Colloidal Membranes
Lecture Series: Colloidal Phenomena

AGENDA

1 Introduction/Disambiguation
2 Membranes by surfactant self-assembly
3 Polymeric membranes
4 Summary
Introduction

- Main discrimination possible between:
  - Natural (biological) vs. Artificial (man-made) membranes

- Further discrimination on the basis of transport properties, material properties (surfactants, polymers, etc.), pore sizes, etc.

Unifying concept: **Separation of compartments!**

Membranes by surfactant self-assembly

**Reminder:**

Amphiphilic molecules

$\rightarrow$ Self-assembly in aqueous solution

Different morphologies:

# spherical micelles (a)
# worm-like micelles (e)
# vesicles (d)
# bilayers (c)

Driving force: hydrophobic effect

$\rightarrow$ exclusion of hydrophobic part from water to minimize water contact

![Figure 2](image-url) Common lamellar and nonlamellar self-assembled structures of lipids: (a) micelle, (e) inverse micelle, (c) lamellar bilayer, (d) bilayer vesicle, (e) hexagonal, (f) inverse hexagonal.
Membranes by surfactant self-assembly

form of an aggregate is determined by the surfactant geometry

universal validity:
low molecular weight surfactants → amphiphilic block copolymers

Other factors:
# polarity
# chain: length, branching, flexibility
# charge
# concentration
# temperature

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**Geometrical Contribution**

<table>
<thead>
<tr>
<th>LIPID</th>
<th>LIPID SHAPE</th>
<th>ORGANIZATION</th>
<th>PHASE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soaps, detergents</td>
<td>Inverted cone (β&lt;sub&gt;2&lt;/sub&gt;)</td>
<td>Needle</td>
<td>Isotropic hexagonal I</td>
</tr>
<tr>
<td>Phospholipid bilayer</td>
<td>Cylinder (β&lt;sub&gt;2&lt;/sub&gt;)</td>
<td>Bilayer</td>
<td>Lamellar (cubic)</td>
</tr>
<tr>
<td>Phospholipid micelles</td>
<td>Cone</td>
<td>Reverse micelle</td>
<td>Revers micelle, hexagonal II</td>
</tr>
<tr>
<td>Mixtures</td>
<td>P&lt;sub&gt;1&lt;/sub&gt;</td>
<td>Bilayer</td>
<td>Hexalinear</td>
</tr>
</tbody>
</table>

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**Lipids**

membrane lipids are the building blocks of natural bilayer systems

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Figure A.1: Schematic structure of some common classes of lipids. The phospholipids represent the main component of the lipid bilayer of natural membranes and bacteria.
Bilayer membranes

- approaches to achieve \( P = \frac{v}{(l^* a_0)} \approx 1 \)

small headgroup and/or bulky apolar tails
- Two alkyl chains instead of one

\[
\begin{align*}
\text{vs.} & \quad \text{vs.} \\
\end{align*}
\]

- smaller headgroups (size reduction in case of nonionic surfactants, introduction of cosurfactants with very small headgroups (e.g. addition of alkanols like decanol)

\[
C_{12}E_4 \text{ forms lamellae at room temperature} \\
C_{12}E_5 \text{ forms lamellae at } 50^\circ\text{C}
\]

Lipids

<table>
<thead>
<tr>
<th>Fuel Chain</th>
<th>Common Name</th>
<th>Symbol</th>
</tr>
</thead>
<tbody>
<tr>
<td>C8:0</td>
<td>stearin</td>
<td>0:0</td>
</tr>
<tr>
<td>C10:0</td>
<td>oleic</td>
<td>0:1</td>
</tr>
<tr>
<td>C12:0</td>
<td>linoleic</td>
<td>0:2</td>
</tr>
<tr>
<td>C14:0</td>
<td>linolenic</td>
<td>0:3</td>
</tr>
<tr>
<td>C16:0</td>
<td>palmitic</td>
<td>0:4</td>
</tr>
<tr>
<td>C18:0</td>
<td>stearic</td>
<td>0:5</td>
</tr>
<tr>
<td>C20:0</td>
<td>arachidonic</td>
<td>0:6</td>
</tr>
<tr>
<td>C22:0</td>
<td>docosahexaenoic</td>
<td>0:7</td>
</tr>
</tbody>
</table>

