PART 3
From simple molecules to complex materials
PREMISE: Artificial and Biomolecular Machines are Densely Packed Multicomponent Assemblies (1D, 2D and 3D Crystals)

Types of Motion (Periodic)
  — Rotary
  — Oscillatory

Functional Design
  — Free Volume
  — Volume Conserving Motions
  — Correlated Motions


What Do We Know About Dynamics and Order in Dense Media?
Condensed Phase Matter and Molecular Dynamics
(Crystals of molecules with arbitrary shapes)

Diffusion:
\[ D = 7 \times 10^{-16} \text{ m}^2 \text{ s}^{-1} \]
\[ D = 7 \times 10^{-7} \text{ nm}^2 \text{ ns}^{-1} \]

Conformational Motions
Very fast >10^9 s^{-2}

Phonons:
\[ \lambda \sim 0.01 \text{ cm} \]
\[ v \sim 100 \text{ cm}^{-1} \]
\[ (\sim 10^{12} \text{ s}^{-1}) \]

Statistical theories of crystal packing
Condensed Phase Matter and Molecular Dynamics

- **Crystals**
  - Rigidity
  - Homogeneity
  - Periodicity

- **Plastic Crystals**
  - Reorientational motion
  - Homogeneity
  - Periodicity

- **Liquid Crystals**
  - Reorientation and translational motion
  - Preferred molecular orientation
  - Average molecular periodicity

- **Glasses**
  - Rigidity
  - Inhomogeneity

- **Liquids**
  - Molecular freedom
  - Average homogeneity
Condensed Phase Matter and Molecular Dynamics

- **Crystals**: Rigidity, Homogeneity, Periodicity
- **Plastic Crystals**: Reorientational motion, Homogeneity, Periodicity
- **Liquid Crystals**: Reorientation and translational motion, Preferred molecular orientation, Average molecular periodicity
- **Glasses**: Rigidity, Inhomogeneity
- **Liquids**: Molecular freedom, Average homogeneity
Challenge: Artificial Molecular Machines

I: Emulate structural attributes of macroscopic and biomolecular machines

Motions in dense media demand:
- Free Volume
- Volume-Conserving motions
- Correlated Motions
- Periodic, Rotary, or Oscillatory
I: Emulate structural attributes of macroscopic and biomolecular machines

Motions in dense media demand:
- Free Volume
- Volume-Conserving motions
- Correlated Motions
- Periodic, Rotary, or Oscillatory

II: Characterize their equilibrium dynamics

- Solid State NMR
- Dielectric spectroscopy
- Electronic, vibrational and microwave spectroscopies
- X-Ray diffraction, Neutron Scattering, computational chemistry, etc.

III: Characterize their dynamics upon external excitation to design input-output processes
Where to Start?

Molecular Rotors!
Compasses and Gyroscopes
(navigational instruments or "machines")

1850’s: Named by Focault
1907: Navigational Machine by H. Anschütz-Kaempfe
1909-1916: Automatic Pilot for ships
... INS in aircraft, missiles, satellites

500 BC: First used in China (floating)
700 AC: Needle compass developed
XII AC: First used in Europe
XVII AC: Permanently magnetized steel needles introduced

—Moment of mass and rotary motion
—Angular Momentum

—Magnetic dipole and rotary motion
—Magnetic Moment
—Energy is Orientation Dependent
A Promising Model: Gyroscopes and Compasses

Dynamic Attributes: Free Volume, Volume Conserving, Correlated Processes

Design Elements (and color code):

—ROTATOR (reorienting dipole)

—AXLE (alkyne linkages)

—STATOR (shielding groups)

Molecular Compasses and Gyroscopes: STATOR Structures and Topologies

Closed (triply bridged)

Open (sterically shielded)
Synthesis of Triptycyl Stators


Triarylmethyl Stators

Synthesis:
Dominguez et al. *JACS*, 2002, 124, 2398

—For analogous structures with Ph₃B- stators:
Gardinier et al., *JACS*, 2005, 127, 12448
Packing Rigid Rods with a Six-Fold Phenyl Embrace

Complementary edge-face interactions
Conformational Diversity and Crystal Forms

Crystallization from solvents at 298 K
Yields different polymorphs

From C₆H₆

From CH₂Cl₂
DSC, TGA, Thermal microscopy

Closed Topologies ...

