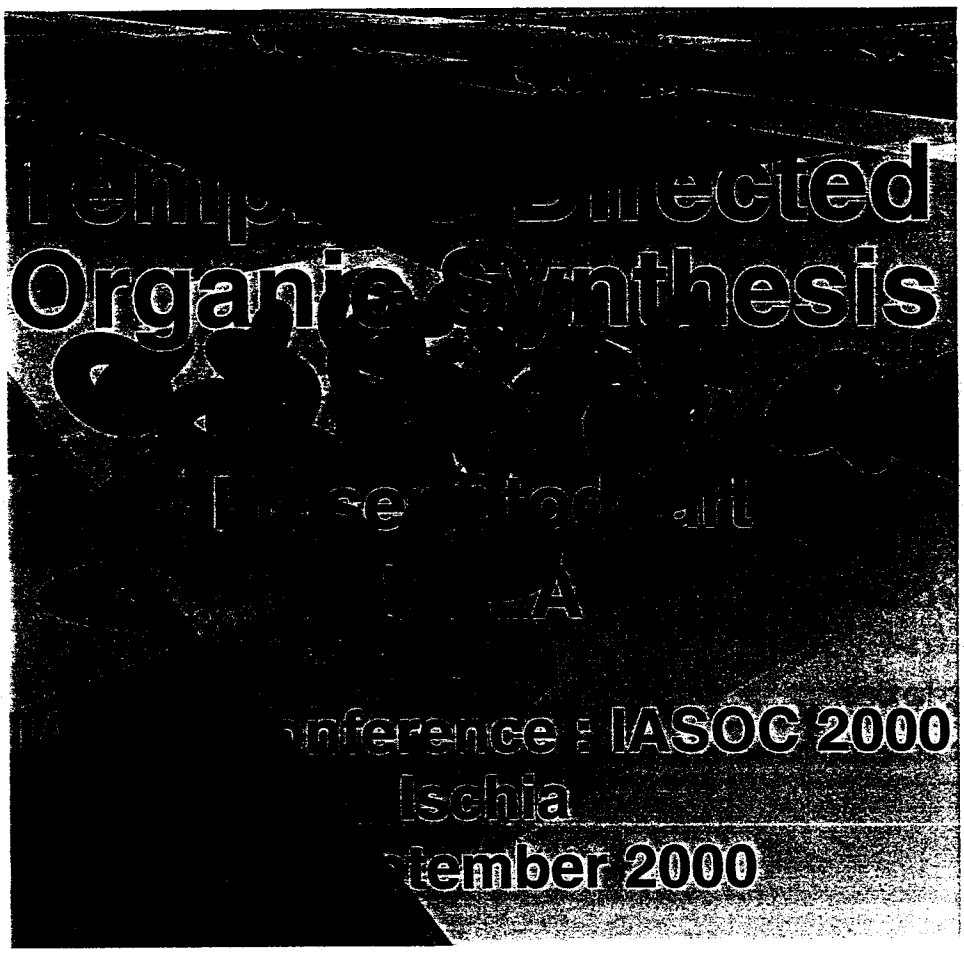


Chemical Synthesis

Supramolecular Chemistry

Supramolecular Synthesis

The creation of multicomponent supramolecular architectures utilizing noncovalent bonding interactions

- Noncovalent Synthesis of Supermolecules
- Noncovalent Synthesis of Supramolecular Arrays