Lamellar phase at room temperature
**Bilayer formation vs. Micelle formation**

<table>
<thead>
<tr>
<th>Property</th>
<th>Micelles</th>
<th>Bilayers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Monomer solubility</td>
<td>$\sim 10^{-2}$ M</td>
<td>$10^{-1} - 10^{-4}$ M</td>
</tr>
<tr>
<td>$t$ for monomer exchange</td>
<td>$10^{-2} - 10^{-3}$ s</td>
<td>$10^{-2} - 10^{-3}$ s</td>
</tr>
<tr>
<td>Characteristic temperature</td>
<td>Kraft temperature</td>
<td>Chain-melting temperature</td>
</tr>
<tr>
<td>Structural directionality</td>
<td>All directions equivalent</td>
<td>Lateral diffusion rapid, flip-flop</td>
</tr>
<tr>
<td>Aggregation pattern</td>
<td>Forms well-defined aggregate at well-defined CMC</td>
<td>Basic structural unit appears in a variety of global structures</td>
</tr>
</tbody>
</table>

- Micelles will not grow in size but in number upon surfactant addition
- Idealistic: No molecular limit for bilayer growth in lateral direction → but line tension will force defects or closure: vesicles!

**Planar bilayer:**
- problem: # edges in contact with water → increase of line energy ($E_{\text{line}}$) – surface tension along the circular rim

**Vesicular structure:**
- problem: # bending of the bilayer → deformation of amphiphiles ($E_{\text{bend}}$)
vesicles

Uni-lamellar vesicle  Multi-lamellar vesicle

SUV (small unilamellar vesicle): ~ 20 nm
LUV (large unilamellar vesicle): ~ 100 nm
GUV (giant unilamellar vesicle): ~ 1-100 μm

Sizes, type and polydispersity depend also on preparation!

Inner Structure of Bilayer Systems

Figure 4.3 When alkyl chains crystallize, they have a cross-sectional area of 3-5 Å² per chain in a plane perpendicular to the direction of the chain. If the area of the polar groups in the bilayer matches that of the chain, a structure \( l_{a} \) is adopted. In the more likely case of a mismatch between polar head and chain areas, a tilted structure, as in \( l_{t} \), or a plugged structure, as in \( P_{t} \), are seen. For single-chain amphiphiles, chains may even interdigitate, making the thickness of the polar layer the same as the length of a single chain.

How was this picture developed?
Characterization of bilayer systems

- Complete characterisation requires use of multiple techniques:
  - X-ray or Neutron diffraction (lamellae size, repeat unit, …)
  - Microscopy (vesicle size, morphology)
  - Light Scattering methods (vesicle size, shape)
  - Nuclear Magnetic Resonance spectroscopy (molecular level structure)
  - Calorimetry (phase transitions, enthalpies, etc.)
  - ...many more techniques are available
Calorimetry

The specific heat of molten chains increases with temperature, as shown in the graph. The transition from the ordered state to the molten state is indicated by a peak in the specific heat curve. The experiments were conducted using digital video enhanced microscopy (VEM) and Transmission Electron Microscopy (TEM). Cryo-TEM, which involves rapid freezing of the sample, was used to obtain high-resolution images. Plain TEM was also used, but only if the self-assembled structure survived dehydration. Wolfgang Meier from Basel provided the TEM images of negatively stained vesicles.
Pipette aspiration

- Vesicles are captured by a micropipette
- Transfer in other media is possible
- Pressure manipulation by applied suction pressure

→ Access to physical properties of bilayer membranes (rigidity, interactions, thermal transitions, ...)

