerobic Oxidative Coupling of Amines by Carbon Nitride Photocatalysis with Visible Light. In: *Angewandte Chemie-International Edition* 50, 3, 657-660 (2011).
- Tauer, K., H. Hernandez, N. Weber and F. Roohi: Molecular Versus Conventional Kinetics of Emulsion Polymerization. In: *Macromolecular Symposia* 302, 110-120 (2011).
- ten Brummelhuis, N. and H. Schlaad: Stimuli-responsive star polymers through thiol-yne core functionalization/crosslinking of block copolymer micelles. In: *Polymer Chemistry* 2, 5, 1180-1184 (2011).
- Texter, J., R. Crombez, X. M. Ma, F. P. Caballero, L. Zhao, M. M. Titirici and M. Antonietti: Waterborne nanocarbon dispersions for electronic and fuel applications. In: *Abstracts of Papers of the American Chemical Society* 241, (2011).
- Texter, J., R. Crombez, X. Ma, M. M. Titirici and M. Antonietti: Aqueous nanocarbon dispersions for electronic and energy applications. In: *Abstracts of Papers of the American Chemical Society* 241, (2011).
- Thiel, K., T. Klamroth, P. Strauch and A. Taubert: On the interaction of ascorbic acid and the tetrachlorocuprate ion $[\text{CuCl}_4]^{2-}$ in CuCl nanoplatelet formation from an ionic liquid precursor (ILP). In: *Physical Chemistry Chemical Physics* 13, 30, 13537-13543 (2011).
- Unterlass, M. M., D. Kopetzki, M. Antonietti and J. Weber: Mechanistic study of hydrothermal synthesis of aromatic polyimides. In: *Polymer Chemistry* 2, 8, 1744-1753 (2011).
- Verch, A., D. Gebauer, M. Antonietti and H. Cölfen: How to control the scaling of CaCO_3 : a "fingerprinting technique" to classify additives. In: *Physical Chemistry Chemical Physics* 13, 37, 16811-16820 (2011).
- Wagner, C. S., S. Shehata, K. Henzler, J. Y. Yuan and A. Wittemann: Towards nanoscale composite particles of dual complexity. In: *Journal of Colloid and Interface Science* 355, 1, 115-123 (2011).
- Wang, Y., H. R. Li, J. Yao, X. C. Wang and M. Antonietti: Synthesis of boron doped polymeric carbon nitride solids and their use as metal-free catalysts for aliphatic C-H bond oxidation. In: *Chemical Science* 2, 3, 446-450 (2011).
- Wang, Y., J. Yao, H. R. Li, D. S. Su and M. Antonietti: Highly Selective Hydrogenation of Phenol and Derivatives over a Pd@Carbon Nitride Catalyst in Aqueous Media. In: *Journal of the American Chemical Society* 133, 8, 2362-2365 (2011).
- Weber, J., N. Y. Du and M. D. Guiver: Influence of Intermolecular Interactions on the Observable Porosity in Intrinsically Microporous Polymers. In: *Macromolecules* 44, 7, 1763-1767 (2011).
- Weber, N., J. Texter and K. Tauer: The Synthesis of Special Block Copolymers Using a Reaction Calorimeter. In: *Macromolecular Symposia* 302, 224-234 (2011).
- Weber, N., B. Tiersch, M. M. Unterlass, A. Heilig and K. Tauer: "Schizomorphic" Emulsion Copolymerization Particles. In: *Macromolecular Rapid Communications* 32, 23, 1925-1929 (2011).
- Weber, N., M. M. Unterlass and K. Tauer: High Ionic Strength Promotes the Formation of Spherical Copolymer Particles. In: *Macromolecular Chemistry and Physics* 212, 19, 2071-2086 (2011).
- White, R. J., N. Yoshizawa, M. Antonietti and M. M. Titirici: A sustainable synthesis of nitrogen-doped carbon aerogels. In: *Green Chemistry* 13, 9, 2428-2434 (2011).
- Wilke, A. and J. Weber: Hierarchical nanoporous melamine resin sponges with tunable porosity-porosity analysis and CO_2 sorption properties. In: *Journal of Materials Chemistry* 21, 14, 5226-5229 (2011).
- Wilke, A., F. Yazdanbakhsh and J. Weber: Mesoporous polymer networks by hard templating: High surface area resins, hydrogels of reversible porosity and CO_2 capture materials. In: *Abstracts of Papers of the American Chemical Society* 242 (2011).
- Xie, Z. L. and A. Taubert: Thermomorphic Behavior of the Ionic Liquids $[\text{C}_6\text{mim}][\text{FeCl}_4]$ and $[\text{C}_{12}\text{mim}][\text{FeCl}_4]$. In: *ChemPhysChem* 12, 2, 364-368 (2011).
- Xie, Z. L., R. J. White, J. Weber, A. Taubert and M. M. Titirici: Hierarchical porous carbonaceous materials via ionothermal carbonization of carbohydrates. In: *Journal of Materials Chemistry* 21, 20, 7434-7442 (2011).
- Yang, S. B., X. L. Feng, X. C. Wang and K. Müllen: Graphene-Based Carbon Nitride Nanosheets as Efficient Metal-Free Electrocatalysts for Oxygen Reduction Reactions. In: *Angewandte Chemie-International Edition* 50, 23, 5339-5343 (2011).
- Yang, W., T. P. Fellingner and M. Antonietti: Efficient Metal-Free Oxygen Reduction in Alkaline Medium on High-Surface-Area Mesoporous Nitrogen-Doped Carbons Made from Ionic Liquids and Nucleobases. In: *Journal of the American Chemical Society* 133, 2, 206-209 (2011).
- Yuan, J. Y. and M. Antonietti: Poly(ionic liquid)s: Polymers expanding classical property profiles. In: *Polymer* 52, 7, 1469-1482 (2011).
- Yuan, J. Y. and M. Antonietti: Poly(ionic liquid) Latexes Prepared by Dispersion Polymerization of Ionic Liquid Monomers. In: *Macromolecules* 44, 4, 744-750 (2011).

Publications/Department of Colloid Chemistry

- Yuan, J. Y., A. G. Marquez, J. Reinacher, C. Giordano, J. Janek and M. Antonietti: Nitrogen-doped carbon fibers and membranes by carbonization of electrospun poly(ionic liquid)s. In: *Polymer Chemistry* 2, 8, 1654-1657 (2011).
- Yuan, J. Y., H. Schlaad, C. Giordano and M. Antonietti: Double hydrophilic diblock copolymers containing a poly(ionic liquid) segment: Controlled synthesis, solution property, and application as carbon precursor. In: *European Polymer Journal* 47, 4 Sp. Iss. Sp. Iss. SI, 772-781 (2011).
- Yuan, J. Y., S. Soll, M. Drechsler, A. H. E. Müller and M. Antonietti: Self-Assembly of Poly(ionic liquid)s: Polymerization, Mesosstructure Formation, and Directional Alignment in One Step. In: *Journal of the American Chemical Society* 133, 44, 17556-17559 (2011).
- Yuan, J. Y., N. ten Brummelhuis, M. Junginger, Z. L. Xie, Y. Lu, A. Taubert and H. Schlaad: Diversified Applications of Chemically Modified 1,2-Polybutadiene. In: *Macromolecular Rapid Communications* 32, 15, 1157-1162 (2011).
- Yuan, J. Y., Y. Y. Xu and A. H. E. Müller: One-dimensional magnetic inorganic-organic hybrid nanomaterials. In: *Chemical Society Reviews* 40, 2, 640-655 (2011).
- Zhang, J. S., J. H. Sun, K. Maeda, K. Domen, P. Liu, M. Antonietti, X. Z. Fu and X. C. Wang: Sulfur-mediated synthesis of carbon nitride: Band-gap engineering and improved functions for photocatalysis. In: *Energy & Environmental Science* 4, 3, 675-678 (2011).
- Zhang, P. F., Y. Wang, J. Yao, C. M. Wang, C. Yan, M. Antonietti and H. R. Li: Visible-Light-Induced Metal-Free Allylic Oxidation Utilizing a Coupled Photocatalytic System of g-C₃N₄ and N-Hydroxy Compounds. In: *Advanced Synthesis & Catalysis* 353, 9, 1447-1451 (2011).
- Zhao, J. P. and H. Schlaad: Controlled Anionic Graft Polymerization of Ethylene Oxide Directly from Poly (N-isopropylacrylamide). In: *Macromolecules* 44, 15, 5861-5864 (2011).
- Zhou, H. X., D. Steinhilber, H. Schlaad, A. L. Sisson and R. Haag: Glycerol based polyether-nanogels with tunable properties via acid-catalyzed epoxide-opening in miniemulsion. In: *Reactive & Functional Polymers* 71, 3 Sp. Iss., 356-361 (2011).
- Colloid Chemistry 2012**
- Atilkan, N., Y. Nur, J. Hacaloglu and H. Schlaad: Direct Insertion Mass Spectrometric Analysis of Thermal Degradation of Poly(2-alkyl-2-oxazoline). In: *Macromolecular Chemistry and Physics* 213, 9, 945-951 (2012).
- Avola, S., F. Goettmann, M. Antonietti and W. Kunz: Organic reactivity of alcohols in superheated aqueous salt solutions: an overview. In: *New Journal of Chemistry* 36, 8, 1568-1573 (2012).
- Behra, M., S. Schmidt, J. Hartmann, D. V. Volodkin and L. Hartmann: Synthesis of Porous PEG Microgels Using CaCO₃ Microspheres as Hard Templates. In: *Macromolecular Rapid Communications* 33, 12, 1049-1054 (2012).
- Brown, P., C. P. Butts, J. Eastoe, S. Glatzel, I. Grillo, S. H. Hall, S. Rogers and K. Trickett: Microemulsions as tunable nanomagnets. In: *Soft Matter*, 8, 11609-11612 (2012).
- Casse, O., A. Shkilnyy, J. Linders, C. Mayer, D. Haussinger, A. Völkel, A. F. Thünemann, R. Dimova, H. Cölfen, W. Meier, H. Schlaad and A. Taubert: Solution Behavior of Double-Hydrophilic Block Copolymers in Dilute Aqueous Solution. In: *Macromolecules* 45, 11, 4772-4777 (2012).
- Cui, Y. J., Z. X. Ding, P. Liu, M. Antonietti, X. Z. Fu and X. C. Wang: Metal-free activation of H₂O₂ by g-C₃N₄ under visible light irradiation for the degradation of organic pollutants. In: *Physical Chemistry Chemical Physics* 14, 4, 1455-1462 (2012).
- Debatin, F., K. Behrens, J. Weber, I. A. Baburin, A. Thomas, J. Schmidt, I. Senkovska, S. Kaskel, A. Kelling, N. Hedin, Z. Bacsik, S. Leoni, G. Seifert, C. Jäger, C. Günter, U. Schilde, A. Friedrich and H. J. Holdt: An Isoreticular Family of Microporous Metal-Organic Frameworks Based on Zinc and 2-Substituted Imidazolate-4-amide-5-imidate: Syntheses, Structures and Properties. In: *Chemistry-A European Journal* 18, 37, 11630-11640 (2012).
- Delahaye, E., R. Göbel, R. Löbbicke, R. Guillot, C. Sieber and A. Taubert: Silica ionogels for proton transport. In: *Journal of Materials Chemistry* 22, 33, 17140-17146 (2012).
- Falco, C., M. Sevilla, R. J. White, R. Rothe and M. M. Titirici: Renewable Nitrogen-Doped Hydrothermal Carbons Derived from Microalgae. In: *ChemSusChem* 5, 9, 1834-1840 (2012).
- Fechler, N., T. P. Fellingner and M. Antonietti: Template-Free One-Pot Synthesis of Porous Binary and Ternary Metal Nitride@N-Doped Carbon Composites from Ionic Liquids. In: *Chemistry of Materials* 24, 4, 713-719 (2012).
- Fellinger, T. P., F. Hasche, P. Strasser and M. Antonietti: Mesoporous Nitrogen-Doped Carbon for the Electrocatalytic Synthesis of Hydrogen Peroxide. In: *Journal of the American Chemical Society* 134, 9, 4072-4075 (2012).
- Fellinger, T. P., D. S. Su, M. Engenhorst, D. Gautam, R. Schlögl and M. Antonietti: Thermolytic synthesis of graphitic boron carbon nitride from an ionic liquid precursor: mechanism, structure analysis and electronic properties. In: *Journal of Materials Chemistry* 22, 45, 23996-24005 (2012).
- Fellinger, T. P., R. J. White, M. M. Titirici and M. Antonietti: Borax-Mediated Formation of Carbon Aerogels from Glucose. In: *Advanced Functional Materials* 22, 15, 3254-3260 (2012).
- Gao, Q. S., S. N. Wang, H. C. Fang, J. W. Weng, Y. H. Zhang, J. J. Mao and Y. Tang: One-dimensional growth of MoO_x-based organic-inorganic hybrid nanowires with tunable photochromic properties. In: *Journal of Materials Chemistry* 22, 11, 4709-4715 (2012).
- Gao, Q. S., S. N. Wang, Y. C. Ma, Y. Tang, C. Giordano and M. Antonietti: SiO₂-Surface-Assisted Controllable Synthesis of TaON and Ta₃N₅ Nanoparticles for Alkene Epoxidation. In: *Angewandte Chemie-International Edition* 51, 4, 961-965 (2012).
- Gao, Q. S., S. N. Wang, Y. Tang and C. Giordano: Preparation of organic-inorganic hybrid Fe-MoO_x/ polyaniline nanorods as efficient catalysts for alkene epoxidation. In: *CHEMICAL COMMUNICATIONS* 48, 2, 260-262 (2012).
- Gobel, R., R. J. White, M. M. Titirici and A. Taubert: Carbon-based ionogels: tuning the properties of the ionic liquid via carbon-ionic liquid interaction. In: *Physical Chemistry Chemical Physics* 14, 17, 5992-5997 (2012).
- Göbel, R., Z. L. Xie, M. Neumann, C. Günter, R. Löbbicke, S. Kubo, M. M. Titirici, C. Giordano and A. Taubert: Synthesis of mesoporous carbon/iron carbide hybrids with unusually high surface areas from the ionic liquid precursor [Bmim][FeCl₄]. In: *CrystEngComm* 14, 15, 4946-4951 (2012).