Supramolecular Assistance to Molecular Synthesis

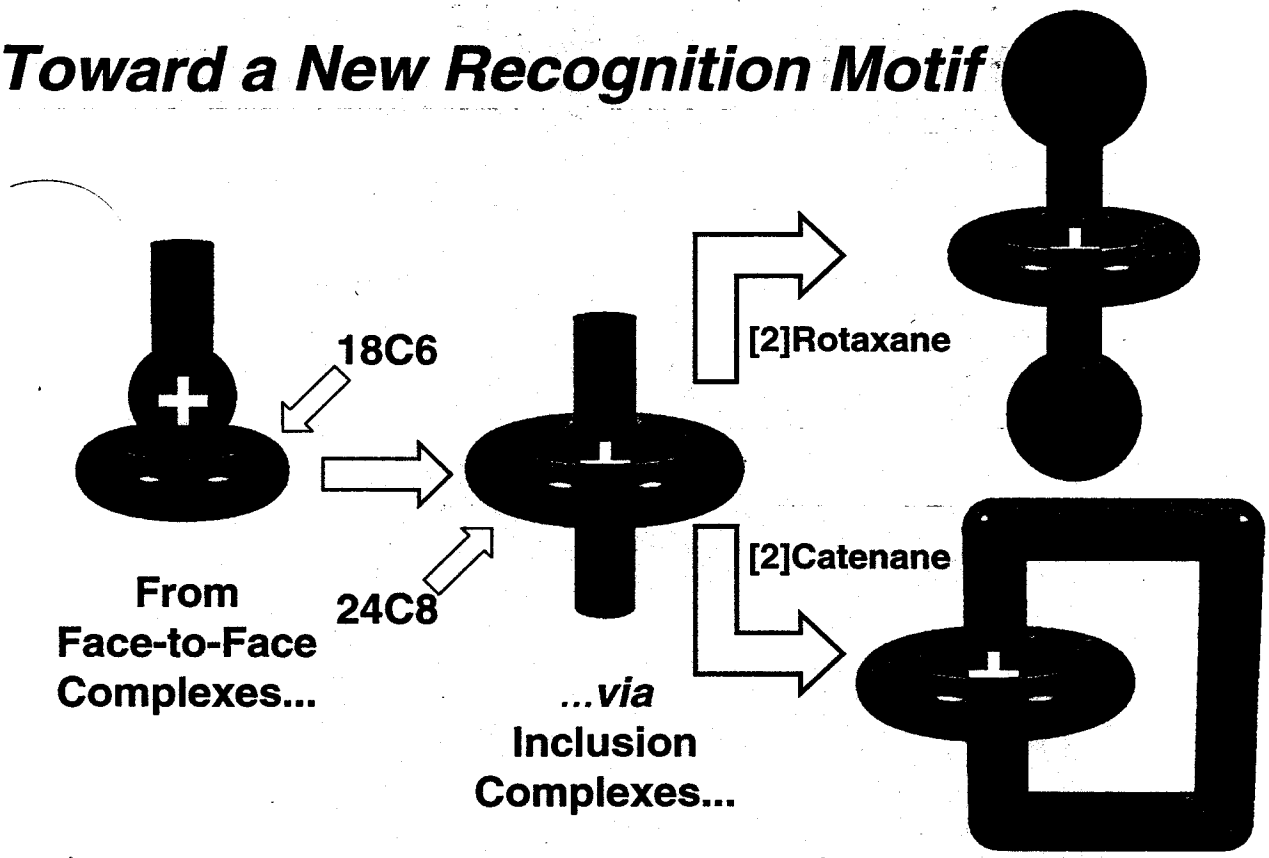
The synthesis of discrete molecular entities — held together using wholly covalent and/or mechanical bonds — aided and abetted by intermolecular noncovalent interactions

- Supramolecular Assistance to Covalent Synthesis
- Supramolecular Assistance to the Synthesis of Interlocked Molecules

Thermodynamic Control ——— **Kinetic Control**

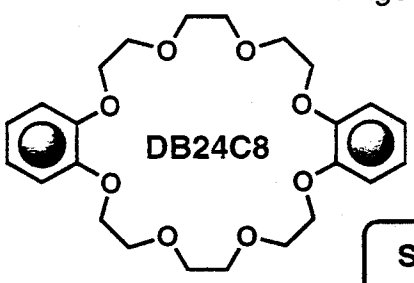
The Impetus for the Development of the Methodologies has been Self-Assembly

Toward a New Recognition Motif

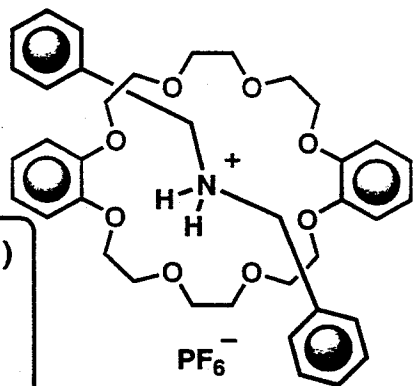


Secondary Dialkylammonium Ion Binding

Angew. Chem. Int. Ed. Engl. **1995**, *34*, 1865-1869



Solution



Solvent	K_a (M^{-1})	$\Delta G°$ (kcal mol^{-1})
CD_3SOCD_3	0	—
CD_3COCD_3	360	–3.5
CD_3CN	420	–3.6
$CDCl_3$	27000	–6.0