**Advantage:** projection length ~ change in total area
(vesicle volume = constant at the applied pressures)
small area changes are amplified and easily detectable


**Physical Properties of Sulfonated Bilayer Membranes: Thermal Transitions, Elasticity, Rigidity, Conformation, and Colloidal Interactions**

*Enrico Cozzini*

University of British Columbia, Vancouver, BC, Canada, 1987

and *David Venables*

Mechanical Engineering and Materials Science, Duke University, Durham, North Carolina, 1987

Monaco, February 2, 1987

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**Pipette aspiration**

*Figure 3. Video microscopy of giant bilayer vesicle aspiration inside a pipette.*

- Lg: Initial bilayer height
- P: Pressure
- L0: Final bilayer height

*Figure 4. Effect of bilayer area on solid DMPC bilayer structure and phase formation. Relative vesicle area is plotted vs. temperature for fixed bilayer tension. Values of the solid chain tilt in the bilayer normal (angle in parenthesis) were derived from the ratio of projected areas for the rippled-solid and phase-solid surfaces at the same temperature.*
Light Scattering

Measurement of radius of gyration $R_g$ (static light scattering) and hydrodynamic radius $R_h$ (dynamic light scattering) gives $\rho$-parameter:

$$\rho = \frac{R_g}{R_h}$$

- for coils: $\rho = 1.73$
- for vesicles: $\rho = 1.0$
- for spheres (e.g. micelles): $\rho = 0.775$

Example (Helmut Schlaad, MPIKG)

<table>
<thead>
<tr>
<th>$w_{hydrophilic}$</th>
<th>$R_h,0 / \text{nm}$</th>
<th>$R_g,0 / \text{nm}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.76</td>
<td>550 ± 20</td>
<td>520 ± 20</td>
</tr>
<tr>
<td>0.58</td>
<td>270 ± 40</td>
<td>280 ± 30</td>
</tr>
</tbody>
</table>

DLS/SLS 0.025-0.1 wt % polymer in water

Basic functions of lipid membranes

- Barrier for passive diffusional motion of solutes (e.g. ions, sugar, protein, polysaccharides, nucleic acids, …)
- Unique solvation environment for membrane proteins
- Internal organization of cells (compartmentalization)
Diffusional processes are always operable in living cells

**Characterized by:**
- flux ($J$)
- permeability ($P$)
- concentration gradient ($\Delta c$)
- Diffusion coefficient ($D$)
- Partition coefficient ($K$) (describes partition of solute between bulk in membrane interior)
- Membrane thickness ($d$)

\[
J = -P \Delta c = -D \frac{dc}{dz}
\]
(Fick's 1st law)

\[
P = \frac{D K}{d}
\]

**For ions:** additional electrostatic effects!

\[
J(z) = -\frac{D}{RT} c(z) \frac{d\mu}{dz}
\]

(use of electrochemical potential yields correct description!)

Experimental approach to investigate diffusion/transport:

**typical values for permeabilities of small solutes:**

- $P$(water) $\sim 5 \times 10^{-6}$ m/s
- $P$(polar solutes, e.g. glucose, urea, glycerol) $\sim 5 \times 10^{-10}$ m/s
- $P$(small ions, e.g. Na+, K+, Cl-) $\sim 1 \times 10^{-14}$ m/s
Multilayer systems

- Hindered Transport \((D_{\perp})\)
- Easy transport in parallel direction \((D_{\parallel})\)

Membrane proteins

- Typical membranes consist of 25-75 wt.% lipids, other species are: proteins, glycoproteins, lipoproteins, sugars...
- Proteins can be incorporated in a number of ways:

**Attention:** Proteins are inserted with a prescribed orientation!
Cell membranes are asymmetric, i.e., the surface of both sides are different (outer surface is often covered by sugars)
Protein mediated transmembrane transport

Pathway I for ion transport through a membrane (carrier transport)

Pathway II for ion transport through a membrane (channel transport)

Larger substances are transported by endo/exocytosis

Compartmentalization

Generally: Compartmentalization is required to provide the different unique environments for various processes

Typically: folding of membranes increases area/volume ratio
From Liposomes to Polymersomes

Universal validity of packing parameter:

low molecular weight surfactants → amphiphilic block copolymers

Advantage of high molecular weight surfactants (amphiphilic block copolymers)