Publications/Department of Colloid Chemistry

- Green, D. C., S. Glatzel, A. M. Collins, A. J. Patil and S. R. Hall: A New General Synthetic Strategy for Phase-Pure Complex Functional Materials. In: *Advanced Materials* 24, 42, 5767-5772 (2012).
- Haase, A., A. Mantion, P. Graf, J. Plendl, A. F. Thuenemann, W. Meier, A. Taubert and A. Luch: A novel type of silver nanoparticles and their advantages in toxicity testing in cell culture systems. In: *Archives of Toxicology* 86, 7 Sp. Iss. SI, 1089-1098 (2012).
- Haase, A., S. Rott, A. Mantion, P. Graf, J. Plendl, A. F. Thuenemann, W. P. Meier, A. Taubert, A. Luch and G. Reiser: Effects of Silver Nanoparticles on Primary Mixed Neural Cell Cultures: Uptake, Oxidative Stress and Acute Calcium Responses. In: *Toxicological Sciences* 126, 2, 457-468 (2012).
- Hasche, F., T. P. Fellingner, M. Oezaslan, J. P. Paraknowitsch, M. Antonietti and P. Strasser: Mesoporous Nitrogen Doped Carbon Supported Platinum PEM Fuel Cell Electrocatalyst Made From Ionic Liquids. In: *ChemCatChem* 4, 4, 479-483 (2012).
- Jiang, Y., L. Gower, D. Volkmer and H. Cölfen: The existence region and composition of a polymer-induced liquid precursor phase for DL-glutamic acid crystals. In: *Physical Chemistry Chemical Physics* 14, 2, 914-919 (2012).
- Kiskan, B., M. Antonietti and J. Weber: Teaching New Tricks to an Old Indicator: pH-Switchable, Photoactive Microporous Polymer Networks from Phenolphthalein with Tunable CO₂ Adsorption Power. In: *Macromolecules* 45, 3, 1356-1361 (2012).
- Kiskan, B. and J. Weber: Versatile Postmodification of Conjugated Microporous Polymers Using Thiolyne Chemistry. In: *ACS Macro Letters* 1, 1, 37-40 (2012).
- Kiskan, B., J. S. Zhang, X. C. Wang, M. Antonietti and Y. Yagci: Mesoporous Graphitic Carbon Nitride as a Heterogeneous Visible Light Photoinitiator for Radical Polymerization. In: *ACS Macro Letters* 1, 5, 546-549 (2012).
- Koebe, M., M. Drechsler, J. Weber and J. Y. Yuan: Crosslinked Poly(ionic liquid) Nanoparticles: Inner Structure, Size, and Morphology. In: *Macromolecular Rapid Communications* 33, 8, 646-651 (2012).
- Köth, A., B. Tiersch, D. Appelhans, M. Gradzielski, H. Cölfen and J. Koetz: Synthesis of Core-Shell Gold Nanoparticles with Maltose-Modified Poly(Ethyleneimine). In: *Journal of Dispersion Science and Technology* 33, 1-3, 52-60 (2012).
- Konne, J., S. A. Davis, S. Glatzel, M. R. Lees and S. R. Hall: A new stoichiometry of cuprate nanowires. In: *Superconductor Science & Technology* 25, 11, Seq. No.: 115005 (2012).
- Krannig, K. S. and H. Schlaad: pH-Responsive Bioactive Glycopolypeptides with Enhanced Helicity and Solubility in Aqueous Solution. In: *Journal of the American Chemical Society* 134, 45, 18542-18545 (2012).
- Kuttner, C., M. Tebbe, H. Schlaad, I. Burgert and A. Fery: Photochemical Synthesis of Polymeric Fiber Coatings and Their Embedding in Matrix Material: Morphology and Nanomechanical Properties at the Fiber-Matrix Interface. In: *ACS Applied Materials & Interfaces* 4, 7, 3484-3492 (2012).
- Laurino, P., H. F. Hernandez, J. Bräuer, K. Krüger, H. Grützmacher, K. Tauer and P. H. Seeberger: Snowballing Radical Generation Leads to Ultrahigh Molecular Weight Polymers. In: *Macromolecular Rapid Communications* 33, 20, 1770-1774 (2012).
- Liu, X. F., C. Giordano and M. Antonietti: A molten-salt route for synthesis of Si and Ge nanoparticles: chemical reduction of oxides by electrons solvated in salt melt. In: *Journal of Materials Chemistry* 22, 12, 5454-5459 (2012).
- Li, X. H., J. S. Chen, X. C. Wang, M. E. Schuster, R. Schlogl and M. Antonietti: A Green Chemistry of Graphene: Photochemical Reduction towards Monolayer Graphene Sheets and the Role of Water Adlayers. In: *ChemSusChem* 5, 4, 642-646 (2012).
- Li, X. H., S. Kurasch, U. Kaiser and M. Antonietti: Synthesis of Monolayer-Patched Graphene from Glucose. In: *Angewandte Chemie-International Edition* 51, 38, 9689-9692 (2012).
- Li, X. H., X. C. Wang and M. Antonietti: Solvent-Free and Metal-Free Oxidation of Toluene Using O₂ and g-C₃N₄ with Nanopores: Nanostructure Boosts the Catalytic Selectivity. In: *ACS Catalysis* 2, 10, 2082-2086 (2012).
- Li, X. H., X. C. Wang and M. Antonietti: Mesoporous g-C₃N₄ nanorods as multifunctional supports of ultrafine metal nanoparticles: hydrogen generation from water and reduction of nitrophenol with tandem catalysis in one step. In: *Chemical Science* 3, 6, 2170-2174 (2012).
- Men, Y. J., X. H. Li, M. Antonietti and J. Y. Yuan: Poly(tetrabutylphosphonium 4-styrenesulfonate): a poly(ionic liquid) stabilizer for graphene being multi-responsive. In: *Polymer Chemistry* 3, 4, 871-873 (2012).
- Möhlmann, L., M. Baar, J. Riess, M. Antonietti, X. C. Wang and S. Blechert: Carbon Nitride-Catalyzed Photoredox C-C Bond Formation with N-Aryltetrahydroisoquinolines. In: *Advanced Synthesis & Catalysis* 354, 10, 1909-1913 (2012).
- Müllen, K. and M. Antonietti: Carbon Materials with a Kick!. In: *Macromolecular Chemistry and Physics* 213, 10-11 Sp. Iss. SI, 999-1000 (2012).
- Neumann, M., R. Nöske, A. Taubert, B. Tiersch and P. Strauch: Highly structured, biomorphous β-SiC with high specific surface area from Equisetaceae. In: *Journal of Materials Chemistry* 22, 18, 9046-9051 (2012).
- Politi, Y., M. Priezwasser, E. Pippel, P. Zaslansky, J. Hartmann, S. Siegel, C. H. Li, F. G. Barth and P. Fratzl: A Spider's Fang: How to Design an Injection Needle Using Chitin-Based Composite Material. In: *Advanced Functional Materials* 22, 12, 2519-2528 (2012).
- Robinson, J. W. and H. Schlaad: A versatile polypeptoid platform based on N-allyl glycine. In: *Chemical Communications* 48, 63, 7835-7837 (2012).
- Roeser, J., K. Kailasam and A. Thomas: Covalent Triazine Frameworks as Heterogeneous Catalysts for the Synthesis of Cyclic and Linear Carbonates from Carbon Dioxide and Epoxides. In: *ChemSusChem* 5, 9, 1793-1799 (2012).
- Roeser, J., M. Kronstein, M. Litschauer, A. Thomas and M. A. Neouze: Ionic Nanoparticle Networks as Solid State Catalysts. In: *European Journal of Inorganic Chemistry*, 32 Sp. Iss. SI, 5305-5311 (2012).
- Schlaad, H. and R. Hoogenboom: Poly(2-oxazoline)s and Related Pseudo-Polypeptides. In: *Macromolecular Rapid Communications* 33, 19 Sp. Iss. SI, 1599-1599 (2012).

Publications/Department of Colloid Chemistry

- Schliehe, C., J. Yuan, S. Glatzel, K. Siemensmeyer, K. Kiefer and C. Giordano: Iron Nitride and Carbide: from Crystalline Nanoparticles to Stable Aqueous Dispersions. In: *Chemistry of Materials* 24, 14, 2716-2721 (2012).
- Seto, J., Y. R. Ma, S. A. Davis, F. Meldrum, A. Gourrier, Y. Y. Kim, U. Schilde, M. Sztucki, M. Burghammer, S. Maltsev, C. Jäger and H. Cölfen: Structure-property relationships of a biological mesocrystal in the adult sea urchin spine. In: *Proceedings of the National Academy of Sciences of the United States of America* 109, 10, 3699-3704 (2012).
- Singha, N. K. and H. Schlaad: Thiol-ene based functionalization of polymers. In: *Functional Polymers by Post-Polymerization: Concepts, Guidelines, and Applications*. (Eds.) Theato, P.; Klok, H.-A. Wiley-VCH, Weinheim (2012) 65-86.
- Si, S., A. Taubert, A. Manton, G. Rogez and P. Rabu: Peptide-intercalated layered metal hydroxides: effect of peptide chain length and side chain functionality on structural, optical and magnetic properties. In: *Chemical Science* 3, 6, 1945-1957 (2012).
- Soininen, A. J., I. Tanionou, N. ten Brummelhuis, H. Schlaad, N. Hadjichristidis, O. Ikkala, J. Raula, R. Mezzenga and J. Ruokolainen: Hierarchical Structures in Lamellar Hydrogen Bonded LC Side Chain Diblock Copolymers. In: *Macromolecules* 45, 17, 7091-7097 (2012).
- Soll, S., M. Antonietti and J. Y. Yuan: Double Stimuli-Responsive Copolymer Stabilizers for Multiwalled Carbon Nanotubes. In: *ACS Macro Letters* 1, 1, 84-87 (2012).
- Su, F. Z., M. Antonietti and X. C. Wang: mpg-C₃N₄ as a solid base catalyst for Knoevenagel condensations and transesterification reactions. In: *Catalysis Science & Technology* 2, 5, 1005-1009 (2012).
- Tang, K., L. J. Fu, R. J. White, L. H. Yu, M. M. Titirici, M. Antonietti and J. Maier: Hollow Carbon Nanospheres with Superior Rate Capability for Sodium-Based Batteries. In: *Advanced Energy Materials* 2, 7 Sp. Iss. SI, 873-877 (2012).
- Tang, K., R. J. White, X. K. Mu, M. M. Titirici, P. A. van Aken and J. Maier: Hollow Carbon Nanospheres with a High Rate Capability for Lithium-Based Batteries. In: *ChemSusChem* 5, 2 Sp. Iss. SI, 400-403 (2012).
- Tan, I., F. Roohi and M. M. Titirici: Thermoresponsive polymers in liquid chromatography. In: *ANALYTICAL METHODS* 4, 1, 34-43 (2012).
- Taubert, A., F. Stange, Z. H. Li, M. Junginger, C. Günter, M. Neumann and A. Friedrich: CuO Nanoparticles from the Strongly Hydrated Ionic Liquid Precursor (ILP) Tetrabutylammonium Hydroxide: Evaluation of the Ethanol Sensing Activity. In: *ACS Applied Materials & Interfaces* 4, 2, 791-795 (2012).
- ten Brummelhuis, N. and H. Schlaad: Radical thiol-X click chemistry. In: *Encyclopedia of Radicals in Chemistry, Biology and Materials*. (Eds.) Chatgililoglu, C.; Studer, A. Wiley, Chichester (2012) 2017-2056.
- ten Brummelhuis, N., C. Secker and H. Schlaad: Hofmeister Salt Effects on the LCST Behavior of Poly(2-Oxazoline) Star Ionomers. In: *Macromolecular Rapid Communications* 33, 19 Sp. Iss. SI, 1690-1694 (2012).
- Titirici, M. M., R. J. White, C. Falco and M. Sevilla: Black perspectives for a green future: hydrothermal carbons for environment protection and energy storage. In: *Energy & Environmental Science* 5, 5, 6796-6822 (2012).
- Verch, A., M. Antonietti and H. Cölfen: Mixed calcium-magnesium pre-nucleation clusters enrich calcium. In: *Zeitschrift für Kristallographie* 227, 11, 718-722 (2012).
- Vilela, F., K. Zhang and M. Antonietti: Conjugated porous polymers for energy applications. In: *Energy & Environmental Science* 5, 7, 7819-7832 (2012).
- Villa, A., S. Campisi, C. Giordano, K. Otte and L. Prati: Mo and W Carbide: Tunable Catalysts for Liquid Phase Conversion of Alcohols. In: *ACS Catalysis* 2, 7, 1377-1380 (2012).
- Wang, X. C., S. Blechert and M. Antonietti: Polymeric Graphitic Carbon Nitride for Heterogeneous Photocatalysis. In: *ACS Catalysis* 2, 8, 1596-1606 (2012).
- Wang, Y., X. C. Wang and M. Antonietti: Polymeric Graphitic Carbon Nitride as a Heterogeneous Organocatalyst: From Photochemistry to Multipurpose Catalysis to Sustainable Chemistry. In: *Angewandte Chemie-International Edition* 51, 1, 68-89 (2012).
- Wen, Z. H., X. C. Wang, S. Mao, Z. Bo, H. Kim, S. M. Cui, G. H. Lu, X. L. Feng and J. H. Chen: Crumpled Nitrogen-Doped Graphene Nanosheets with Ultrahigh Pore Volume for High-Performance Supercapacitor. In: *Advanced Materials* 24, 41, 5610-5616 (2012).
- Wilke, A. and J. Weber: Mesoporous Polymer Networks-Ultraporous DVB Resins by Hard-Templating of Close-Packed Silica Spheres. In: *Macromolecular Rapid Communications* 33, 9 Sp. Iss. SI, 785-790 (2012).
- Wilke, A., J. Y. Yuan, M. Antonietti and J. Weber: Enhanced Carbon Dioxide Adsorption by a Mesoporous Poly(ionic liquid). In: *ACS Macro Letters* 1, 8, 1028-1031 (2012).
- Wohlgemuth, S. A., F. Vilela, M. M. Titirici and M. Antonietti: A one-pot hydrothermal synthesis of tunable dual heteroatom-doped carbon microspheres. In: *Green Chemistry* 14, 3, 741-749 (2012).
- Wohlgemuth, S. A., R. J. White, M. G. Willinger, M. M. Titirici and M. Antonietti: A one-pot hydrothermal synthesis of sulfur and nitrogen doped carbon aerogels with enhanced electrocatalytic activity in the oxygen reduction reaction. In: *Green Chemistry* 14, 5, 1515-1523 (2012).
- Wojcik, F., S. Mosca and L. Hartmann: Solid-Phase Synthesis of Asymmetrically Branched Sequence-Defined Poly/Oligo(amidoamines). In: *Journal of Organic Chemistry* 77, 9, 4226-4234 (2012).
- Xie, Z. L., H. B. Xu, A. Gessner, M. U. Kumke, M. Priebe, K. M. Fromm and A. Taubert: A transparent, flexible, ion conductive, and luminescent PMMA ionogel based on a Pt/Eu bimetallic complex and the ionic liquid [Bmim][N(Tf)₂]. In: *Journal of Materials Chemistry* 22, 16, 8110-8116 (2012).
- Yildiz, U., B. Hazer and K. Tauer: Tailoring polymer architectures with macromonomer azoinitiators. In: *Polymer Chemistry* 3, 5, 1107-1118 (2012).