1) BrC6H4Br, Pd(0)
2) BBr3
3) NaH, Br(CH2)10Br

1) TBDMSCl
2) BBr3

KH, DMSO

Br(CH2)10O
Br(CH2)10O
Br(CH2)10O
Br(CH2)10O

Bu4NF

Pd(0)
NEED “THICKER” BRIDGES
One-Step Synthesis of Triply-Bridged Gyroscopes

Pat Commins
**Stator Effects by SSNMR (ca. 0-10^{10} s^{-1})**

<table>
<thead>
<tr>
<th>Compound</th>
<th>k (298)</th>
<th>( E_a ) (kcal/mol)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>800 s(^{-1})</td>
<td>&gt;&gt; 20</td>
</tr>
<tr>
<td>2</td>
<td>6000 s(^{-1})</td>
<td>11.3</td>
</tr>
<tr>
<td>3</td>
<td>&gt; 100x10^6 s(^{-1})</td>
<td>10.5</td>
</tr>
<tr>
<td>4</td>
<td>&lt; 5</td>
<td>4.3</td>
</tr>
<tr>
<td>5</td>
<td>1.11x10^9 s(^{-1})</td>
<td></td>
</tr>
</tbody>
</table>

This Mac has a 2 GHz processor


“Rotation” in the Solid State

**Solid State NMR** √
- VT $^{13}$C CPMAS NMR (~100-1000 Hz)
- VT Quadrupolar Echo $^2$H NMR (10$^4$-10$^8$ Hz)
- VT Spin-Lattice Relaxation

**VT X-Ray Diffraction (ADP)** √
(≤ 20 kcal/mol)

**VT Dielectric Spectroscopy** √
(10 Hz - 10$^{12}$ Hz)

**Computer Modeling** √

**Fluorescence Anisotropy Decay**
(10$^8$-10$^{11}$ Hz)

**Inelastic Neutron Scattering**
(10$^{10}$-10$^{12}$ Hz)
VT 13C CPMAS NMR: Rotation in the Hz-kHz Regimes

(if signals not resolved... use isotopic labeling!

\[
\begin{align*}
&\text{d}_{30}-\text{Trityl-}h_4\text{-phenylene} \\
&k_{280} = 611.6 \text{ Hz} \\
&E_a = 12.8 \text{kcal/mol}
\end{align*}
\]

Steve Karlen
Stator Effects on Phenylene Rotation
MHz Regime by $^2$H NMR

$k_{rot} \approx 0.1 \text{ THz} @ 400 \text{ K}$

$A = 1.45 \times 10^{12}; \quad E_a = 4.3 \text{ kcal/mol}$

Carlos Godínez
Molecular Compasses and Gyroscopes: Internal Rotation

Conformational energy

\[ E(\Theta) \approx S(\Theta) \]
Low barrier (\(E_a < kT\)): Gyroscopic (inertial) motion

Two degenerate states, \(j = \pm n, n \neq 0\)

\[kT \text{ at } 300 \text{ K}\]

\[\begin{align*}
\text{AM1 Method} \\
\text{Energy (kcal/mol)} \\
\text{Phenylene Rotation (degrees)} \\
\end{align*}\]

\[\begin{array}{c}
305.600 \\
305.700 \\
305.800 \\
305.900 \\
306.000 \\
306.100 \\
\end{array}\]

\[\begin{array}{c}
50 \\
100 \\
150 \\
\end{array}\]

6-minima

\[\text{C}_2 + \text{S}_6 = \] \[\text{Inertial Rotation} : \]

\[\tau_{FR}^{-1} = 2.4 \times 10^{12} \text{ sec}^{-1} \text{ at } 298 \text{ K}\]

\[\left[ \tau_{FR} = \frac{2\pi}{9} \left( \frac{I}{kT} \right)^{1/2} \right] \]

I= moment of inertia of the 1,4-phenylene with respect to the 1,4-axis

“Free Rotation” about sp-sp\(^a\) single bonds:
(b) Sipachev et al. J. Mol. Struct. 2000, 523, 1
Hindered Rotation ($E_a \gg kT$): Brownian Rotor

Oscillation, jumps, random direction

Exchange (NMR)