Evidence for Complexation

LSI Mass Spectrometry

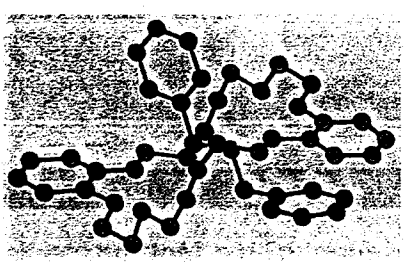
^{1}H NMR - $\Delta\delta$ Values

^{1}H NOE Experiments

X-Ray Crystallography

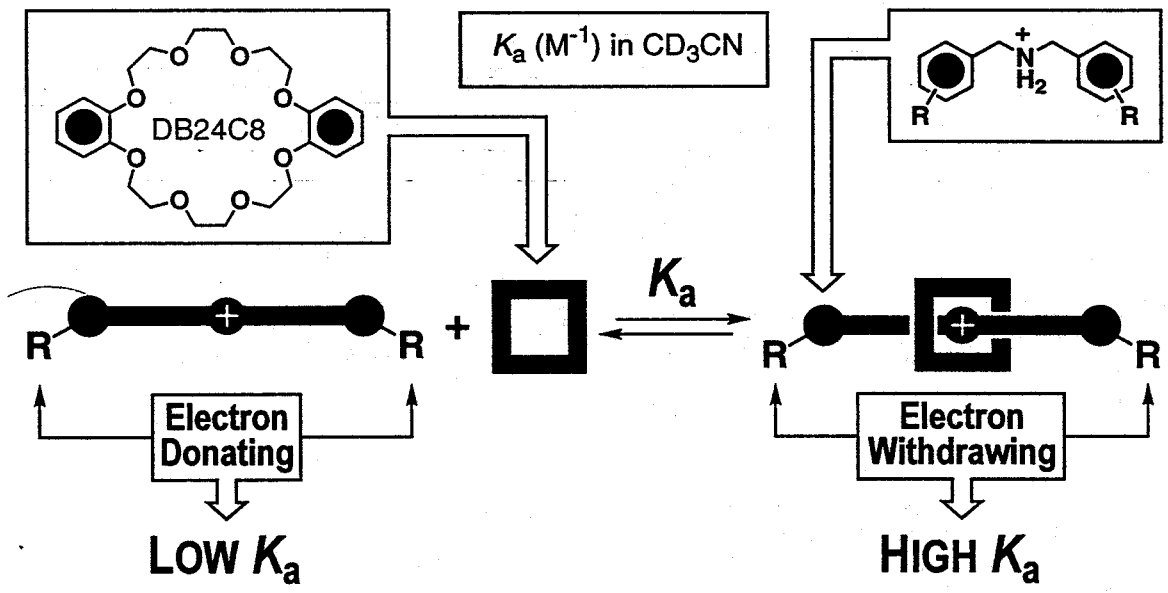
X-Ray Crystal Structure

- [N^+–H···O]
- [C–H···O]
- [π···π]

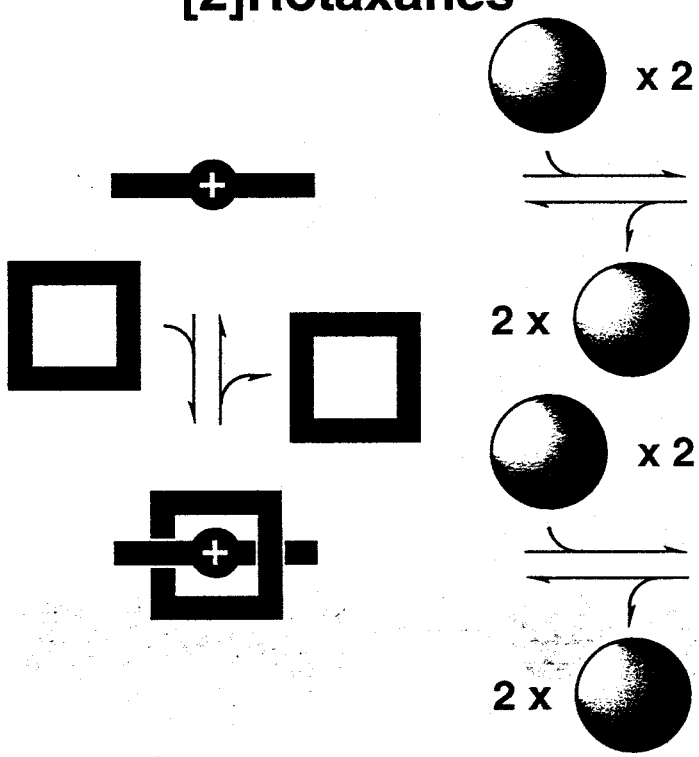


Structure–Activity Relationships and DB24C8–Dibenzylammonium Ion-Based Pseudorotaxanes