Publications/Department of Colloid Chemistry

- Yuan, J. Y., S. Wunder, F. Warmuth and Y. Lu: Spherical polymer brushes with vinylimidazolium-type poly(ionic liquid) chains as support for metallic nanoparticles. In: *Polymer* 53, 1, 43-49 (2012).
- Yu, L. H., C. Falco, J. Weber, R. J. White, J. Y. Howe and M. M. Titirici: Carbohydrate-Derived Hydrothermal Carbons: A Thorough Characterization Study. In: *Langmuir* 28, 33, 12373-12383 (2012).
- Zhang, J. S., M. Grzelczak, Y. D. Hou, K. Maeda, K. Domen, X. Z. Fu, M. Antonietti and X. C. Wang: Photocatalytic oxidation of water by polymeric carbon nitride nanohybrids made of sustainable elements. In: *Chemical Science* 3, 2, 443-446 (2012).
- Zhang, J. S., G. G. Zhang, X. F. Chen, S. Lin, L. Möhlmann, G. Dolega, G. Lipner, M. Antonietti, S. Blechert and X. C. Wang: Co-Monomer Control of Carbon Nitride Semiconductors to Optimize Hydrogen Evolution with Visible Light. In: *Angewandte Chemie-International Edition* 51, 13, 3183-3187 (2012).
- Zhang, P. F., Y. Wang, H. R. Li and M. Antonietti: Metal-free oxidation of sulfides by carbon nitride with visible light illumination at room temperature. In: *Green Chemistry* 14, 7, 1904-1908 (2012).
- Zhao, J. P., J. Jeromenok, J. Weber and H. Schlaad: Thermoresponsive Aggregation Behavior of Triterpene-Poly(ethylene oxide) Conjugates in Water. In: *Macromolecular Bioscience* 12, 9, 1272-1278 (2012).
- Zhao, J. P., H. Schlaad, S. Weidner and M. Antonietti: Synthesis of terpene-poly(ethylene oxide)s by t-BuP4-promoted anionic ring-opening polymerization. In: *Polymer Chemistry* 3, 7, 1763-1768 (2012).
- Zhao, Q., T. P. Fellingner, M. Antonietti and J. Y. Yuan: Nitrogen-Doped Carbon Capsules via Poly(ionic liquid)-Based Layer-by-Layer Assembly. In: *Macromolecular Rapid Communications* 33, 13, 1149-1153 (2012).
- Zhao, Q., P. F. Zhang, M. Antonietti and J. Y. Yuan: Poly(ionic liquid) Complex with Spontaneous Micro-/Mesoporosity: Template-Free Synthesis and Application as Catalyst Support. In: *Journal of the American Chemical Society* 134, 29, 11852-11855 (2012).

Interfaces 2011

- Akentieva, A. V., A. Y. Bilibin, I. M. Zorin, S. Y. Lin, G. Loglio, R. Miller and B. A. Noskov: Scanning probe microscopy of adsorption layers of sodium polystyrenesulfonate/dodecyltrimethylammonium bromide complexes. In: *Colloid Journal* 73, 4, 437-444 (2011).
- Arabadzhieva, D., E. Mileva, P. Tchoukov, R. Miller, F. Ravera and L. Liggieri: Adsorption layer properties and foam film drainage of aqueous solutions of tetraethyleneglycol monododecyl ether. In: *Colloids and Surfaces A-Physicochemical and Engineering Aspects* 392, 1, 233-241 (2011).
- Arabadzhieva, D., P. Tchoukov, E. Mileva, R. Miller and B. Soklev: Impact of amphiphilic nanostructures on formation and rheology of interfacial layers and on foam film drainage. In: *Ukrainian Journal of Physics* 56, 801-810 (2011).
- Babu, S. S., A. Saeki, S. Seki, H. Möhwald and T. Nakanishi: Millimeter-sized flat crystalline sheet architectures of fullerene assemblies with anisotropic photoconductivity. In: *Physical Chemistry Chemical Physics* 13, 11, 4830-4834 (2011).
- Belova, V., T. Borodina, H. Möhwald and D. G. Shchukin: The effect of high intensity ultrasound on the loading of Au nanoparticles into titanium dioxide. In: *Ultrasonics Sonochemistry* 18, 1, 310-317 (2011).
- Belova, V., D. A. Gorin, D. G. Shchukin and H. Möhwald: Controlled Effect of Ultrasonic Cavitation on Hydrophobic/Hydrophilic Surfaces. In: *ACS Applied Materials & Interfaces* 3, 2, 417-425 (2011).
- Belova, V., D. G. Shchukin, D. A. Gorin, A. Kopyshchev and H. Möhwald: A new approach to nucleation of cavitation bubbles at chemically modified surfaces. In: *Physical Chemistry Chemical Physics* 13, 17, 8015-8023 (2011).
- Borcia, R., S. Menzel, M. Bestehorn, S. Karpitschka and H. Riegler: Delayed coalescence of droplets with miscible liquids: Lubrication and phase field theories. In: *European Physical Journal E* 34, 3, Seq. No.: 11024-9 (2011).
- Borisova, D., H. Möhwald and D. G. Shchukin: Mesoporous Silica Nanoparticles for Active Corrosion Protection. In: *ACS Nano* 5, 3, 1939-1946 (2011).
- Borodina, T., D. Grigoriev, E. Markvicheva, H. Möhwald and D. Shchukin: Vitamin E Microspheres Embedded Within a Biocompatible Film for Planar Delivery. In: *Advanced Engineering Materials* 13, 3 Sp. Iss., B123-B130 (2011).
- Bratashov, D. N., A. Masic, A. M. Yashchenok, M. F. Bedard, O. A. Inozemtseva, D. A. Gorin, T. Basova, T. K. Sievers, G. B. Sukhorukov, M. Winterhalter, H. Möhwald and A. G. Skirtach: Raman imaging and photodegradation study of phthalocyanine containing microcapsules and coated particles. In: *Journal of Raman Spectroscopy* 42, 10, 1901-1907 (2011).
- Brezesinski, G., I. Berndt, B. Dobner and D. Vollhardt: Dominance of long-chain N,O-diacylated ethanolamine in mixed amphiphilic acid amide monolayers. In: *Colloids and Surfaces A-Physicochemical and Engineering Aspects* 391, 2-9 (2011).
- Brezesinski, G., B. Dobner, C. Stefaniu and D. Vollhardt: Monolayer Characteristics of a Long-Chain N,O-Diacyl Substituted Ethanolamine at the Air/Water Interface. In: *Langmuir* 27, 9, 5386-5392 (2011).
- Brezesinski, G., B. Dobner, C. Stefaniu and D. Vollhardt: Monolayer Characteristics of an N-Acylated Ethanolamine at the Air/Water Interface. In: *Journal of Physical Chemistry C* 115, 16, 8206-8213 (2011).
- De Cock, L. J., J. Lenoir, S. De Koker, V. Vermeersch, A. G. Skirtach, P. Dubruel, E. Adriaens, C. Vervaeet, J. P. Remon and B. G. De Geest: Mucosal irritation potential of polyelectrolyte multilayer capsules. In: *Biomaterials* 32, 7, 1967-1977 (2011).
- Delcea, M., N. Madaboosi, A. M. Yashchenok, P. Subedi, D. V. Volodkin, B. G. De Geest, H. Möhwald and A. G. Skirtach: Anisotropic multi-compartment micro- and nano-capsules produced via embedding into biocompatible PLL/HA films. In: *Chemical Communications* 47, 7, 2098-2100 (2011).
- Delcea, M., H. Möhwald and A. G. Skirtach: Stimuli-responsive LbL capsules and nanoshells for drug delivery. In: *Advanced Drug Delivery Reviews* 63, 9, 730-747 (2011).
- Dittrich, M., M. Böttcher, J. S. L. Oliveira, B. Dobner, H. Möhwald and G. Brezesinski: Physical-chemical characterization of novel cationic transfection lipids and the binding of model DNA at the air-water interface. In: *SOFT MATTER* 7, 21, 10162-10173 (2011).
- Dittrich, M., M. Heinze, C. Wölk, S. S. Funari, B. Dobner, H. Möhwald and G. Brezesinski: Structure-Function Relationships of New Lipids Designed for DNA Transfection. In: *ChemPhysChem* 12, 12, 2328-2337 (2011).
- Dopierala, K., A. Javadi, J. Krägel, K. H. Schano, E. P. Kalogianni, M. E. Leser and R. Miller: Dynamic interfacial tensions of dietary oils. In: *Colloids and Surfaces A-Physicochemical and Engineering Aspects* 382, 1-3 Sp. Iss., 261-265 (2011).
- Du, M. C., P. L. Zhu, X. H. Yan, Y. Su, W. X. Song and J. B. Li: Honeycomb Self-Assembled Peptide Scaffolds by the Breath Figure Method. In: *Chemistry-A European Journal* 17, 15, 4238-4245 (2011).
- Fainerman, V. B., E. V. Aksenenko, V. I. Kovalchuk, A. Javadi and R. Miller: Study of the co-adsorption of hexane from the gas phase at the surface of aqueous C₁₀EO₈ drops. In: *Soft Matter* 7, 17, 7860-7865 (2011).
- Fainerman, V. B., E. V. Aksenenko, J. T. Petkov and R. Miller: Equilibrium adsorption layer characteristics of mixed sodium dodecyl sulphate/Triton solutions. In: *Colloids and Surfaces A-Physicochemical and Engineering Aspects* 385, 1-3, 139-143 (2011).
- Farajzadeh, R., R. M. Muruganathan, W. R. Rossen and R. Krastev: Effect of gas type on foam film permeability and its implications for foam flow in porous media. In: *ADVANCES IN COLLOID AND INTERFACE SCIENCE* 168, 1-2 Sp. Iss. SI, 71-78 (2011).
- Fathima, N. N., A. Dhathathreyan, T. Ramasami, J. Krägel and R. Miller: Degree of crosslinking of collagen at interfaces: Adhesion and shear rheological indicators. In: *International Journal of Biological Macromolecules* 48, 1, 67-73 (2011).
- Fix, D., E. V. Skorb, D. G. Shchukin and H. Möhwald: Quantitative analysis of scanning electric current density and pH-value observations in corrosion studies. In: *Measurement Science & Technology* 22, 7, Seq. No.: 075704 (2011).

Publications/Department of Interfaces

- Gaponik, N., D. G. Shchukin and D. V. Sviridov: Electrochemical Patterning of Polyaniline on Insulating Substrates. In: *Zeitschrift für Physikalische Chemie-International Journal of Research in Physical Chemistry & Chemical Physics* 225, 3, 373-378 (2011).
- Georgiev, G. A., N. Yokoi, K. Koev, E. Kutsarova, S. Ivanova, A. Kyumurkov, A. Jordanova, R. Krastev and Z. Lalchev: Surface Chemistry Study of the Interactions of Benzalkonium Chloride with Films of Meibum, Corneal Cells Lipids, and Whole Tears. In: *Investigative Ophthalmology & Visual Science* 52, 7, 4645-4654 (2011).
- Gochev, G., H. Petkova, T. Kolarov, K. Khristov, B. Levecke, T. F. Tadros and D. Exerowa: Effect of the degree of grafting in hydrophobically modified inulin polymeric surfactants on the steric forces in foam and oil-in-water emulsion films. In: *Colloids and Surfaces A-Physicochemical and Engineering Aspects* 391, 1-3 Sp. Iss. SI, 101-104 (2011).
- González-Delgado, A. M., J. J. Giner-Casares, C. Rubia-Paya, M. Pérez-Morales, M. T. Martin-Romero, G. Brezesinski and L. Camacho: The Effect of the Reduction of the Available Surface Area on the Hemicyanine Aggregation in Laterally Organized Langmuir Monolayers. In: *Journal of Physical Chemistry C* 115, 18, 9059-9067 (2011).
- Gröning, A., H. Ahrens, T. Ortmann, F. Lawrenz, G. Brezesinski, F. Scholz and C. A. Helm: Molecular mechanisms of phosphatidylcholine monolayer solidification due to hydroxyl radicals. In: *Soft Matter* 7, 14, 6467-6476 (2011).
- Gzyl-Malcher, B., M. Filek and G. Brezesinski: Mixed DPPC/DPTAP Monolayers at the Air/Water Interface: Influence of Indolilo-3-acetic Acid and Selenate Ions on the Mono layer Morphology. In: *Langmuir* 27, 17, 10886-10893 (2011).
- Haase, M. F., D. Grigoriev, H. Möhwald, B. Tiersch and D. G. Shchukin: Nanoparticle Modification by Weak Polyelectrolytes for pH-Sensitive Pickering Emulsions. In: *Langmuir* 27, 1, 74-82 (2011).
- Hamdy, A. S., I. Doench and H. Möhwald: Intelligent self-healing corrosion resistant vanadia coating for AA2024. In: *Thin Solid Films* 520, 5, 1668-1678 (2011).
- Hamdy, A. S., I. Doench and H. Möhwald: Smart self-healing anti-corrosion vanadia coating for magnesium alloys. In: *Progress in Organic Coatings* 72, 3, 387-393 (2011).
- Hamdy, A. S., I. Dönch and H. Möhwald: Assessment of a one-step intelligent self-healing vanadia protective coatings for magnesium alloys in corrosive media. In: *Electrochimica Acta* 56, 2493-2502 (2011).
- Hoernke, M., J. A. Falenski, C. Schwieger, B. Koksich and G. Brezesinski: Triggers for β -Sheet Formation at the Hydrophobic-Hydrophilic Interface: High Concentration, In-Plane Orientational Order, and Metal Ion Complexation. In: *Langmuir* 27, 23, 14218-14231 (2011).
- Hörnke, M., J. Falenski, B. Koksich and G. Brezesinski: Beta-sheet Structure Formation at the Air-Water Interface: Triggers, Transitions and Orientations. In: *European Biophysics Journal with Biophysics Letters* 40, Suppl. 1, 89-89 (2011).
- Hoernke, M., B. Koksich and G. Brezesinski: Amyloidogenic Peptides at Hydrophobic-Hydrophilic Interfaces: Coordination Affinities and the Chelate Effect Dictate the Competitive Binding of Cu_{2+} and Zn_{2+} . In: *ChemPhysChem* 12, 12, 2225-2229 (2011).
- Hollamby, M. J., D. Fix, I. Dönch, D. Borisova, H. Möhwald and D. Shchukin: Hybrid Polyester Coating Incorporating Functionalized Mesoporous Carriers for the Holistic Protection of Steel Surfaces. In: *Advanced Materials* 23, 11, 1361-1365 (2011).
- Inozemtseva, O. A., T. A. Kolesnikova, D. A. Gorin, N. V. Shvyndina and V. Ya. Shklover: Functionalization of direct emulsion disperse phase surface by zinc oxide nanoparticles using layer-by-layer electrostatic assembly. In: *Nanotechnologies in Russia* 6, 3-4, 211-217 (2011).
- Jimenez-Millan, E., J. J. Giner-Casares, M. T. Martin-Romero, G. Brezesinski and L. Camacho: Chiral Textures inside 2D Achiral Domains. In: *JOURNAL OF THE AMERICAN CHEMICAL SOCIETY* 133, 47, 19028-19031 (2011).
- Jimenez-Millan, E., J. J. Giner-Casares, E. Munoz, M. T. Martin-Romero and L. Camacho: Self-Assembly of Acridine Orange into H-Aggregates at the Air/Water Interface: Tuning of Orientation of Headgroup. In: *Langmuir* 27, 24, 14888-14899 (2011).
- Kalogianni, E. P., T. D. Karapantsios and R. Miller: Effect of repeated frying on the viscosity, density and dynamic interfacial tension of palm and olive oil. In: *Journal of Food Engineering* 105, 1, 169-179 (2011).
- Kazakova, L. I., L. I. Shabarchina and G. B. Sukhorukov: Co-encapsulation of enzyme and sensitive dye as a tool for fabrication of microcapsule based sensor for urea measuring. In: *Physical Chemistry Chemical Physics* 13, 23, 11110-11117 (2011).
- Kazakov, V. N., E. L. Barkalova, L. A. Levchenko, T. M. Klimenko, V. B. Fainerman and R. Miller: Dilation rheology as medical diagnostics of human biological liquids. In: *Colloids and Surfaces A-Physicochemical and Engineering Aspects* 391, 190-194 (2011).
- Kiel, M., H. Möhwald and M. Bargheer: Broadband measurements of the transient optical complex dielectric function of a nanoparticle/polymer composite upon ultrafast excitation. In: *Physical Review B* 84, 16, Seq. No.: 165121 (2011).
- Köhler, R., J. Restolho, R. Krastev, K. Shimizu, J. N. C. Lopes and B. Saramago: Liquid- or Solid-Like Behavior of [omim][BF₄] at a Solid Interface?. In: *Journal of Physical Chemistry Letters* 2, 13, 1551-1555 (2011).
- Kohler, D., M. Schneider, M. Krüger, C. M. Lehr, H. Möhwald and D. Y. Wang: Template-Assisted Polyelectrolyte Encapsulation of Nanoparticles into Dispersible, Hierarchically Nanostructured Microfibers. In: *Advanced Materials* 23, 11, 1376-1379 (2011).
- Kolesnikova, T. A., I. A. Fedorova, A. A. Gusev and D. A. Gorin: Acute toxicity analysis of polyelectrolyte microcapsules with zinc oxide nanoparticles and microcapsule shell components using the aquatic organisms. In: *Nanotechnologies in Russia* 6, 3-4, 244-255 (2011).
- Kovalchuk, V. I., M. P. Bondarenko, E. K. Zholkovskiy, V. M. Starov and D. Vollhardt: Ions Redistribution and Meniscus Relaxation during Langmuir Wetting Process. In: *Journal of Physical Chemistry B* 115, 9, 1999-2005 (2011).
- Kovalchuk, V. I., E. K. Zholkovskiy, M. P. Bondarenko, V. M. Starov and D. Vollhardt: Concentration polarization effect at the deposition of charged Langmuir monolayers. In: *Advances in Colloid and Interface Science* 168, 1-2, 114-123 (2011).
- Kristen-Hochrein, N., A. Laschewsky, R. Miller and R. von Klitzing: Stability of Foam Films of Oppositely Charged Polyelectrolyte/Surfactant Mixtures: Effect of Isoelectric Point. In: *Journal of Physical Chemistry B* 115, 49, 14475-14483 (2011).

