Collective Molecular Dynamics in Proteins and Membranes

Maikel C. Rheinstädter
Laboratory for Membrane and Protein Dynamics
McMaster University, Hamilton ON
and
Canadian Neutron Beam Centre, Chalk River ON

Pontificia Universidad Catolica de Chile
Facultad de Fisica
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Mini Curso II/III,
Red Nacional de Postgrado en Ciencias Físicas:
“Dynamics in Soft-Matter and Biology Studied by Coherent Scattering Probes”
Biological Physics and Techniques

Hierarchy of biological systems:
- Atom
- Molecule
- Biological Macromolecule
- Functional Module
- Organelle
- Cytoskeleton
- Cell
- Organ
- Organism

Optical Techniques:
- Electron Microscope
- Atomic Force Microscope

Neutron, X-ray Scattering

Maikel Rheinstädter, Mini Curso Red Nacional de Postgrado en Ciencias Físicas, October 2009
Membrane Dynamics

‘multi-scale’: relevant dynamics in a large range of length and time scales

missing or not well developed periodic structure (BZ concept)

high ‘intrinsic’ background

• different molecular components
• single and collective molecular motions

Membrane is the primary site of (inter)action

Bert L. de Groot, Rainer A. Böckmann, and Helmut Gruber
Membrane Dynamics

**Local modes in bilayers**

- Vertical vibrations
- Lateral diffusion
- Rotational diffusion

**Collective excitations**

- Incoherent, single molecule
- Coherent, interactions

**Correlated molecular motions drive “functionalities” of membranes and proteins and structural changes**
Inelastic Scattering Experiments

Membrane Properties
- Elasticity
- Permeability

Inter and Intra Protein Dynamics

Solvent interaction

How does membrane composition and properties determine protein dynamics and function of proteins at work
Scientific Impact
Part III and IV

- Production of Neutrons and X-rays
- Properties of Neutrons and X-rays
  - Elastic and Inelastic Scattering
  - Coherent and Incoherent Scattering
- Local and Collective Molecular Motions
- Selective Deuteration
Production of X-rays

X-ray tube

Synchrotron Sources
X-ray Tube
Synchrotron Source
Production of Neutrons

**Reactor Sources**

The Institut Laue-Langevin (ILL) in Grenoble, France, operates the world’s most powerful neutron reactor. Thermal power 58MW, peak core flux >10^12 neutrons cm^-2 s^-1.

- **Beam tubes**
- **DO moderator tank (300K)**
- **U enriched fuel elements**
- **Cold moderator (liquid H)**
- **Neutron guides (total reflection by Ni coating)**

**Spallation Sources**

The Spallation Neutron Source (SNS) in Oakridge, USA, is the world’s most powerful neutron spallation source.

- **Linear accelerator (1GeV)**
- **Proton stripper**
- **Accumulator ring**
- **Production of H ions (2.5MeV)**
- **Liquid mercury target**
- **Neutron instruments**

2 MW spallation neutron source.
Production of Neutrons - Fission
Production of Neutrons - Spallation

Very energetic proton

Pb
Nuclear Reactors

Nuclear Power Plant

Neutron Reactor
## Properties of Neutrons and X-rays

<table>
<thead>
<tr>
<th></th>
<th>Neutron</th>
<th>Mass</th>
<th>$1.675 \times 10^{-27}$ kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>Velocity</td>
<td>$500 \text{ m/s} \text{ - } 2200 \text{ m/s}$</td>
<td></td>
</tr>
<tr>
<td>$p = \hbar q = \frac{h}{2\pi}$</td>
<td>Momentum</td>
<td>$p = m_n \cdot v$</td>
<td></td>
</tr>
<tr>
<td>$E = \hbar \omega = c \cdot p = c \cdot t \cdot q$</td>
<td>Energy</td>
<td>$E = \frac{1}{2} m v^2 = \frac{h^2}{2m} \cdot q^2$</td>
<td></td>
</tr>
<tr>
<td>$\phi$</td>
<td>Charge</td>
<td>$\phi$</td>
<td></td>
</tr>
<tr>
<td>$\phi$</td>
<td>Magnetic moment</td>
<td>Spin $\frac{1}{2}$</td>
<td></td>
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</tbody>
</table>
Why Neutrons?