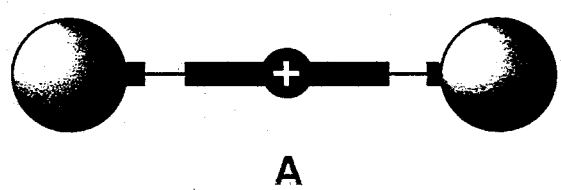
R	*p*-OMe	*p*-Me	*m*-Me	H	*m*-OMe	*p*-Br	*p*-Cl	*p*-CO_2H	*m*-Br	*m*-Cl	*m*-CO_2H	*p*-NO_2	*m*-NO_2	R
K_a	130	170	180	200	280	460	470	510	570	580	660	1300	1350	K_a



Supramolecular Assistance to the Covalent Synthesis of [2]Rotaxanes

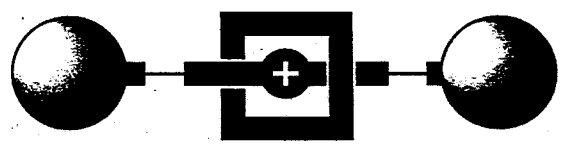


Thermodynamic Control



A

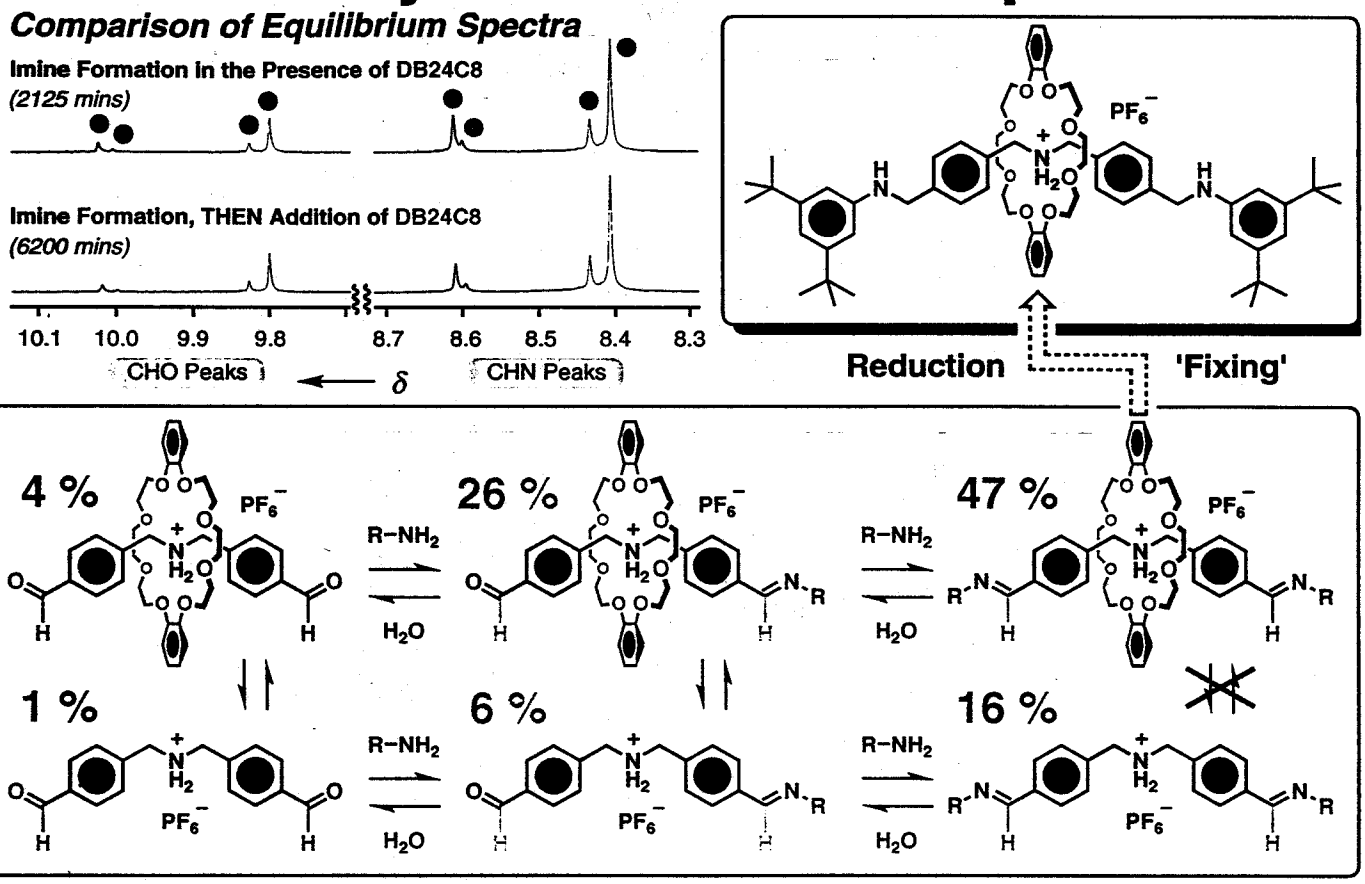
Covalent Modification



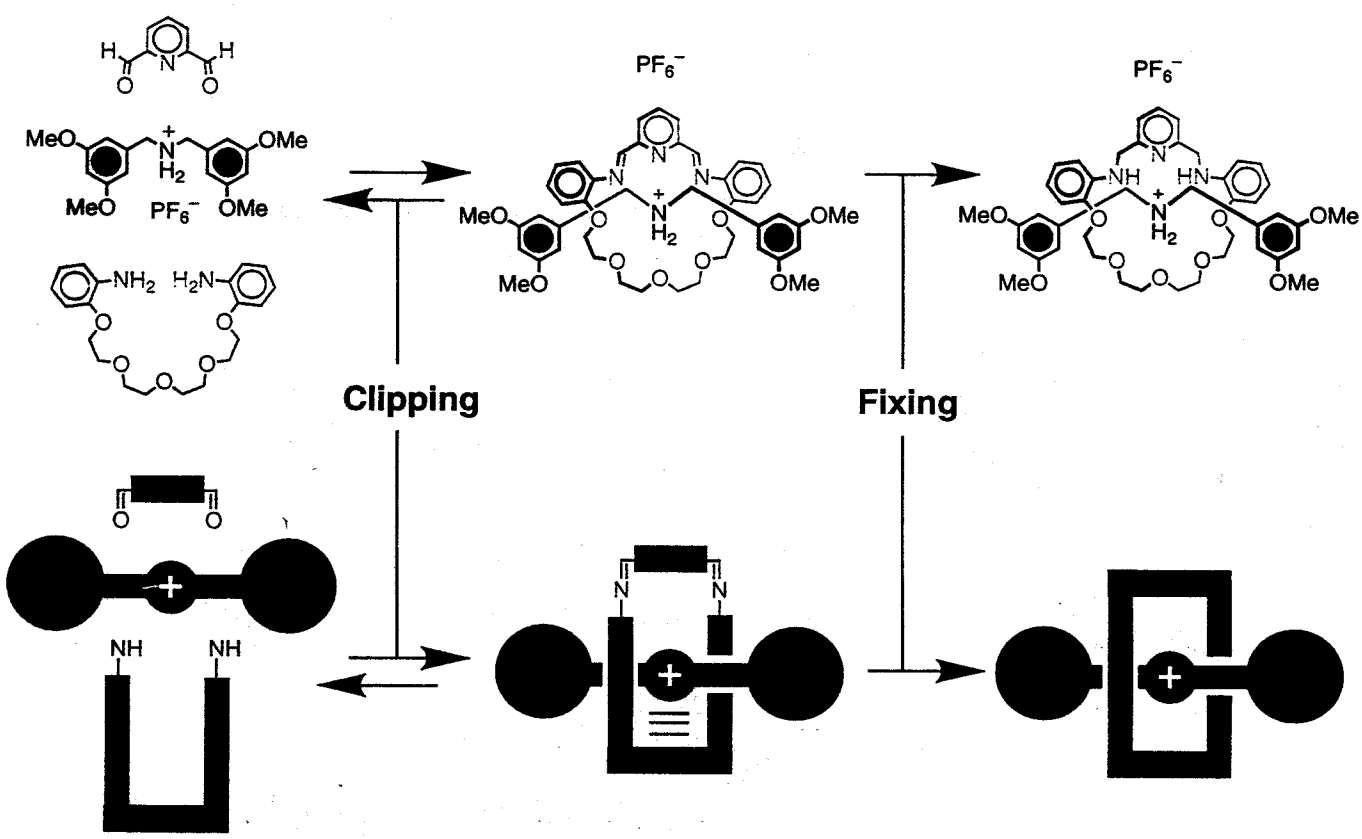
B

- The ratio of A:B is dependent only upon the relative stabilities of A and B.