Publications/Department of Interfaces

- Latnikova, A., D. O. Grigoriev, J. Hartmann, H. Möhwald and D. G. Shchukin: Polyfunctional active coatings with damage-triggered water-repelling effect. In: *Soft Matter* 7, 2, 369-372 (2011).
- Li, H., M. J. Hollamby, T. Seki, S. Yagai, H. Möhwald and T. Nakanishi: Multifunctional, Polymorphic, Ionic Fullerene Supramolecular Materials: Self-Assembly and Thermotropic Properties. In: *Langmuir* 27, 12, 7493-7501 (2011).
- Liu, B., J. W. J. de Folter and H. Möhwald: Magnetic nanoparticles-induced anisotropic shrinkage of polymer emulsion droplets. In: *Soft Matter* 7, 8, 3744-3749 (2011).
- Löbbecke, R., M. Chanana, H. Schlaad, C. Pilz-Allen, C. Günter, H. Möhwald and A. Taubert: Polymer Brush Controlled Bioinspired Calcium Phosphate Mineralization and Bone Cell Growth. In: *BIO-MACROMOLECULES* 12, 10, 3753-3760 (2011).
- Maestro, A., E. Guzman, R. Chulia, F. Ortega, R. G. Rubio and R. Miller: Fluid to soft-glass transition in a quasi-2D system: thermodynamic and rheological evidences for a Langmuir monolayer. In: *Physical Chemistry Chemical Physics* 13, 20, 9534-9539 (2011).
- Maestro, A., F. Ortega, R. G. Rubio, M. A. Rubio, J. Krägel and R. Miller: Rheology of poly(methyl methacrylate) Langmuir monolayers: Percolation transition to a soft glasslike system. In: *Journal of Chemical Physics* 134, 10, Seq. No.: 104704 (2011).
- Mao, Z., R. Cartier, A. Hohl, M. Farinacci, A. Dorhoi, T. L. Nguyen, P. Mulvaney, J. Ralston, S. H. E. Kaufmann, H. Möhwald and D. Y. Wang: Cells as Factories for Humanized Encapsulation. In: *Nano Letters* 11, 5, 2152-2156 (2011).
- Mikhailovskaya, A. A., S. Y. Lin, G. Loglio, R. Miller and B. A. Noskov: Effect of a cationic surfactant on protein unfolding at the air-solution interface. In: *Mendelev Communications* 21, 6, 341-343 (2011).
- Mikhailovskaya, A. A., B. A. Noskov, S. Y. Lin, G. Loglio and R. Miller: Formation of Protein/Surfactant Adsorption Layer at the Air/Water Interface as Studied by Dilational Surface Rheology. In: *Journal of Physical Chemistry B* 115, 33, 9971-9979 (2011).
- Miller, R.: In honour of the 65th birthday of Valentin B. Fainerman. In: *Advances in Colloid and Interface Science* 163, 2, 85-89 (2011).
- Mucic, N., A. Javadi, N. M. Kovalchuk, E. V. Aksenenko and R. Miller: Dynamics of interfacial layers-Experimental feasibilities of adsorption kinetics and dilational rheology. In: *ADVANCES IN COLLOID AND INTERFACE SCIENCE* 168, 1-2 Sp. Iss. SI, 167-178 (2011).
- Negm, N. A. and R. Miller: Sequential and simultaneous adsorption of mucin-4-[(dodecylimino)methyl]-N,N,N-trimethyl anilinium iodide mixed system using drop profile analysis tensiometry. In: *Colloids and Surfaces A-Physicochemical and Engineering Aspects* 391, 145-149 (2011).
- Noskov, B. A., G. Loglio and R. Miller: Dilational surface visco-elasticity of polyelectrolyte/surfactant solutions: Formation of heterogeneous adsorption layers. In: *ADVANCES IN COLLOID AND INTERFACE SCIENCE* 168, 1-2 Sp. Iss. SI, 179-197 (2011).
- Nunes, C., G. Brezesinski, J. L. F. C. Lima, S. Reis and M. Lucio: Synchrotron SAXS and WAXS Study of the Interactions of NSAIDs with Lipid Membranes. In: *Journal of Physical Chemistry B* 115, 24, 8024-8032 (2011).
- Nunes, C., G. Brezesinski, J. L. F. C. Lima, S. Reis and M. Lucio: Effects of non-steroidal anti-inflammatory drugs on the structure of lipid bilayers: therapeutical aspects. In: *Soft Matter* 7, 6, 3002-3010 (2011).
- Nunes, C., G. Brezesinski, D. Lopes, J. L. F. C. Lima, S. Reis and M. Lucio: Lipid-Drug Interaction: Biophysical Effects of Tolmetin on Membrane Mimetic Systems of Different Dimensionality. In: *Journal of Physical Chemistry B* 115, 43, 12615-12623 (2011).
- Nunes, C., G. Brezesinski, C. Pereira-Leite, J. L. F. C. Lima, S. Reis and M. Lucio: NSAIDs Interactions with Membranes: A Biophysical Approach. In: *Langmuir* 27, 17, 10847-10858 (2011).
- Pavlov, A. M., A. V. Sapelkin, X. Y. Huang, K. M. Y. P'ng, A. J. Bushby, G. B. Sukhorukov and A. G. Skirtach: Neuron Cells Uptake of Polymeric Microcapsules and Subsequent Intracellular Release. In: *Macromolecular Bioscience* 11, 6, 848-854 (2011).
- Pomorska, A., K. Yliniemi, B. P. Wilson, D. Shchukin, D. Johannsmann and G. Grundmeier: QCM study of the adsorption of polyelectrolyte covered mesoporous TiO₂ nanocontainers on SAM modified Au surfaces. In: *Journal of Colloid and Interface Science* 362, 1, 180-187 (2011).
- Pradines, V., V. B. Fainerman, E. V. Aksenenko, J. Krägel, R. Wüstneck and R. Miller: Adsorption of Protein-Surfactant Complexes at the Water/Oil Interface. In: *Langmuir* 27, 3, 965-971 (2011).
- Radziuk, D., A. Skirtach, A. Gessner, M. U. Kumke, W. Zhang, H. Möhwald and D. Shchukin: Ultrasonic Approach for Formation of Erbium Oxide Nanoparticles with Variable Geometries. In: *Langmuir* 27, 23, 14472-14480 (2011).
- Radziuk, D. V. and H. Möhwald: Spectroscopic investigation of composite polymeric and monocrySTALLINE systems with ionic conductivity. In: *Polymers* 3, 674-692 (2011).
- Radziuk, D. V., D. G. Shchukin and H. Möhwald: Acoustic cavitation for engineering of gold sols in silver nitrate solutions. In: *Ultrasonics Sonochemistry* 18, 4 Sp. Iss., 853-863 (2011).
- Ramanathan, M., H. J. Müller, H. Möhwald and R. Krastev: Foam Films as Thin Liquid Gas Separation Membranes. In: *ACS Applied Materials & Interfaces* 3, 3, 633-637 (2011).
- Ramirez, P., L. Maria Perez, L. Alfonso Trujillo, M. Ruiz, J. Munoz and R. Miller: Equilibrium and surface rheology of two polyoxyethylene surfactants (CiEOj) differing in the number of oxyethylene groups. In: *Colloids and Surfaces A-Physicochemical and Engineering Aspects* 375, 1-3, 130-135 (2011).
- Ramirez, P., J. Munoz, V. B. Fainerman, E. V. Aksenenko, N. Mucic and R. Miller: Dynamic interfacial tension of triblock copolymers solutions at the water-hexan interface. In: *Colloids and Surfaces A-Physicochemical and Engineering Aspects* 391, 119-124 (2011).
- Roldan-Carmona, C., A. M. Gonzalez-Delgado, A. Guerrero-Martinez, L. De Cola, J. J. Giner-Casares, M. Perez-Morales, M. T. Martin-Romero and L. Camacho: Molecular organization and effective energy transfer in iridium metallo-surfactant-porphyrin assemblies embedded in Langmuir-Schaefer films. In: *Physical Chemistry Chemical Physics* 13, 7, 2834-2841 (2011).

