Soft Matter Physics and the Physics of Living Matter

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Soft Matter

New term in Condensed Matter Physics

First introduced by Pierre-Gilles de Gennes, NPW, in his Nobel Lecture (1991)


Pierre-Gilles de Gennes (1932-2007)

- Complex liquids: caoutchouc. Milk, blood, ink, latex, mayonnaise.
- Soft condensed media: colloids, emulsions, suspensions, polymers, liquid crystals, etc.
- Mechanical properties of soft media: shear elastic modulus drastically lower than bulk compressibility modulus.

- Space scales of molecular organization:
  - microscopic (< 1 nm) isotropic liquids
  - mesoscopic (1–100 nm) soft matter
  - macroscopic (> 1 μm) solid crystals
Soft Matters Physics Chapters

- **Liquid crystal physics.** Thermotropics and lyotropics. Plastic crystals.
- **Polymer physics.** Melts, solutions, biopolymers.
- **Physical chemistry.** Colloids and surfactans, foams, emulsions.
- **Physics of networks.** Glues, rubbers, gels, cytoskeletons.
- **Membrane biophysics.** Liquid crystalline biostructures.
- **Physics of granular matter.** Sand, snow.

Basic question

Why is living matter soft?
Liquid Crystal Physics

Georges Friedel

États mésomorphes de la matière
*(Annales de Physique, 18, 273, 374, 1922)*

*(1865-1933)*

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Melting

<table>
<thead>
<tr>
<th>$T$</th>
<th>isotropic liquid</th>
<th>orient melting</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_{tr}$</td>
<td>nematic</td>
<td></td>
</tr>
<tr>
<td>$T_{trans}$</td>
<td>smectic A (normal)</td>
<td></td>
</tr>
<tr>
<td>$T_{sym}$</td>
<td>smectic A (twisted)</td>
<td></td>
</tr>
<tr>
<td>$T_{iso}$</td>
<td>smectic B</td>
<td></td>
</tr>
<tr>
<td>$T_{iso}$</td>
<td>layer-to-layer translation</td>
<td></td>
</tr>
</tbody>
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solid crystals | plastic crystals | liquid crystals
Thermotropic liquid crystals

Temperature

• 3-D lattice
• orientation
• solid

• 1- (2-)D lattice
• orientation
• fluid

• no lattice
• orientation
• fluid

• no lattice
• no orientation
• fluid

• no lattice
• no orientation
• isotropic

Liquid crystalline mesophases
between the solid and isotropic liquid phase

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NEMATIC

Photo courtesy:
Dr. Mary Neubert
LCI-KSU
Phase transitions in thermotropics. Temperature wedge

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Photo courtesy: Dr. Arif Nesrullaev, Mugla University, TR

Unique properties

orientational order + fluidity

“soft materials”

anisotropic fluids

e.g. birefringent

easily manipulated by external fields

strong: magneto-optical
electro-optical
opto-optical
effects

displays

nonlinear optics

Physical properties of thermotropic liquid crystals
Thermotropic and lyotropic mesogens

Liquid Crystal World: H. Ringsdorf
LEGOs of Liquid Crystals

**Small organic molecules**

4,4’-dimethoxyazoxybenzene (p-azoxyanisole)

- Anisotropy
- Stiff backbone and flexible tails
- Typically thermotropic

P-azoxyanisole (PAA)

Cholesteryl ester

2-(4-n-pentylphenyl)-5-(4-n-pentyloxyphenyl)-pyrimidine

Phospholipid molecules

Specific Group
Myoglobin

Deoxyribonucleic acid - DNA

Van der Waals diagrams of Z-DNA (left) and B-DNA (right). The solid black line goes from phosphate group to phosphate group along the chain. The zig-zag form of the Z-DNA form is evident. Z-DNA has a slightly smaller diameter than B-DNA and it no longer has the wide major groove that is seen in B-DNA. Phosphorus is yellow; oxygen, red; nitrogen, blue; hydrogen, white; and carbon is shown by concentric circles.
The Hydrophobic Effect
Charles Tanford (1973)

Configurations of liquid water molecules near hydrophobic cavities in molecular dynamics simulations. The blue and white particles represent the oxygen (O) and hydrogen (H) atoms, respectively, of the water molecules. The dashed lines indicate hydrogen bonds (that is, O-H•••O within 35° of being linear and O-to-O bonds of no more than 0.35 nm in length). The space-filling size of the hydrophobic (red) particle in a is similar to that of a methane molecule. The hydrophobic cluster in b contains 135 methane-like particles that are hexagonally close-packed to form a roughly spherical unit of radius larger than 1 nm.
Length scales of amphiphiles in dynamic equilibrium with micelles. The blue and red spheres depict the hydrophilic heads and the hydrophobic tails, respectively, of the amphiphiles. The typical length over which hydrophobic and hydrophilic components are separated within a single molecule is given by $\delta$.

Assuming a roughly spherical structure and tightly packed oily components in the centre, the micelle radius is $L \approx (\alpha^2 \delta)^{3/4}n^{1/4}$, where $n$ is the number of surfactants in the micelle.

**Lyotropic LC phases**

K-stearate  $\text{H}_2\text{O}$
Cubic lyotropic phases

BICONTINUAL CUBIC

MICELLAR CUBIC

Cubic phases with various nanoscale structures

Pn 3m (Q^{24})

Im3m (Q^{24})

Ia 3d (Q^{24})
Soft living matter

Singer and Nicolson (1972): Fluid Lipid Globular Protein Mosaic Model of Membranes

Soft membrane structures in a living cell

Membrane and cytoskeleton
Rat cerebellum

Alamethicin ion channel in a lipid bilayer membrane

Computer simulation
Theoretical description of soft matter

Integrating out of external degrees of freedom
Coarse-graining

Generalized molecular asymmetry model
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Generalized fields

Because it is made of large molecules (aggregates) whose strong atom-atom interactions (charges, valent bonds) are saturated within a molecule.

Intermolecular interactions are thus weaker and non-specific (dipole-dipole, dipole-induced dipole, double layer forces, dispersion forces, entropic forces, hydrophobic interactions, fluctuation forces, etc.)

Consequently, molecules are farther apart and only partially ordered. Theoretical description by point generalized dipoles is thus rendered possible.

Basic question of SM physics

Why is living matter soft?

Lesson from LC physics

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