Diffuse $e^-$ density (X-Ray)

Correlated motions (modeling)

$\text{Correlated motions (modeling)}$

Exchange (NMR)

Diffuse $e^-$ density (X-Ray)

$\text{Correlated motions (modeling)}$

Rotation in the Excited State

Ultrafast (THz) Electrochromics

Rotation and Planarization effects on arylene ethynylenes:


Measurements in solution (black) and in stretched polyethylene (red at 300 K and blue at 77K)
**Internal Rotation of Polar Groups**

Inertial Rotation: \( \tau_{FR}^{-1} = 2.4 \times 10^{12} \text{ sec}^{-1} \) at 298 K

\[ \tau_{FR} = \frac{2 \pi}{9} \left( \frac{I}{kT} \right)^{1/2} \]

\( I \) = moment of inertia with respect to the 1,4-axis
Stator Effects by SSNMR (ca. $0-10^{10}$ s$^{-1}$)

<table>
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<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>H</td>
<td>H</td>
<td>OMe</td>
<td>OMe</td>
<td>Me</td>
</tr>
<tr>
<td>C</td>
<td>C</td>
<td>MeO</td>
<td>tBu</td>
<td>Me</td>
</tr>
<tr>
<td>H</td>
<td>H</td>
<td>H</td>
<td>H</td>
<td>H</td>
</tr>
</tbody>
</table>

$k$ (298) Static
$E_a$ (kcal/mol) $>> 20$
$800$ s$^{-1}$
$6000$ s$^{-1}$
$> 100 \times 10^6$ s$^{-1}$
$1.11 \times 10^9$ s$^{-1}$

$E_a (\text{kcal/mol})$
$11.3$
$10.5$
$< 5$
$4.3$

A benchmark...

and a target:
$E_a << kT$ (0.6 kcal/mol)

3.0 kcal/mol in the gas phase!
Rotator Effects on Rotary Motion?

High Symmetry Order Rotors

— Low rotational barriers
— High radial resolution (polarity)
— Cogitation (gearing)
Rotator Effects on Rotary Motion?
Rotator Effects (keep stator constant)

A Constant Stator: $\text{Ph}_3\text{Si}$-

Phenylene 2-Fold

Bicyclo[2.2.2]octane 3-Fold (6-fold)

$p$-Carborane 5-Fold (10-Fold)

Garcia-Garibay and Karlen, unpublished
**Synthetic Strategy**

1. LAH
2. Swern

\[ \text{Phenylene 2-Fold} \]

\[ \text{Bicyclo[2,2,2]octane 3-Fold (6-fold)} \]

\[ \text{p-Carborane 5-Fold (10-Fold)} \]
Determine rotational correlation times by $^1H\ T_1$ at $\nu_L = 300\ MHz$
Kubo and Tomita relaxation expression:

\[ T_1^{-1} = C \left[ t_c \left( 1 + w^2 t_c^2 \right)^{-1} + 4 t_c \left( 1 + 4 w^2 t_c^2 \right)^{-1} \right] \]

\[ t_c = t_o \exp \left( \frac{E_a}{RT} \right) \]

\[ \tau_c = 300 \text{ MHz} \]

\[ \tau_c = 2.1 \text{ GHz} \]

\[ R = 0.992 \]

\[ E_a = 2.92 \text{ kcal/mol} \]

\[ \tau_o = 2.7 \times 10^{11} \text{ s}^{-1} \]
High Rotational Symmetry Rotators

- **Bicyclo[2,2,2]octane**
  - $E_a = 3.57$ kcal/mol

- **Phenylene**
  - $E_a \approx 8$ kcal/mol

- **p - Carborane**
  - $E_a = 2.92$ kcal/mol
Subtleties about Rotational Potentials

\[7\text{-fold} \times 6\text{ fold} = 42\]
Potential Short Term Applications
Molecular Compasses

1D-Chain

1D-Stack

E_{dd} = \mu_i \mu_j / \epsilon (r_{ij})^3 [\cos \chi - 3 \cos \alpha_1 \cos \alpha_2]

\epsilon = \text{dielectric constant}
\chi = \text{dihedral angle between dipoles}
\alpha_1, \alpha_2 = \text{angle between dipole vector and line}
R_{ij} = \text{distance between dipoles}