Publications/Department of Interfaces

- Santini, E., J. Krägel, F. Ravera, L. Liggieri and R. Miller: Study of the monolayer structure and wettability properties of silica nanoparticles and CTAB using the Langmuir trough technique. In: *Colloids and Surfaces A-Physicochemical and Engineering Aspects* 382, 1-3 Sp. Iss., 186-191 (2011).
- Schelero, N., A. Stocco, H. Möhwald and T. Zemb: Pickering emulsions stabilized by stacked cationic micro-crystals controlled by charge regulation. In: *SOFT MATTER* 7, 22, 10694-10700 (2011).
- Schmidt, S., P. A. L. Fernandes, B. G. De Geest, M. Delcea, A. G. Skirtach, H. Möhwald and A. Fery: Release Properties of Pressurized Microgel Templated Capsules. In: *Advanced Functional Materials* 21, 8, 1411-1418 (2011).
- Schneider, J., R. Pflieger, S. I. Nikitenko, D. Shchukin and H. Möhwald: Line Emission of Sodium and Hydroxyl Radicals in Single-Bubble Sonoluminescence. In: *Journal of Physical Chemistry A* 115, 2, 136-140 (2011).
- Sevilla, M., A. B. Fuertes and R. Mokaya: Preparation and hydrogen storage capacity of highly porous activated carbon materials derived from polythiophene. In: *International Journal of Hydrogen Energy* 36, 24, 15658-15663 (2011).
- Sharipova, A., S. Aidarova, V. B. Fainerman and R. Miller: Study of dynamic interfacial tension of alkyl sulphates with different alkyl chain lengths at the water/hexane interface. In: *Colloids and Surfaces A-Physicochemical and Engineering Aspects* 382, 1-3 Sp. Iss., 181-185 (2011).
- Sharipova, A., S. Aidarova, V. B. Fainerman, A. Stocco, P. Cernoch and R. Miller: Dynamics of adsorption of polyallylamine hydrochloride/sodium dodecyl sulphate at water/air and water/hexane interfaces. In: *Colloids and Surfaces A-Physicochemical and Engineering Aspects* 391, 112-118 (2011).
- Sharipova, A., S. Aidarova, N. Mucic and R. Miller: Dilational rheology of polymer/surfactant mixtures at water/hexane interface. In: *Colloids and Surfaces A-Physicochemical and Engineering Aspects* 391, 130-134 (2011).
- Shchukina, E. M. and D. G. Shchukin: LbL coated microcapsules for delivering lipid-based drugs. In: *Advanced Drug Delivery Reviews* 63, 9, 837-846 (2011).
- Shchukin, D. G. and H. Möhwald: Smart nanocontainers as depot media for feedback active coatings. In: *Chemical Communications* 47, 31, 8730-8739 (2011).
- Shchukin, D. G., E. Skorb, V. Belova and H. Möhwald: Ultrasonic Cavitation at Solid Surfaces. In: *Advanced Materials* 23, 17, 1922-1934 (2011).
- Shen, Y. F., J. S. Reparaz, M. R. Wagner, A. Hoffmann, C. Thomsen, J. O. Lee, S. Heeg, B. Hatting, S. Reich, A. Saeki, S. Seki, K. Yoshida, S. S. Babu, H. Möhwald and T. Nakanishi: Assembly of carbon nanotubes and alkylated fullerenes: nanocarbon hybrid towards photovoltaic applications. In: *CHEMICAL SCIENCE* 2, 11, 2243-2250 (2011).
- Skirtach, A. G., A. M. Yashchenok and H. Möhwald: Encapsulation, release and applications of LbL polyelectrolyte multilayer capsules. In: *Chemical Communications* 47, 48, 12736-12746 (2011).
- Skorb, E. V., D. V. Andreeva, A. P. Raiski, N. A. Belyasova, H. Möhwald and D. V. Sviridov: Titanium dioxide-assisted photocatalytic induction of prophages to lytic cycle. In: *PHOTOCHEMICAL & PHOTOBIOLOGICAL SCIENCES* 10, 12, 1974-1978 (2011).
- Skorb, E. V., D. Fix, D. G. Shchukin, H. Möhwald, D. V. Sviridov, R. Mousa, N. Wanderka, J. Schäferhans, N. Pazos-Perez, A. Fery and D. V. Andreeva: Sonochemical formation of metal sponges. In: *Nanoscale* 3, 3, 985-993 (2011).
- Song, W. X., Y. Yang, H. Möhwald and J. B. Li: Two-dimensional polyelectrolyte hollow sphere arrays at a liquid-air interface. In: *Soft Matter* 7, 2, 359-362 (2011).
- Stefaniu, C., M. Chanana, H. Ahrens, D. Y. Wang, G. Brezesinski and H. Möhwald: Conformational induced behaviour of copolymer-capped magnetite nanoparticles at the air/water interface. In: *Soft Matter* 7, 9, 4267-4275 (2011).
- Stefaniu, C., M. Chanana, D. Y. Wang, G. Brezesinski and H. Möhwald: Stimuli-Responsive Magnetite Nanoparticle Monolayers. In: *Journal of Physical Chemistry C* 115, 13, 5478-5484 (2011).
- Stefaniu, C., M. Chanana, D. Y. Wang, D. V. Novikov, G. Brezesinski and H. Möhwald: Langmuir and Gibbs Magnetite NP Layers at the Air/Water Interface. In: *Langmuir* 27, 3, 1192-1199 (2011).
- Stocco, A., F. Garcia-Moreno, I. Manke, J. Banhart and D. Langevin: Particle-stabilised foams: structure and aging. In: *Soft Matter* 7, 2, 631-637 (2011).
- Stocco, A., E. Rio, B. P. Binks and D. Langevin: Aqueous foams stabilized solely by particles. In: *Soft Matter* 7, 4, 1260-1267 (2011).
- Su, Y., Q. A. He, X. H. Yan, J. B. Fei, Y. E. Cui and J. B. Li: Peptide Mesocrystals as Templates to Create an Au Surface with Stronger Surface-Enhanced Raman Spectroscopic Properties. In: *Chemistry-A European Journal* 17, 12, 3370-3375 (2011).
- Vollhardt, D., N. Nandi and S. D. Banik: Nanoaggregate shapes at the air/water interface. In: *Physical Chemistry Chemical Physics* 13, 11, 4812-4829 (2011).
- Volodkin, D., A. Skirtach, N. Madaboosi, J. Blacklock, R. v. Klitzing, A. Lankenau, C. Duschl and H. Möhwald: IR-light triggered drug delivery from micron-sized polymer biocoatings. In: *Journal of Controlled Release* 148, E70-E71 (2011).
- Volodkin, D., A. Skirtach and H. Möhwald: LbL Films as Reservoirs for Bioactive Molecules. In: *Advances in Polymer Science* 240, 135-161 (2011).
- Vysotsky, U. B., E. A. Belyaeva, E. S. Fomina, V. B. Fainerman, E. V. Aksenenko, D. Vollhardt and R. Miller: Superposition-additive approach: thermodynamic parameters of clusterization of monosubstituted alkanes at the air/water interface. In: *Physical Chemistry Chemical Physics* 13, 20927-20932 (2011).
- Vysotsky, Y. B., E. S. Fomina, E. A. Belyaeva, E. V. Aksenenko, V. B. Fainerman, D. Vollhardt and R. Miller: Quantum-Chemical Analysis of Thermodynamics of Two-Dimensional Cluster Formation of Racemic α -Amino Acids at the Air/Water Interface. In: *Journal of Physical Chemistry B* 115, 10, 2264-2281 (2011).
- Wang, Z. P., H. Möhwald and C. Y. Gao: Nanotubes Protruding from Poly(allylamine hydrochloride)-Graft-Pyrene Microcapsules. In: *ACS Nano* 5, 5, 3930-3936 (2011).
- Wang, Z. P., H. Möhwald and C. Y. Gao: Preparation and Redox-Controlled Reversible Response of Ferrocene-Modified Poly(allylamine hydrochloride) Microcapsules. In: *Langmuir* 27, 4, 1286-1291 (2011).

Publications/Department of Interfaces

Wang, Z. P., A. G. Skirtach, Y. Xie, M. Y. Liu, H. Möhwald and C. Y. Gao: Core-Shell Poly(allylamine hydrochloride)-Pyrene Nanorods Decorated with Gold Nanoparticles. In: *Chemistry of Materials* 23, 21, 4741-4747 (2011).

Wegerich, F., P. Turano, M. Allegrozzi, H. Möhwald and F. Lisdat: Electroactive Multilayer Assemblies of Bilirubin Oxidase and Human Cytochrome C Mutants: Insight in Formation and Kinetic Behavior. In: *Langmuir* 27, 7, 4202-4211 (2011).

Wolk, C., M. Heinze, P. Kreideweiss, M. Dittrich, G. Brezesinski, A. Langner and B. Dohner: Synthesis and DNA transfection properties of new head group modified malonic acid diamides. In: *International Journal of Pharmaceutics* 409, 1-2, 46-56 (2011).

Wu, C. Z., S. Bai, M. B. Ansoorge-Schumacher and D. Y. Wang: Nanoparticle Cages for Enzyme Catalysis in Organic Media. In: *ADVANCED MATERIALS* 23, 47, 5694-5699 (2011).

Xu, H. L., X. K. Liu and D. Y. Wang: Interfacial Basicity-Guided Formation of Polydopamine Hollow Capsules in Pristine O/W Emulsions - Toward Understanding of Emulsion Template Roles. In: *Chemistry of Materials* 23, 23, 5105-5110 (2011).

Yan, X. H., J. B. Li and H. Möhwald: Self-Assembly of Hexagonal Peptide Microtubes and Their Optical Waveguiding. In: *Advanced Materials* 23, 25, 2796-2801 (2011).

Yan, X. H., Y. Su, J. B. Li, J. Früh and H. Möhwald: Uniaxially-oriented peptide crystals for optical waveguiding. In: *Angewandte Chemie-International Edition* 50, 11186-11191 (2011).

Interfaces 2012

Alahverdijeva, V. S., D. O. Grigoriev, A. Javadi, C. Kotsmar, J. Krägel, A. V. Makievski, R. Miller and V. Pradines: Mixed Protein/Surfactant Interfacial Layers as Studied by Drop Shape Analysis and Capillary Pressure Tensiometry. In: *Recent Trends in Surface and Colloid Science*. (Eds.) Paul, B. K.; Moulik, S. World Scientific, Singapore (2012) 85-104.

Andreeva, D. V., D. V. Sviridov, A. Masic, H. Möhwald and E. V. Skorb: Nanoengineered Metal Surface Capsules: Construction of a Metal-Protection System. In: *Small* 8, 6, 820-825 (2012).

Bohinc, K., G. Brezesinski and S. May: Modeling the influence of adsorbed DNA on the lateral pressure and tilt transition of a zwitterionic lipid monolayer. In: *Physical Chemistry Chemical Physics* 14, 30, 10613-10621 (2012).

Borisova, D., H. Möhwald and D. G. Shchukin: Influence of Embedded Nanocontainers on the Efficiency of Active Anticorrosive Coatings for Aluminum Alloys Part I: Influence of Nanocontainer Concentration. In: *ACS Applied Materials & Interfaces* 4, 6, 2931-2939 (2012).

Brotchie, A., D. Borisova, V. Belova, H. Möhwald and D. Shchukin: Ultrasonic Modification of Aluminum Surfaces: Comparison between Thermal and Ultrasonic Effects. In: *Journal of Physical Chemistry C* 116, 14, 7952-7956 (2012).

Brotchie, A., J. Schneider, R. Pflieger, D. Shchukin and H. Möhwald: Sonochemiluminescence from a Single Cavitation Bubble in Water. In: *Chemistry-A European Journal* 18, 36, 11201-11204 (2012).

Chevalier, N. R., C. Chevillard, M. Goldmann, G. Brezesinski and P. Guenoun: CaCO₃ Mineralization under beta-Sheet Forming Peptide Monolayers. In: *Crystal Growth & Design* 12, 5, 2299-2305 (2012).

Christoforou, M., E. Leontidis and G. Brezesinski: Effects of Sodium Salts of Lyotropic Anions on Low-Temperature, Ordered Lipid Monolayers. In: *Journal of Physical Chemistry B* 116, 50, 14602-14612 (2012).

Dan, A., G. Gochev, C. Kotsmar, J. K. Ferri, A. Javadi, M. Karbaschi, J. Krägel, R. Wüstneck and R. Miller: Simultaneous vs. Sequential Adsorption of β -Casein/SDS Mixtures. Comparison of Water/Air and Water/Hexane Interfaces. In: *ACS Symposium Series* 1120, 153-178 (2012).

Dan, A., C. Kotsmar, J. K. Ferri, A. Javadi, M. Karbaschi, J. Krägel, R. Wüstneck and R. Miller: Mixed protein-surfactant adsorption layers formed in a sequential and simultaneous way at water-air and water-oil interfaces. In: *Soft Matter* 8, 22, 6057-6065 (2012).

Dannehl, C., O. G. Travkova and G. Brezesinski: Effect of SDS and CTAB on Derivatives of Antimicrobial Peptides Arenicin and LL-37. In: *Chemistry Letters* 41, 10 Sp. Iss. SI, 1178-1180 (2012).

Delcea, M., N. Sternberg, A. M. Yashchenok, R. Georgieva, H. Bäuml, H. Möhwald and A. G. Skirtach: Nanoplasmonics for Dual-Molecule Release through Nanopores in the Membrane of Red Blood Cells. In: *ACS Nano* 6, 5, 4169-4180 (2012).

Duan, L., X. H. Yan, A. H. Wang, Y. Jia and J. B. Li: Highly Loaded Hemoglobin Spheres as Promising Artificial Oxygen Carriers. In: *ACS Nano* 6, 8, 6897-6904 (2012).

Dulle, J., S. Nemeth, E. V. Skorb and D. V. Andreeva: Sononanostructuring of zinc based materials. In: *Rcs Advances* 2, 12460-12465 (2012).

Dulle, J., S. Nemeth, E. V. Skorb, T. Irrgang, J. Senker, R. Kempe, A. Fery and D. V. Andreeva: Sonochemical Activation of Al/Ni Hydrogenation Catalyst. In: *Advanced Functional Materials* 22, 15, 3128-3135 (2012).

Fainerman, V. B., E. V. Aksenenko, J. T. Petkov and R. Miller: Influence of solubilised dodecane on the dynamic surface tension and dilational rheology of micellar Triton X-45 and SDS solutions. In: *Colloids and Surfaces A-Physicochemical and Engineering Aspects* 413, Sp. Iss. SI, 125-129 (2012).

Fainerman, V. B., S. V. Lylyk, E. V. Aksenenko, N. M. Kovalchuk, V. I. Kovalchuk, J. T. Petkov and R. Miller: Effect of water hardness on surface tension and dilational visco-elasticity of sodium dodecyl sulphate solutions. In: *Journal of Colloid and Interface Science* 377, 1-6 (2012).

Ferri, J. K., P. A. L. Fernandes, J. T. McRuiz and F. Gambinossi: Elastic nanomembrane metrology at fluid-fluid interfaces using axisymmetric drop shape analysis with anisotropic surface tensions: deviations from Young-Laplace equation. In: *Soft Matter* 8, 40, 10352-10359 (2012).