Neutrons and Biology

• Neutrons are (coherently) scattered equally well by light and heavy atoms

• Neutrons penetrate deeply into matter (little absorption by sample and substrate)

• H and D scatter very differently (selective deuteration)

• Neutrons are gentle, causing little or no damage to delicate systems

• Incident energy of the neutrons in the range of the excitations -> good energy resolution
Elastic and Inelastic Neutron Scattering

**Elastic Scattering**

- $v_i$ (incident neutrons)
- $v_f$ (final neutrons)
- $S(q)$

**Inelastic Scattering**

- $v_i$ (incident neutrons)
- $v_f$ (final neutrons)
- $v_i \leftrightarrow v_f$
- $S(q, \omega)$
Scattering Laws

**Scattering laws**

- **momentum**: \[ \vec{q} = \frac{m}{\hbar} (\vec{v}_1 - \vec{v}_2) \]
- **energy**: \[ \hbar \omega = \frac{1}{2} m (v_2^2 - v_1^2) \]

**Limits of inelastic x-ray and neutron scattering?**
Neutron and X-ray Spectroscopy
Interaction with Matter

- **x-ray**
- **neutron**
- **electron shell**
- **nucleus spin**
- **nucleus**
  - $I = \frac{1}{2}$
  - $I = -\frac{1}{2}$
Scattering Cross Sections

Scattering Cross Section:
Probability that a neutron will interact with a nucleus

\[ \frac{b}{\lambda} e^{ikr} \]

b: scattering length

Spherical wave

X-ray cross section

Neutron cross section

H  D  C  O  Al  Si  Fe
Coherent and Incoherent Scattering

Interactions between molecules

Coherent scattering

x-rays, neutrons?

Incoherent scattering

Individual molecule
Coherent and Incoherent Scattering

**X-rays**
- all atoms are the same
- $\Rightarrow$ only coherent scattering
- $\Rightarrow$ interactions, collective dynamics

**Neutrons**
- different isotopes, different orientations of nuclear spin
- $\Rightarrow$ coherent and incoherent scattering
- $\Rightarrow$ interactions and local dynamics
Scattering Function

self intermediate scattering function

\[ I_{self}^n(q, t) = \frac{1}{N_n} \left\langle \sum_{j=1}^{N_n} e^{i\vec{q} \cdot [\vec{r}_{j}^n(0) - \vec{r}_{j}^n(t)]} \right\rangle \]

incoherent

intermediate scattering function

\[ I^{n,m}(q, t) = \frac{1}{N_n N_m} \left\langle \sum_{j,j'=1}^{N_n N_m} e^{i\vec{q} \cdot [\vec{r}_{j}^n(0) - \vec{r}_{j'}^m(t)]} \right\rangle \]

coherent
Membrane Dynamics

Local modes in bilayers

Incoherent, single molecule

Correlated molecular motions drive “functionalities” of membranes and proteins and structural changes

Collective excitations

Coherent, interactions
Selective Deuteration

Coherent and Incoherent Scattering Cross Sections

<table>
<thead>
<tr>
<th>Nuclide</th>
<th>$\sigma_{coh}$ (b)</th>
<th>$\sigma_{inc}$ (b)</th>
<th>Nuclide</th>
<th>$\sigma_{coh}$ (b)</th>
<th>$\sigma_{inc}$ (b)</th>
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<tbody>
<tr>
<td>$^1$H</td>
<td>1.7583</td>
<td>80.27</td>
<td>$^{12}$C</td>
<td>5.559</td>
<td>0</td>
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<tr>
<td>$^2$H</td>
<td>5.592</td>
<td>2.05</td>
<td>$^{13}$C</td>
<td>4.81</td>
<td>0.034</td>
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<tr>
<td>$^3$H</td>
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<td>0.14</td>
<td>$^{16}$O</td>
<td>4.232</td>
<td>0</td>
</tr>
<tr>
<td>$^{14}$N</td>
<td>11.03</td>
<td>0.5</td>
<td>$^{17}$O</td>
<td>4.2</td>
<td>0.004</td>
</tr>
<tr>
<td>$^{15}$N</td>
<td>5.21</td>
<td>0.00005</td>
<td>$^{18}$O</td>
<td>4.29</td>
<td>0</td>
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Protonated $\leftrightarrow$ Incoherent

Deuterated $\leftrightarrow$ Coherent

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