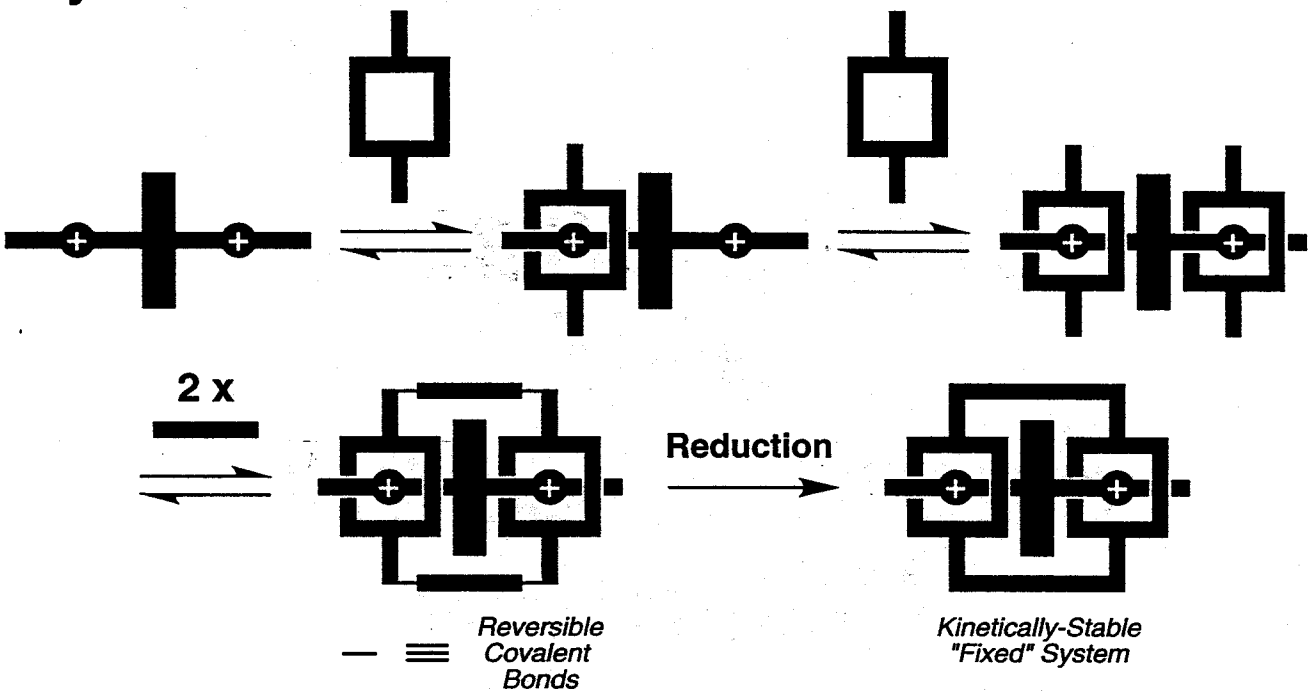
Thermodynamic Control Operates

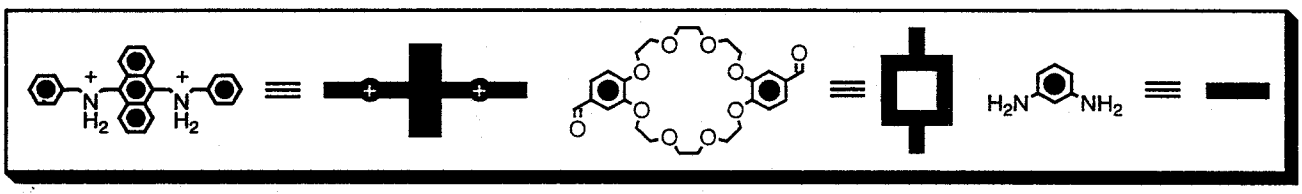


A Clipping Approach to [2]Rotaxanes

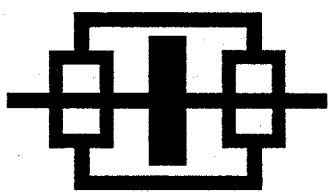


Dynamic Formation of New Interlocked Molecules

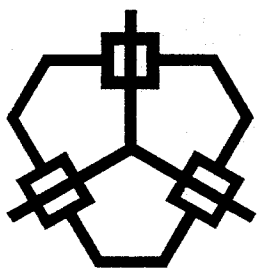




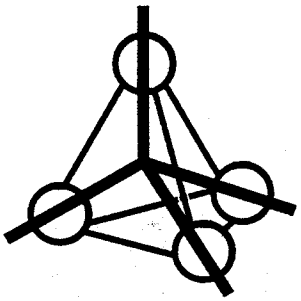