Publications/Department of Interfaces

- Fix, D., S. Puchegger, C. Pilz-Allen, P. Roschger, S. Blouin, P. Fratzl and R. Weinkamer: Functional mapping of bone on the micrometer-scale by scanning acoustic microscopy. In: *Bone* 50, Suppl. 1, S125-S126 (2012).
- Frueh, J., N. Nakashima, Q. He and H. Möhwald: Effect of Linear Elongation on Carbon Nanotube and Polyelectrolyte Structures in PDMS-Supported Nanocomposite LbL Films. In: *Journal of Physical Chemistry B* 116, 40, 12257-12262 (2012).
- Frueh, J., G. Reiter, H. Möhwald, Q. He and R. Krastev: Orientation change of polyelectrolytes in linearly elongated polyelectrolyte multilayer measured by polarized UV spectroscopy. In: *Colloids and Surfaces A-Physicochemical and Engineering Aspects* 415, 366-373 (2012).
- Gabrieli, R., G. Loglio, P. Pandolfini, A. Fabbri, M. Simoncini, V. I. Kovalchuk, B. A. Noskov, A. V. Makievskii, J. Krägel, R. Miller, F. Ravera and L. Liggieri: Spherical cap-shaped emulsion films: thickness evaluation at the nanoscale level by the optical evanescent wave effect. In: *Colloids and Surfaces A-Physicochemical and Engineering Aspects* 413, Sp. Iss. SI, 101-107 (2012).
- Gawlitza, K., C. Z. Wu, R. Georgieva, D. Y. Wang, M. B. Ansorge-Schumacher and R. von Klitzing: Immobilization of lipase B within micron-sized poly-N-isopropylacrylamide hydrogel particles by solvent exchange. In: *Physical Chemistry Chemical Physics* 14, 27, 9594-9600 (2012).
- Gensel, J., T. Borke, N. Pazos Perez, A. Fery, D. V. Andreeva, E. Betthausen, A. H. E. Muller, H. Möhwald and E. V. Skorb: Cavitation Engineered 3D Sponge Networks and Their Application in Active Surface Construction. In: *Advanced Materials* 24, 7, (2012).
- Georgiev, G. A., N. Yokoi, S. Ivanova, R. Krastev and Z. Lalchev: Surface Chemistry Study of the Interactions of Pharmaceutical Ingredients with Human Meibum Films. In: *Investigative Ophthalmology & Visual Science* 53, 8, 4605-4615 (2012).
- Ghani, F., I. Bochukov, K. Fostiropoulos and H. Riegler: Hybrid solution/vacuum-processed bilayer heterojunction organic solar cells: Structural characterization and performance. In: *Thin Solid Films* 525, 177-181 (2012).
- Ghani, F., J. Kristen and H. Riegler: Solubility Properties of Unsubstituted Metal Phthalocyanines in Different Types of Solvents. In: *Journal of Chemical and Engineering Data* 57, 2, 439-449 (2012).
- Giner-Casares, J. J., G. Brezesinski and H. Möhwald: Interplay of Hydrophobic and Hydrophilic Interactions in a Mixed Polyoxometalate/Organic Langmuir Monolayer. In: *Chemistry Letters* 41, 10 Sp. Iss. SI, 1185-1187 (2012).
- Giner-Casares, J. J., G. Brezesinski, H. Möhwald, S. Landsmann and S. Polarz: Polyoxometalate Surfactants as Unique Molecules for Interfacial Self-Assembly. In: *Journal of Physical Chemistry Letters* 3, 3, 322-326 (2012).
- Giner-Casares, J. J., J. Keller, C. Rotger, A. Costa and G. Brezesinski: Mechanism of Action of Cyclic Oligosquaramides on DPPC Phospholipid Monolayers. In: *ChemPhysChem* 13, 2, 453-458 (2012).
- Glampedaki, P., J. Krägel, G. Petzold, V. Dutschk, R. Miller and M. M. C. G. Warmoeskerken: Polyester textile functionalisation through incorporation of pH/thermo-responsive microgels. Part I: Microgel preparation and characterisation. In: *Colloids and Surfaces A-Physicochemical and Engineering Aspects* 413, Sp. Iss. SI, 334-341 (2012).
- Glampedaki, P., G. Petzold, V. Dutschk, R. Miller and M. M. C. G. Warmoeskerken: Physicochemical properties of biopolymer-based polyelectrolyte complexes with controlled pH/thermo-responsiveness. In: *Reactive & Functional Polymers* 72, 7, 458-468 (2012).
- Haase, M. F., D. O. Grigoriev, H. Möhwald and D. G. Shchukin: Development of Nanoparticle Stabilized Polymer Nanocontainers with High Content of the Encapsulated Active Agent and Their Application in Water-Borne Anticorrosive Coatings. In: *Advanced Materials* 24, 18, 2429-2435 (2012).
- Hamdy, A. S., I. Doench and H. Möhwald: The Effect of Vanadia Surface Treatment on the Corrosion Inhibition Characteristics of an Advanced Magnesium Elektron 21 alloy in Chloride Media. In: *International Journal of Electrochemical Science* 7, 9, 7751-7761 (2012).
- Hamdy, A. S., I. Doench and H. Möhwald: Vanadia-based coatings of self-repairing functionality for advanced magnesium Elektron ZE41 Mg-Zn-rare earth alloy. In: *Surface & Coatings Technology* 206, 17, 3686-3692 (2012).
- Hamdy, A. S., I. Dönch and H. Möhwald: The effect of alkaline etching time on the anticorrosion performance of vanadia film formed on high strength AA2024 in chloride media. In: *Journal of Materials Science* 47, 8, 3784-3792 (2012).
- Hamdy, A. S., M. A. Shoeib and H. Hady: The effect of grain refining and phosphides formation on the performance of advanced nanocomposite and ternary alloy coatings on steel. In: *Materials Letters* 80, 191-194 (2012).
- Hollamby, M. J., D. Borisova, P. Brown, J. Eastoe, I. Grillo and D. Shchukin: Growth of Mesoporous Silica Nanoparticles Monitored by Time-Resolved Small-Angle Neutron Scattering. In: *Langmuir* 28, 9, 4425-4433 (2012).
- Hollamby, M. J., D. Borisova, H. Möhwald and D. Shchukin: Porous 'Ouzo-effect' silica-ceria composite colloids and their application to aluminium corrosion protection. In: *CHEMICAL COMMUNICATIONS* 48, 1, 115-117 (2012).
- Javadi, A., J. Krägel, A. V. Makievskii, V. I. Kovalchuk, N. M. Kovalchuk, N. Mucic, G. Loglio, P. Pandolfini, M. Karbaschi and R. Miller: Fast dynamic interfacial tension measurements and dilational rheology of interfacial layers by using the capillary pressure technique. In: *Colloids and Surfaces A-Physicochemical and Engineering Aspects* 407, 159-168 (2012).
- Jimenez-Millan, E., J. J. Giner-Casares, M. T. Martin-Romero, G. Brezesinski and L. Camacho: Tuning of the Hydrophobic and Hydrophilic Interactions in 2D Chiral Domains. In: *Journal of Physical Chemistry C* 116, 37, 19925-19933 (2012).
- Karbaschi, M., D. Bastani, A. Javadi, V. I. Kovalchuk, N. M. Kovalchuk, A. V. Makievskii, E. Bonaccorso and R. Miller: Drop profile analysis tensiometry under highly dynamic conditions. In: *Colloids and Surfaces A-Physicochemical and Engineering Aspects* 413, Sp. Iss. SI, 292-297 (2012).
- Karpitschka, S., E. Dietrich, J. R. T. Seddon, H. J. W. Zandvliet, D. Lohse and H. Riegler: Nonintrusive Optical Visualization of Surface Nanobubbles. In: *Physical Review Letters* 109, 6, Seq. No.: 066102 (2012).
- Karpitschka, S. and H. Riegler: Noncoalescence of Sessile Drops from Different but Miscible Liquids: Hydrodynamic Analysis of the Twin Drop Contour as a Self-Stabilizing Traveling Wave. In: *Physical Review Letters* 109, 6, Seq. No.: 066103 (2012).

Publications/Department of Interfaces

- Kohler, D., N. Madaboosi, M. Delcea, S. Schmidt, B. G. De Geest, D. V. Volodkin, H. Möhwald and A. G. Skirtach: Patchiness of Embedded Particles and Film Stiffness Control Through Concentration of Gold Nanoparticles. In: *Advanced Materials* 24, 8, 1095-1100 (2012).
- Kolesnikova, T. A., G. G. Akchurin, S. A. Portnov, G. B. Khomutov, G. G. Akchurin, O. G. Naumova, G. B. Sukhorukov and D. A. Gorin: Visualization of magnetic microcapsules in liquid by optical coherent tomography and control of their arrangement via external magnetic field. In: *Laser Physics Letters* 9, 9, 643-648 (2012).
- Kolesnikova, T. A., D. Kohler, A. G. Skirtach and H. Möhwald: Laser-Induced Cell Detachment, Patterning, and Regrowth on Gold Nanoparticle Functionalized Surfaces. In: *ACS Nano* 6, 11, 9585-9595 (2012).
- Kovalchuk, N. M.: Spontaneous oscillations due to solutal Marangoni instability: air/water interface. In: *Central European Journal of Chemistry* 10, 5, 1423-1441 (2012).
- Kovalchuk, N. M., V. Pimienta, R. Tadmouri, R. Miller and D. Vollhardt: Ionic Strength and pH as Control Parameters for Spontaneous Surface Oscillations. In: *Langmuir* 28, 17, 6893-6901 (2012).
- Kovalchuk, N. M. and V. M. Starov: Aggregation in colloidal suspensions: Effect of colloidal forces and hydrodynamic interactions. In: *Advances in Colloid and Interface Science* 179, Sp. Iss. SI, 99-106 (2012).
- Kovalchuk, N. M., D. Vollhardt and R. Miller: Spontaneous Nonlinear Oscillations Generated at Liquid Interfaces by Surfactant Transfer. In: *Encyclopedia of Surface and Colloid Science*. (Eds.) Somasundaran, P.; Hubbard, A. Taylor & Francis, New York (2012) 1-14.
- Kulovesi, P., J. Telenius, A. Koivuniemi, G. Brezesinski, I. Vattulainen and J. M. Holopainen: The impact of lipid composition on the stability of the tear fluid lipid layer. In: *Soft Matter* 8, 21, 5826-5834 (2012).
- Kusumaatmaja, H., R. Lipowsky, C. Jin, R. C. Mutihac and H. Riegler: Nonisomorphic Nucleation Pathways Arising from Morphological Transitions of Liquid Channels. In: *Physical Review Letters* 108, 12, Seq. No.: 126102 (2012).
- Latnikova, A., D. O. Grigoriev, H. Möhwald and D. G. Shchukin: Capsules Made of Cross-Linked Polymers and Liquid Core: Possible Morphologies and Their Estimation on the Basis of Hansen Solubility Parameters. In: *Journal of Physical Chemistry C* 116, 14, 8181-8187 (2012).
- Latnikova, A., D. Grigoriev, M. Schenderlein, H. Möhwald and D. Shchukin: A new approach towards "active" self-healing coatings: exploitation of microgels. In: *Soft Matter* 8, 42, 10837-10844 (2012).
- Madaboosi, N., K. Uhlig, M. S. Jäger, H. Möhwald, C. Duschl and D. V. Volodkin: Microfluidics as A Tool to Understand the Build-Up Mechanism of Exponential-Like Growing Films. In: *Macromolecular Rapid Communications* 33, 20, 1775-1779 (2012).
- Madaboosi, N., K. Uhlig, S. Schmidt, M. S. Jäger, H. Möhwald, C. Duschl and D. V. Volodkin: Microfluidics meets soft layer-by-layer films: selective cell growth in 3D polymer architectures. In: *Lab on a Chip* 12, 8, 1434-1436 (2012).
- Maestro, A., C. Kotsmar, A. Javadi, R. Miller, F. Ortega and R. G. Rubio: Adsorption of β -Casein-Surfactant Mixed Layers at the Air-Water Interface Evaluated by Interfacial Rheology. In: *Journal of Physical Chemistry B* 116, 16, 4898-4907 (2012).
- Marchenko, I., A. Yashchenok, T. Borodina, T. Bukreeva, M. Konrad, H. Möhwald and A. Skirtach: Controlled enzyme-catalyzed degradation of polymeric capsules templated on CaCO_3 : Influence of the number of LbL layers, conditions of degradation, and disassembly of multicompartments. In: *Journal of Controlled Release* 162, 3, 599-605 (2012).
- Noskov, B. A., O. Y. Milyaeva, S. Y. Lin, G. Loglio and R. Miller: Dynamic properties of β -casein/surfactant adsorption layers. In: *Colloids and Surfaces A-Physicochemical and Engineering Aspects* 413, Sp. Iss. SI, 84-91 (2012).
- Pazos-Perez, N., J. Schäferhans, E. V. Skorb, A. Fery and D. V. Andreeva: Ultrasound driven formation of metal-supported nanocatalysts. In: *Microporous and Mesoporous Materials* 154, 164-169 (2012).
- Pazos-Perez, N., J. Schäferhans, E. V. Skorb, A. Fery and D. V. Andreeva: Ultrasound driven formation of metal-supported nanocatalysts. In: *Microporous and Mesoporous Materials* 154, Sp. Iss. SI, 164-169 (2012).
- Pechenkin, M. A., H. Möhwald and D. V. Volodkin: pH- and salt-mediated response of layer-by-layer assembled PSS/PAH microcapsules: fusion and polymer exchange. In: *Soft Matter* 8, 33, 8659-8665 (2012).
- Peterson, A. M., H. Möhwald and D. G. Shchukin: pH-Controlled Release of Proteins from Polyelectrolyte-Modified Anodized Titanium Surfaces for Implant Applications. In: *Biomacromolecules* 13, 10, 3120-3126 (2012).
- Pinheiro, M., M. Lucio, S. Reis, J. L. F. C. Lima, J. M. Caio, C. Moiteiro, M. T. Martin-Romero, L. Camacho and J. J. Giner-Casares: Molecular Interaction of Rifabutin on Model Lung Surfactant Monolayers. In: *Journal of Physical Chemistry B* 116, 38, 11635-11645 (2012).
- Ramirez, P., A. Stocco, J. Munoz and R. Miller: Interfacial rheology and conformations of triblock copolymers adsorbed onto the water-oil interface. In: *Journal of Colloid and Interface Science* 378, 135-143 (2012).
- Rocha, S., J. A. Loureiro, G. Brezesinski and M. D. Pereira: Peptide-surfactant interactions: Consequences for the amyloid-beta structure. In: *Biochemical and Biophysical Research Communications* 420, 1, 136-140 (2012).
- Roldan-Carmona, C., J. J. Giner-Casares, M. Perez-Morales, M. T. Martin-Romero and L. Camacho: Revisiting the Brewster Angle Microscopy: The relevance of the polar head-group. In: *Advances in Colloid and Interface Science* 173, 12-22 (2012).
- Sankaranarayanan, K., A. Dhathathreyan, J. Krägel and R. Miller: Interfacial Viscoelasticity of Myoglobin at Air/Water and Air/Solution Interfaces: Role of Folding and Clustering. In: *Journal of Physical Chemistry B* 116, 2, 895-902 (2012).
- Schelero, N., R. von Klitzing, V. B. Fainerman and R. Miller: Chain length effects on complex formation in solutions of sodium alkanoates and tetradecyl trimethyl ammonium bromide. In: *Colloids and Surfaces A-Physicochemical and Engineering Aspects* 413, Sp. Iss. SI, 115-118 (2012).
- Schmidt, S., N. Madaboosi, K. Uhlig, D. Köhler, A. Skirtach, C. Duschl, H. Möhwald and D. V. Volodkin: Control of Cell Adhesion by Mechanical Reinforcement of Soft Polyelectrolyte Films with Nanoparticles. In: *Langmuir* 28, 18, 7249-7257 (2012).