• low CMC (critical micelle concentration)
  (e.g. CMC LMW surf.: $10^{-6}$ - $10^{-7}$ M; CMC polymer: $10^{-9}$ M)
• adjustable hydrophobic-hydrophilic ratio (block length, segregation, solubility)
• adjustable rigidity (Gaussian coil → rigid rod)
• introduction of functions
• adjustable biodegradability, biocompatibility
  → less dynamic structures
# Eisenberg 1995: PS$_{200}$-block-poly acrylic acid$_9$ (water)

# Nolte 1998: Stiffer hydrophobic block
poly(ethylene oxide)-block-poly(methylphenylsilane)

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**Responsive Systems**

**pH-degradable Systems** (H. Schlaad, MPIKG)

pB$_{216}$-block-pMA$_{29} \leftrightarrow$ p-4Me4VP$_{33}$-block-pS$_{211}$

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Asymmetric membrane

In THF: PS outside, PB inside
Inverse structure in hexane/THF
A variety of artificial membranes were developed for various separation/transport tasks.
Proton Conduction Membranes

- Proton exchange membrane fuel cells (PEMFC):

  ![PEM Fuel Cell diagram]

  Key part: **the membrane!**
  
  Good proton transport required! Low crossover of fuel, etc...

  → Microstructure has huge influence on performance

Typically used: Ionomer membranes (hydrophobic backbones with ionic side groups – strong polyelectrolytes which undergo microphase separation upon hydration – water channels!)

SAXS gives information about microstructure:
Microporous polymers (pore sizes ~0.7 nm) have high permeabilities but low selectivity.

Tuning of selectivity by polymer modification (e.g., hydrolysis of side groups).

<table>
<thead>
<tr>
<th>Polymer</th>
<th>Carbon elemental analysis</th>
<th>$P$ (Bar mm)$^a$</th>
<th>$\alpha^b$</th>
<th>$O_2$</th>
<th>$N_2$</th>
<th>$He$</th>
<th>$H_2$</th>
<th>$CO_2$</th>
<th>$O_2/N_2$</th>
<th>$CO_2/H_2$</th>
<th>$He/N_2$</th>
<th>$H_2/N_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>PM1</td>
<td></td>
<td></td>
<td></td>
<td>1790</td>
<td>727</td>
<td>1368</td>
<td>1580</td>
<td>8300</td>
<td>2.5</td>
<td>11</td>
<td>3.9</td>
<td>4.9</td>
</tr>
<tr>
<td>130 °C, 1 h</td>
<td></td>
<td></td>
<td></td>
<td>73.79</td>
<td>934</td>
<td>162</td>
<td>616</td>
<td>1540</td>
<td>2680</td>
<td>3.8</td>
<td>16</td>
<td>3.8</td>
</tr>
<tr>
<td>130 °C, 2 h</td>
<td></td>
<td></td>
<td></td>
<td>73.70</td>
<td>351</td>
<td>106</td>
<td>484</td>
<td>1152</td>
<td>2060</td>
<td>3.5</td>
<td>21</td>
<td>4.9</td>
</tr>
<tr>
<td>130 °C, 3 h</td>
<td></td>
<td></td>
<td></td>
<td>35.57</td>
<td>283</td>
<td>48</td>
<td>299</td>
<td>630</td>
<td>1096</td>
<td>4.2</td>
<td>22</td>
<td>5.4</td>
</tr>
<tr>
<td>130 °C, 3.5 h</td>
<td></td>
<td></td>
<td></td>
<td>70.90</td>
<td>100</td>
<td>24</td>
<td>151</td>
<td>408</td>
<td>620</td>
<td>4.6</td>
<td>26</td>
<td>6.3</td>
</tr>
</tbody>
</table>

$^a$Permeability coefficients measured at 25 °C and 50 psig feed pressure. One Barer = 10$^{-10}$ cm$^3$(STP)-cm/cm$^2$-s-cmHg.

$^b$Ideal selectivity $\alpha = (P_{O_2}/P_{H_2})$.

*Macromolecules* 2009, 42, 6038-6043

DOI: 10.1021/ma9009017
"The Colloidal Domain", by Evans and Wennerström

and references therein