Beyond Catenanes and Rotaxanes...



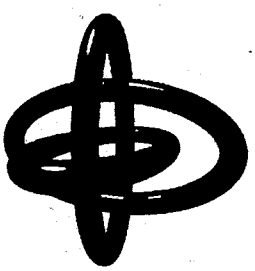
Linear Scaffolds



Trigonal Scaffolds



Tetrahedral Scaffolds



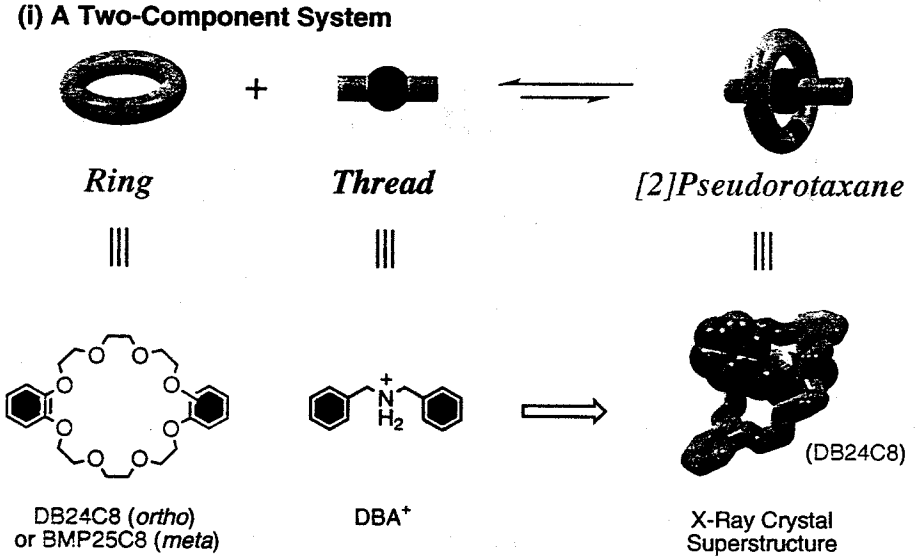
Borromean Rings

...with Thermodynamically-Controlled Covalent Bond Formation

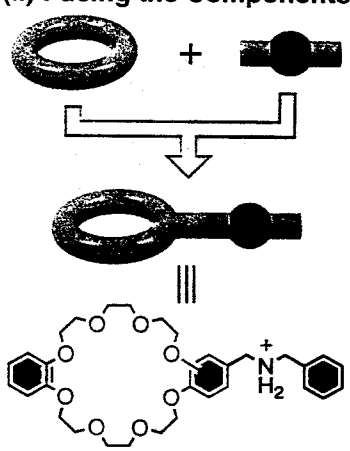
Daisy Chains and Supramolecular Polymers