Publications/Department of Interfaces

- Shchukina, E. M. and D. G. Shchukin: Layer-by-layer coated emulsion microparticles as storage and delivery tool. In: *Current Opinion in Colloid & Interface Science* 17, 5, 281-289 (2012).
- Skorb, E. V., D. V. Andreeva and H. Möhwald: Generation of a Porous Luminescent Structure Through Ultrasonically Induced Pathways of Silicon Modification. In: *Angewandte Chemie-International Edition* 51, 21, 5138-5142 (2012).
- Skorb, E. V., D. V. Andreeva and H. Möhwald: Generation of a Porous Luminescent Structure Through Ultrasonically Induced Pathways of Silicon Modification. In: *Angewandte Chemie International Edition* 51, 5138-5142 (2012).
- Skorb, E. V., O. Baidukova, A. Goyal, A. Brotchie, D. V. Andreeva and H. Möhwald: Sononanoengineered magnesium-polypyrrole hybrid capsules with synergetic trigger release. In: *Journal of Materials Chemistry* 22, 27, 13841-13848 (2012).
- Stefaniu, C., G. Brezesinski and H. Möhwald: Polymer-capped magnetite nanoparticles change the 2D structure of DPPC model membranes. In: *Soft Matter* 8, 30, 7952-7959 (2012).
- Stefaniu, C., G. Brezesinski and D. Vollhardt: Two-Dimensional Miscibility Behavior of Two Chemically Similar Amide Amphiphiles. In: *Journal of Physical Chemistry C* 116, 10, 6268-6274 (2012).
- Stefaniu, C., I. Vilotijevic, M. Santer, D. Varón Silva, G. Brezesinski and P. H. Seeberger: Subgel Phase Structure in Monolayers of Glycosylphosphatidylinositol Glycolipids. In: *Angewandte Chemie International Edition* 51, 12874-12878 (2012).
- Stocco, A., M. Chanana, G. Su, P. Cernoch, B. P. Binks and D. Y. Wang: Bidirectional Nanoparticle Crossing of Oil-Water Interfaces Induced by Different Stimuli: Insight into Phase Transfer. In: *Angewandte Chemie-International Edition* 51, 38, 9647-9651 (2012).
- Üzüm, C., J. Hellwig, N. Madaboosi, D. Volodkin and R. von Klitzing: Growth behaviour and mechanical properties of PLL/HA multilayer films studied by AFM. In: *Beilstein Journal of Nanotechnology* 3, 778-788 (2012).
- Uhlig, K., N. Madaboosi, S. Schmidt, M. S. Jäger, J. Rose, C. Duschl and D. V. Volodkin: 3D localization and diffusion of proteins in polyelectrolyte multilayers. In: *Soft Matter* 8, 47, 11786-11789 (2012).
- Ulaganathan, V., B. Bergenstahl, J. Krägel and R. Miller: Adsorption and shear rheology of β -lactoglobulin/SDS mixtures at water/hexane and water/MCT interfaces. In: *Colloids and Surfaces A-Physicochemical and Engineering Aspects* 413, Sp. Iss. SI, 136-141 (2012).
- Virost, M., R. Pflieger, E. V. Skorb, J. Ravoux, T. Zemb and H. Möhwald: Crystalline Silicon under Acoustic Cavitation: From Mechanoluminescence to Amorphization. In: *Journal of Physical Chemistry C* 116, 29, 15493-15499 (2012).
- Volodkin, D., A. Skirtach and H. Möhwald: Bio-applications of light-sensitive polymer films and capsules assembled using the layer-by-layer technique. In: *Polymer International* 61, 5, 673-679 (2012).
- Volodkin, D. V., S. Schmidt, P. Fernandes, N. I. Larionova, G. B. Sukhorukov, C. Duschl, H. Möhwald and R. von Klitzing: One-Step Formulation of Protein Microparticles with Tailored Properties: Hard Templating at Soft Conditions. In: *Advanced Functional Materials* 22, 9, 1914-1922 (2012).
- Voronin, D. V., D. Borisova, V. Belova, D. A. Gorin and D. G. Shchukin: Effect of Surface Functionalization of Metal Wire on Electrophysical Properties of Inductive Elements. In: *Langmuir* 28, 33, 12275-12281 (2012).
- Vysotsky, Y. B., E. A. Belyaeva, E. S. Fomina, A. O. Vasylyev, D. Vollhardt, V. B. Fainerman, E. V. Aksenenko and R. Miller: Superposition-additive approach in the description of thermodynamic parameters of formation and clusterization of substituted alkanes at the air/water interface. In: *Journal of Colloid and Interface Science* 387, 162-174 (2012).
- Vysotsky, Y. B., E. A. Belyaeva, A. O. Vasylyev, V. B. Fainerman, E. V. Aksenenko, D. Vollhardt and R. Miller: Superposition-additive approach: Thermodynamic parameters of monosubstituted alkanes. In: *Colloids and Surfaces A-Physicochemical and Engineering Aspects* 413, Sp. Iss. SI, 303-306 (2012).
- Vysotsky, Y. B., E. A. Belyaeva, E. S. Fomina, D. Vollhardt, V. B. Fainerman and R. Miller: Thermodynamics of the Clusterization Process of trans-Isomers of Unsaturated Fatty Acids at the Air/Water Interface. In: *Journal of Physical Chemistry B* 116, 7, 2173-2182 (2012).
- Vysotsky, Y. B., E. S. Fomina, E. A. Belyaeva, D. Vollhardt, V. B. Fainerman and R. Miller: A simple method for estimation of the 2D cluster formation temperature of substituted alkanes at the air/water interface. In: *Colloids and Surfaces A-Physicochemical and Engineering Aspects* 413, Sp. Iss. SI, 288-291 (2012).
- Vysotsky, Y. B., E. S. Fomina, E. A. Belyaeva, D. Vollhardt, V. B. Fainerman and R. Miller: Temperature Effect on the Monolayer Formation of Substituted Alkanes at the Air/Water Interface: A Quantum Chemical Approach. In: *Journal of Physical Chemistry B* 116, 30, 8996-9006 (2012).
- Vysotsky, Y. B., E. S. Fomina, E. A. Belyaeva, D. Vollhardt, V. B. Fainerman and R. Miller: Quantum Chemical Analysis of the Thermodynamics of 2D Cluster Formation of Aliphatic Amides at the Air/Water Interface. In: *Journal of Physical Chemistry C* 116, 26358-26376 (2012).
- Wettstein, C., H. Möhwald and F. Lisdat: Coupling of pyrroloquinoline quinone dependent glucose dehydrogenase to (cytochrome c/DNA)-multilayer systems on electrodes. In: *Bioelectrochemistry* 88, 97-102 (2012).
- Winkelmann, M., A. Javadi, R. Miller and H. P. Schuchmann: Characterisation of alkyl amines at the water/air surface with the drop and bubble profile analysis tensiometry. In: *Journal of Colloid and Interface Science* 372, 202-206 (2012).
- Winkelmann, M., L. Schneider, W. Gerlinger, B. Sachweh, R. Miller and H. P. Schuchmann: Mass transport characteristics of alkyl amines in a water/n-decane system. In: *Journal of Colloid and Interface Science* 372, 164-169 (2012).
- Wüstneck, R., V. B. Fainerman, E. V. Aksenenko, C. Kotsmar, V. Pradines, J. Krägel and R. Miller: Surface dilatational behavior of β -casein at the solution/air interface at different pH values. In: *Colloids and Surfaces A-Physicochemical and Engineering Aspects* 404, 17-24 (2012).

Publications/Department of Interfaces

Yan, X. H., J. Blacklock, J. B. Li and H. Möhwald: One-Pot Synthesis of Polypeptide-Gold Nanoconjugates for in Vitro Gene Transfection. In: *ACS Nano* 6, 1, 111-117 (2012).

Yan, X. H., J. B. Li and H. Möhwald: Templating Assembly of Multifunctional Hybrid Colloidal Spheres. In: *Advanced Materials* 24, 20, 2663-2667 (2012).

Yashchenok, A. M., D. Borisova, B. V. Parakhonskiy, A. Masic, B. E. Pinchasik, H. Möhwald and A. G. Skirtach: Nanoplasmonic smooth silica versus porous calcium carbonate bead biosensors for detection of biomarkers. In: *Annalen der Physik* 524, 11, 723-732 (2012).

Yu, Y., B. Ai, H. Möhwald, Z. W. Zhou, G. Zhang and B. Yang: Fabrication of Binary and Ternary Hybrid Particles Based on Colloidal Lithography. In: *Chemistry of Materials* 24, 23, 4549-4555 (2012).

Zech, O., M. F. Haase, D. G. Shchukin, T. Zemb and H. Möhwald: Froth flotation via microparticle stabilized foams. In: *Colloids and Surfaces A-Physicochemical and Engineering Aspects* 413, Sp. Iss. SI, 2-6 (2012).

Zhang, R. J., W. H. Li, L. Li, W. R. Jin, H. Möhwald and W. P. Sui: Calcium-containing disk pattern from microspheres of chitosan with alginate. In: *Thin Solid Films* 520, 19, 6165-6169 (2012).

Zhang, R. J., W. H. Li, H. Möhwald, W. P. Sui, Z. P. Wang and C. Y. Gao: Shell modulation by tailoring substituents in chitosan for LbL-assembled microcapsules. In: *Journal of Colloid and Interface Science* 372, 40-44 (2012).

Publications/Department of Theory & Bio-Systems

Theory & Bio-Systems 2011

- Berger, F., C. Keller, M. J. I. Müller, S. Klumpp and R. Lipowsky: Co-operative transport by molecular motors. In: *BIOCHEMICAL SOCIETY TRANSACTIONS* 39, 1211-1215 (2011).
- Bierbaum, V. and R. Lipowsky: Chemomechanical Coupling and Motor Cycles of Myosin V. In: *Biophysical Journal* 100, 7, 1747-1755 (2011).
- Dimova, R.: Membrane electroporation in high electric fields. In: *Bioelectrochemistry: fundamentals, applications and recent developments.* (Eds.) Alkire, Richard C.; Kolb, Dieter M.; Lipowski, Jacek. Wiley-VCH, Weinheim (2011) 335-367.
- Guo, K. K., W. J. Xiao and D. Qiu: Polymerization of actin filaments coupled with adenosine triphosphate hydrolysis: Brownian dynamics and theoretical analysis. In: *JOURNAL OF CHEMICAL PHYSICS* 135, 10, Seq. No.: 105101 (2011).
- Guskova, O. A. and C. Seidel: Mesoscopic Simulations of Morphological Transitions of Stimuli-Responsive Diblock Copolymer Brushes. In: *Macromolecules* 44, 3, 671-682 (2011).
- Hamdy, A. S.: Electrochemical behavior of diamond-like-carbon coatings deposited on AlTiC (Al₂O₃ + TiC) ceramic composite substrate in HCl solution. In: *Electrochimica Acta* 56, 3, 1554-1562 (2011).
- Hu, J. L., T. Weikl and R. Lipowsky: Vesicles with multiple membrane domains. In: *Soft Matter* 7, 13, 6092-6102 (2011).
- Hundertmark, M., R. Dimova, J. Lengefeld, R. Seckler and D. K. Hinch: The intrinsically disordered late embryogenesis abundant protein LEA18 from *Arabidopsis thaliana* modulates membrane stability through binding and folding. In: *Biochimica et Biophysica Acta-Biomembranes* 1808, 1, 446-453 (2011).
- Jegou, A., T. Niedermayer, J. Orban, D. Didry, R. Lipowsky, M. F. Carlier and G. Romet-Lemonne: Individual Actin Filaments in a Microfluidic Flow Reveal the Mechanism of ATP Hydrolysis and Give Insight Into the Properties of Profilin. In: *PLoS Biology* 9, 9, Seq. No.: e1001161 (2011).
- Kar, P., R. Lipowsky and V. Knecht: Importance of Polar Solvation for Cross-Reactivity of Antibody and Its Variants with Steroids. In: *Journal of Physical Chemistry B* 115, 23, 7661-7669 (2011).
- Klasczyk, B. and V. Knecht: Validating Affinities for Ion-Lipid Association from Simulation against Experiment. In: *Journal of Physical Chemistry A* 115, 38, 10587-10595 (2011).
- Klumpp, S.: Growth-Rate Dependence Reveals Design Principles of Plasmid Copy Number Control. In: *PLoS ONE* 6, 5, Seq. No.: e20403 (2011).
- Klumpp, S.: Pausing and Backtracking in Transcription Under Dense Traffic Conditions. In: *Journal of Statistical Physics* 142, 6, 1252-1267 (2011).
- Kroboth, H., B. Rózycki, R. Lipowsky and T. R. Weikl: Line Tension and Stability of Domains in Cell-Adhesion Zones Mediated by Long and Short Receptor-Ligand Complexes. In: *PLoS ONE* 6, 8, Seq. No.: e23284 (2011).
- Kusumaatmaja, H. and R. Lipowsky: Droplet-induced budding transitions of membranes. In: *Soft Matter* 7, 15, 6914-6919 (2011).
- Lei, W., D. Portehault, R. Dimova and M. Antonietti: Boron Carbon Nitride Nanostructures from Salt Melts: Tunable Water-Soluble Phosphors. In: *Journal of the American Chemical Society* 133, 18, 7121-7127 (2011).
- Li, Y. H., R. Lipowsky and R. Dimova: Membrane nanotubes induced by aqueous phase separation and stabilized by spontaneous curvature. In: *Proceedings of the National Academy of Sciences of the United States of America* 108, 12, 4731-4736 (2011).
- Menche, J., A. Valleriani and R. Lipowsky: Sequences of phase transitions in Ising models on correlated networks. In: *Physical Review E* 83, 6, Seq. No.: 061129 (2011).
- Mertins, O. and R. Dimova: Binding of Chitosan to Phospholipid Vesicles Studied with Isothermal Titration Calorimetry. In: *Langmuir* 27, 9, 5506-5515 (2011).
- Nagar, A., A. Valleriani and R. Lipowsky: Translation by Ribosomes with mRNA Degradation: Exclusion Processes on Aging Tracks. In: *Journal of Statistical Physics* 145, 5, 1385-1404 (2011).
- Rading, M. M., T. A. Engel, R. Lipowsky and A. Valleriani: Stationary Size Distributions of Growing Cells with Binary and Multiple Cell Division. In: *JOURNAL OF STATISTICAL PHYSICS* 145, 1, 1-22 (2011).
- Sahoo, M. and S. Klumpp: Transcriptional proofreading in dense RNA polymerase traffic. In: *EPL* 96, 6, Seq. No.: 60004 (2011).
- Sahoo, M., S. Lahiri and A. M. Jayannavar: Fluctuation theorems and atypical trajectories. In: *Journal of Physics A-Mathematical and Theoretical* 44, 20, Seq. No.: 205001 (2011).
- Schmoller, K. M., T. Niedermayer, C. Zensen, C. Wurm and A. R. Bausch: Fragmentation Is Crucial for the Steady-State Dynamics of Actin Filaments. In: *Biophysical Journal* 101, 4, 803-808 (2011).
- Schuster, M., R. Lipowsky, M. A. Assmann, P. Lenz and G. Steinberg: Transient binding of dynein controls bidirectional long-range motility of early endosomes. In: *Proceedings of the National Academy of Sciences of the United States of America* 108, 9, 3618-3623 (2011).
- Shchelokovskyy, P., S. Tristram-Nagle and R. Dimova: Effect of the HIV-1 fusion peptide on the mechanical properties and leaflet coupling of lipid bilayers. In: *New Journal of Physics* 13, Seq. No.: 025004 (2011).
- Valleriani, A., G. Zhang, A. Nagar, Z. Ignatova and R. Lipowsky: Length-dependent translation of messenger RNA by ribosomes. In: *Physical Review E* 83, 4, Seq. No.: 042903 (2011).
- von Deuster, C. I. E. and V. Knecht: Competing interactions for antimicrobial selectivity based on charge complementarity. In: *Biochimica et Biophysica Acta-Biomembranes* 1808, 12, 2867-2876 (2011).
- Yang, P. and R. Dimova: Nanoparticle synthesis in vesicle microreactors. In: *Biomimetic based applications.* (Eds.) George, A. InTech, Rijeka (2011) 523-552.