Hexagonal Lattice

Square

Hexagonal

3D-Cubic

3D-FCC

High symmetry lattices have an ‘acoustic’ mode with very low frequency at k=0 (Goldstone mode). V. Rozenbaum, et al. Sov. Phys. Usp. 1991, 34, 883.
Molecular Compasses

Photonic Materials

Anisotropic (e.g., Antiferroelectric)

Low T

Anisotropic (Ferroelectric)

Istropic (Paraelectric)

Electric Field

-Dichroism
-Birefringence
-NLO
Polar Rotors

Dipole Moments in Debye (AM1)

Dominguez, Khuong, Dang, Sanrame, Nuñez, Garcia-Garibay, JACS, 2003, 125, 8827.
Isomorphous Crystals
—X-Ray
—DSC
—TGA
—Photophysics
Dielectric Measurements

(Electric Energy is Dissipated when AC Frequency Matches that of the Internal Dipole Dynamics)
(Electric Energy is Dissipated when AC Frequency Matches that of the Internal Dipole Dynamics)
Frequency-Dependent Dielectric

\[
\frac{1}{\tau} = \omega_0 \exp \left( \frac{-E_B}{kT} \right)
\]
\[
\tan(\delta) = \frac{C_R}{C_0} \frac{\omega \tau}{1 + \omega^2 \tau^2}
\]
\[
C_R = \frac{\epsilon_R}{3} + \frac{N_p}{3kT L^2} \cosh^{-2} \left( \frac{S}{2kT} \right)
\]

a) Non-Polar Rotor Gives Baseline
b) Reversible on Heating and cooling cycles
c) Peak Position Depends on AC Freq.
d) Signal Intensity Increases With Temp.
e) Barrier matches that of $^2$H and $^{13}$C NMR and Force Field calculations


**荧光旋转**

ΔE = 12.4 kcal/mol

**横线**

ΔE = 0.8 kcal/mol

**函数图**

Fits with one Debye peak

Ea = 13.7 kcal / mol

ΔE = 1.4 kcal / mol

**温度-频率图**

y-intercept = 34 +/- 1

slope = -6900 +/- 440

**能量-角图**

Ea = 12.8 kcal/mol

ΔE = 2.5 kcal/mol

**分子 mechanics**

Molecular Mechanics Dihedral Drives
Local Model

Ph

Ph

Ph

Ph

Ph

Fits with one Debye peak

Ea = 13.7 kcal / mol

ΔE = 1.4 kcal / mol

**分子力学**

Molecular Mechanics Dihedral Drives
Local Model

ΔE = 15.3 kcal/mol

ΔE = 12.8 kcal/mol

**角-能图**

Ea=12.8 kcal/mol

ΔE= 2.5 kcal/mol
Macroscopic Vs Molecular Machines: Things to Keep in Mind

— Newtonian Mechanics
— Rigid parts
— Arbitrary sizes and shapes
— Joint parts carry no DOF
— Structure’s Tm >> T
— Thermal energy dissipation (vibr) is decoupled from function
— States of absolute rest
— Inertia rules (Large R)
— Need energy for motion and action

— Statistical and Quantum Mechanics
— Non rigid parts
— Limited shapes (structural theories)
— Every part added carries additional DOF’s
— Structure’s Tm ≈ T
— Thermal energy dissipation (vibr, rot, conf, coll.) is part of its function
— Never “rest” (zero point energies)
— Viscous forces rule (small R)
— Need energy to change state of motion for action

The rotary catalytic mechanism of mitochondrial ATP synthase.

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Conclusions: Much Remains to be Done

- **Crystals**
  - Rigidity
  - Homogeneity
  - Periodicity

- **Plastic Crystals**
  - Reorientational motion
  - Homogeneity
  - Periodicity

- **Liquid Crystals**
  - Reorientation and translational motion
  - Preferred molecular orientation
  - Average molecular periodicity

- **Amphidynamic Crystals**

- **Glasses**
  - Rigidity
  - Inhomogeneity

- **Liquids**
  - Molecular freedom
  - Average homogeneity

Control the scale (nano- to macrocrystals), dimensionality (1D, 2D, 3D), and superstructures
Artificial Molecular Machines

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