Theory & Bio-Systems 2012

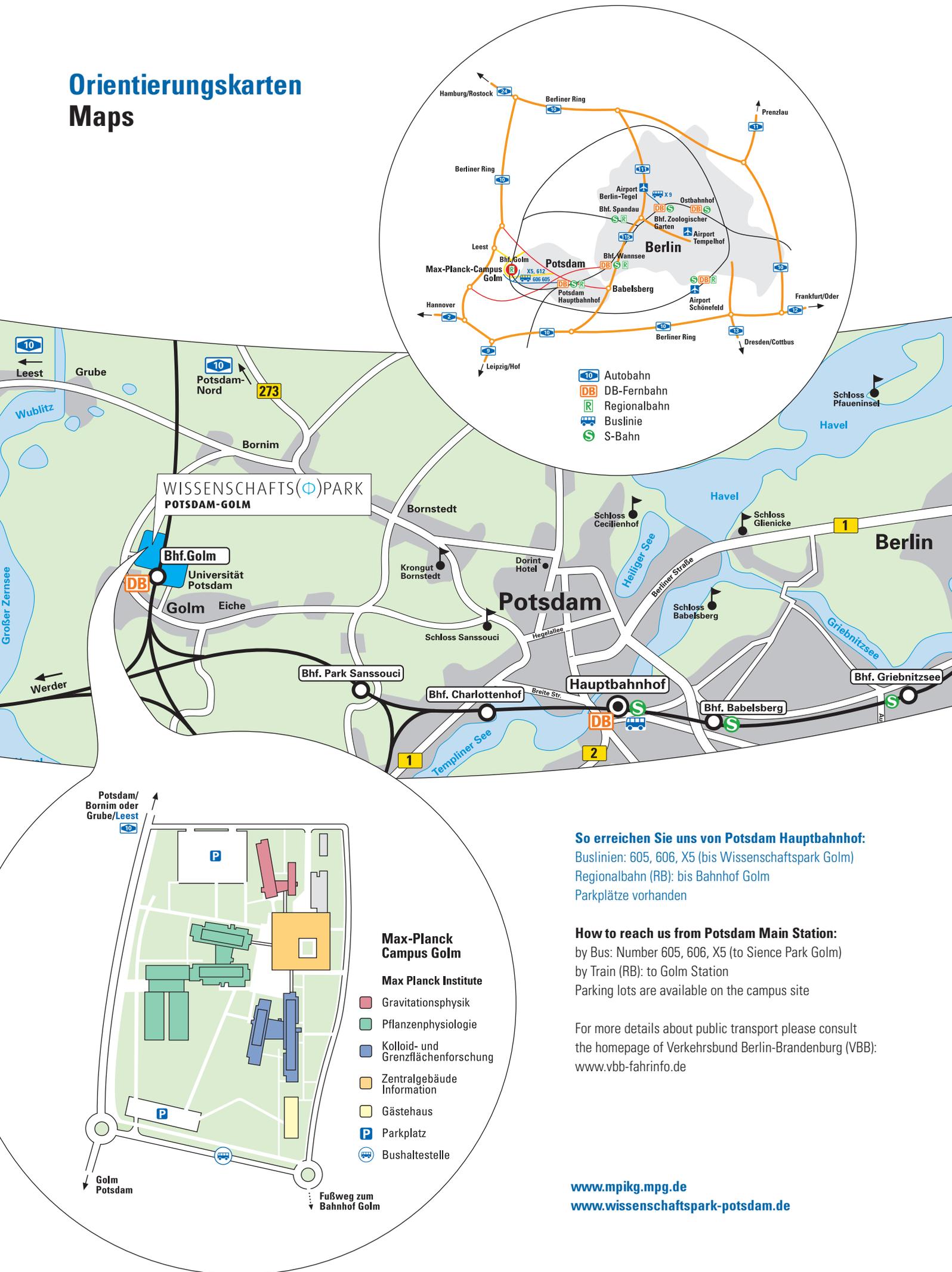
- Bahrami, A. H., R. Lipowsky and T. R. Weikl: Tubulation and Aggregation of Spherical Nanoparticles Adsorbed on Vesicles. In: *Physical Review Letters* 109, 18, Seq. No.: 188102 (2012).
- Berger, F., C. Keller, S. Klumpp and R. Lipowsky: Distinct Transport Regimes for Two Elastically Coupled Molecular Motors. In: *Physical Review Letters* 108, 20, Seq. No.: 208101 (2012).

- Brilliantov, N. V. and C. Seidel: Grafted polyelectrolyte in strong electric field under load: Field-regulated force and chain contraction. In: *EPL* 97, 2, Seq. No.: 28006 (2012).
- Casse, O., A. Shkilnyy, J. Linders, C. Mayer, D. Haussinger, A. Völkel, A. F. Thünemann, R. Dimova, H. Cölfen, W. Meier, H. Schlaad and A. Taubert: Solution Behavior of Double-Hydrophilic Block Copolymers in Dilute Aqueous Solution. In: *Macromolecules* 45, 11, 4772-4777 (2012).
- Deneke, C., S. Rudolf and A. Valleriani: Transient Phenomena in Gene Expression after Induction of Transcription. In: *PLoS ONE* 7, 4, Seq. No.: e35044 (2012).
- Dimova, R.: Giant Vesicles: A Biomimetic Tool for Membrane Characterization. In: *Advances in Planar Lipid Bilayers and Liposomes* 16, 1-50 (2012).
- Dimova, R. and R. Lipowsky: Lipid membranes in contact with aqueous phases of polymer solutions. In: *Soft Matter* 8, 24, 2409-2415 (2012).
- Dong, J. J., S. Klumpp and R. K. P. Zia: Entrainment and Unit Velocity: Surprises in an Accelerated Exclusion Process. In: *Physical Review Letters* 109, 13, Seq. No.: 130602 (2012).
- Faber, M. and S. Klumpp: RNA folding dynamics studied with structure-based models. In: *From Computational Biophysics to Systems Biology (CBSB11)*. (Eds.) Carloni, P. IAS Series 8. Forschungszentrum Jülich, Jülich (2012) 45-48.
- Fedyunin, I., L. Lehnhardt, N. Böhmer, P. Kaufmann, G. Zhang and Z. Ignatova: tRNA concentration fine tunes protein solubility. In: *FEBS Letters* 586, 19, 3336-3340 (2012).
- Garz, A., M. Sandmann, M. Rading, S. Ramm, R. Menzel and M. Steup: Cell-to-Cell Diversity in a Synchronized *Chlamydomonas* Culture As Revealed by Single-Cell Analyses. In: *Biophysical Journal* 103, 5, 1078-1086 (2012).
- Guskova, O. A. and C. Seidel: Assembly of nanoparticles on diblock copolymer brushes: toward laterally nano-structured composites. In: *Soft Matter* 8, 10, 2833-2843 (2012).
- Hausmann, R., M. Grepl, V. Knecht and M. J. Moeller: The glomerular filtration barrier function: new concepts. In: *Current Opinion in Nephrology and Hypertension* 21, 4, 441-449 (2012).
- Kar, P. and V. Knecht: Energetics of Mutation-Induced Changes in Potency of Lersivirine against HIV-1 Reverse Transcriptase. In: *Journal of Physical Chemistry B* 116, 22, 6269-6278 (2012).
- Kar, P. and V. Knecht: Mutation-Induced Loop Opening and Energetics for Binding of Tamiflu to Influenza N8 Neuraminidase. In: *Journal of Physical Chemistry B* 116, 21, 6137-6149 (2012).
- Kar, P. and V. Knecht: Origin of Decrease in Potency of Darunavir and Two Related Antiviral Inhibitors against HIV-2 Compared to HIV-1 Protease. In: *Journal of Physical Chemistry B* 116, 8, 2605-2614 (2012).
- Kar, P. and V. Knecht: Energetic basis for drug resistance of HIV-1 protease mutants against amprenavir. In: *Journal of Computer-Aided Molecular Design* 26, 2, 215-232 (2012).
- Keller, P. and A. Valleriani: Single-molecule stochastic times in a reversible bimolecular reaction. In: *Journal of Chemical Physics* 137, 8, Seq. No.: 084106 (2012).
- Klumpp, S.: Mechanisms and economy of molecular machines. In: *Physica Scripta T151*, Seq. No.: 014066 (2012).
- Klumpp, S., J. J. Dong and T. Hwa: On ribosome load, codon usage and protein abundance. In: *PLoS ONE* 7, Seq. No.: e48542 (2012).
- Klumpp, S. and D. Faivre: Interplay of Magnetic Interactions and Active Movements in the Formation of Magnetosome Chains. In: *PLoS ONE* 7, 3, Seq. No.: e33562 (2012).
- Knorr, R. L., R. Dimova and R. Lipowsky: Curvature of Double-Membrane Organelles Generated by Changes in Membrane Size and Composition. In: *PLoS ONE* 7, 3, Seq. No.: e32753 (2012).
- Kusumaatmaja, H., R. Lipowsky, C. Jin, R. C. Mutihac and H. Riegler: Nonisomorphic Nucleation Pathways Arising from Morphological Transitions of Liquid Channels. In: *Physical Review Letters* 108, 12, Seq. No.: 126102 (2012).
- Lechner, S., P. Patra, S. Klumpp and R. Bertram: Interplay between population dynamics and drug tolerance in *Staphylococcus aureus* persister cells. In: *Journal of Molecular Microbiology and Biotechnology* 22, 381-391 (2012).
- Liu, Y. G., R. Lipowsky and R. Dimova: Concentration Dependence of the Interfacial Tension for Aqueous Two-Phase Polymer Solutions of Dextran and Polyethylene Glycol. In: *Langmuir* 28, 8, 3831-3839 (2012).
- Li, X., R. Lipowsky and J. Kierfeld: Critical Motor Number for Fractional Steps of Cytoskeletal Filaments in Gliding Assays. In: *PLoS ONE* 7, 8, Seq. No.: e43219 (2012).
- Li, Y. H., H. Kusumaatmaja, R. Lipowsky and R. Dimova: Wetting-Induced Budding of Vesicles in Contact with Several Aqueous Phases. In: *Journal of Physical Chemistry B* 116, 6, 1819-1823 (2012).
- Marathe, R., V. Bierbaum, D. Gomez and S. Klumpp: Deterministic and Stochastic Descriptions of Gene Expression Dynamics. In: *Journal of Statistical Physics* 148, 4, 607-626 (2012).
- Marathe, R., D. Gomez and S. Klumpp: Sources of stochasticity in constitutive and autoregulated gene expression. In: *Physica Scripta T151*, Seq. No.: 014068 (2012).
- Miettinen, M. S., V. Knecht, L. Monticelli and Z. Ignatova: Assessing Polyglutamine Conformation in the Nucleating Event by Molecular Dynamics Simulations. In: *Journal of Physical Chemistry B* 116, 34, 10259-10265 (2012).
- Niedermayer, T., A. Jegou, L. Chieze, B. Guichard, E. Helfer, G. Romet-Lemonne, M. F. Carlier and R. Lipowsky: Intermittent depolymerization of actin filaments is caused by photo-induced dimerization of actin protomers. In: *Proceedings of the National Academy of Sciences of the United States of America* 109, 27, 10769-10774 (2012).
- Rozycki, B., E. Boura, J. H. Hurley and G. Hummer: Membrane-Elasticity Model of Coatless Vesicle Budding Induced by ESCRT Complexes. In: *PLoS Computational Biology* 8, 10, Seq. No.: e1002736 (2012).
- Rudolf, S. and J. O. Rädler: Self-Assembly of Stable Monomolecular Nucleic Acid Lipid Particles with a Size of 30 nm. In: *Journal of the American Chemical Society* 134, 28, 11652-11658 (2012).

Publications/Department of Theory & Bio-Systems

- Rusconi, M., A. Valleriani, J. W. C. Dunlop, J. Kurths and R. Weinkamer: Quantitative approach to the stochastics of bone remodeling. In: *EPL* 97, 2, Seq. No.: 28009 (2012).
- Salipante, P. F., R. L. Knorr, R. Dimova and P. M. Vlahovska: Electrodeformation method for measuring the capacitance of bilayer membranes. In: *Soft Matter* 8, 14, 3810-3816 (2012).
- Stefaniu, C., I. Vilotijevic, M. Santer, D. Varón Silva, G. Brezesinski and P. H. Seeberger: Subgel Phase Structure in Monolayers of Glycosylphosphatidylinositol Glycolipids. In: *Angewandte Chemie International Edition* 51, 12874-12878 (2012).
- Stieger, T., M. Schoen and T. R. Weikl: Adhesion of surfaces mediated by adsorbed particles: Monte Carlo simulations and a general relationship between adsorption isotherms and effective adhesion energies. In: *Soft Matter* 8, 11737-11745 (2012).
- Verde, A. V., P. G. Bolhuis and R. K. Campen: Statics and Dynamics of Free and Hydrogen-Bonded OH Groups at the Air/Water Interface. In: *Journal of Physical Chemistry B* 116, 31, 9467-9481 (2012).
- von Deuster, C. I. E. and V. Knecht: Antimicrobial selectivity based on zwitterionic lipids and underlying balance of interactions. In: *Biochimica et Biophysica Acta-Biomembranes* 1818, 9, 2192-2201 (2012).
- Wehle, M., I. Vilotijevic, R. Lipowsky, P. H. Seeberger, D. V. Silva and M. Santer: Mechanical Compressibility of the Glycosylphosphatidylinositol (GPI) Anchor Backbone Governed by Independent Glycosidic Linkages. In: *Journal of the American Chemical Society* 134, 46, 18964-18972 (2012).
- Weikl, T. R. and D. D. Boehr: Conformational selection and induced changes along the catalytic cycle of *Escherichia coli* dihydrofolate reductase. In: *Proteins-Structure Function and Bioinformatics* 80, 10, 2369-2383 (2012).
- Zhang, G., I. Fedyunin, S. Kirchner, C. L. Xiao, A. Valleriani and Z. Ignatova: FANSe: an accurate algorithm for quantitative mapping of large scale sequencing reads. In: *Nucleic Acids Research* 40, 11, Seq. No.: e83 (2012).

Orientierungskarten Maps



So erreichen Sie uns von Potsdam Hauptbahnhof:

Buslinien: 605, 606, X5 (bis Wissenschaftspark Golm)
 Regionalbahn (RB): bis Bahnhof Golm
 Parkplätze vorhanden

How to reach us from Potsdam Main Station:

by Bus: Number 605, 606, X5 (to Science Park Golm)
 by Train (RB): to Golm Station
 Parking lots are available on the campus site

For more details about public transport please consult the homepage of Verkehrsverbund Berlin-Brandenburg (VBB): www.vbb-fahrinfo.de

www.mpikg.mpg.de
www.wissenschaftspark-potsdam.de