The Aggregation of Self Complementary Molecules

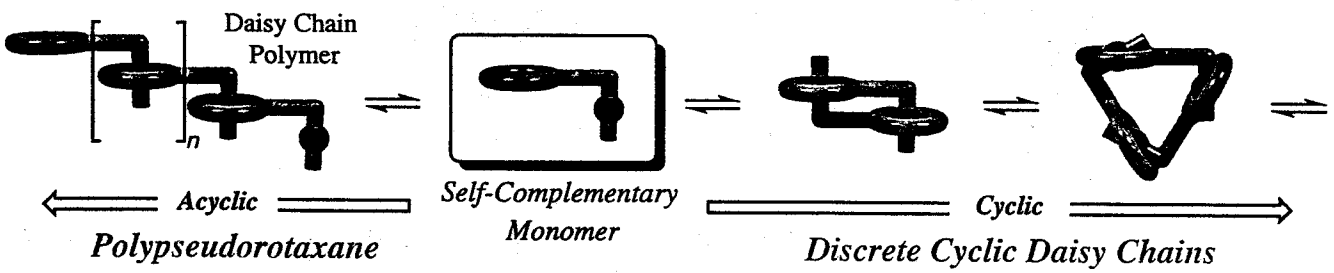
(i) A Two-Component System

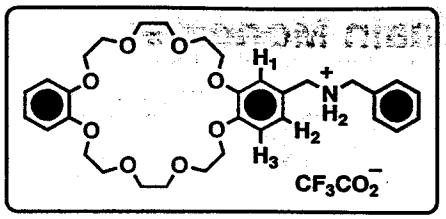


(ii) Fusing the Components

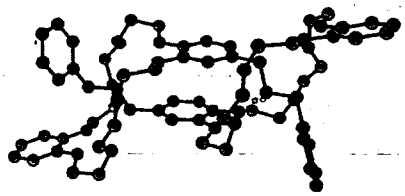


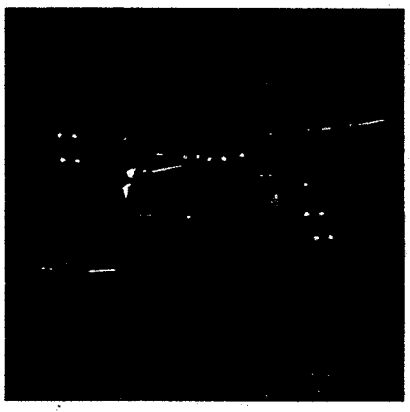
(iii) Possible Aggregation Geometries *(assuming no intramolecular 'self-biting')*



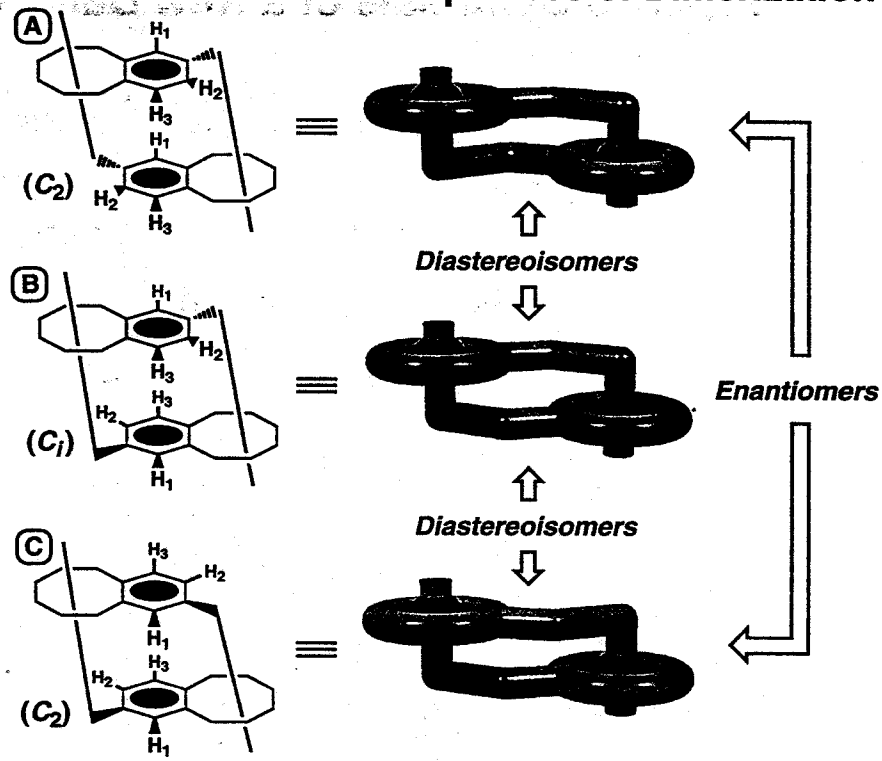


A Solid State Head-to-Tail Dimer



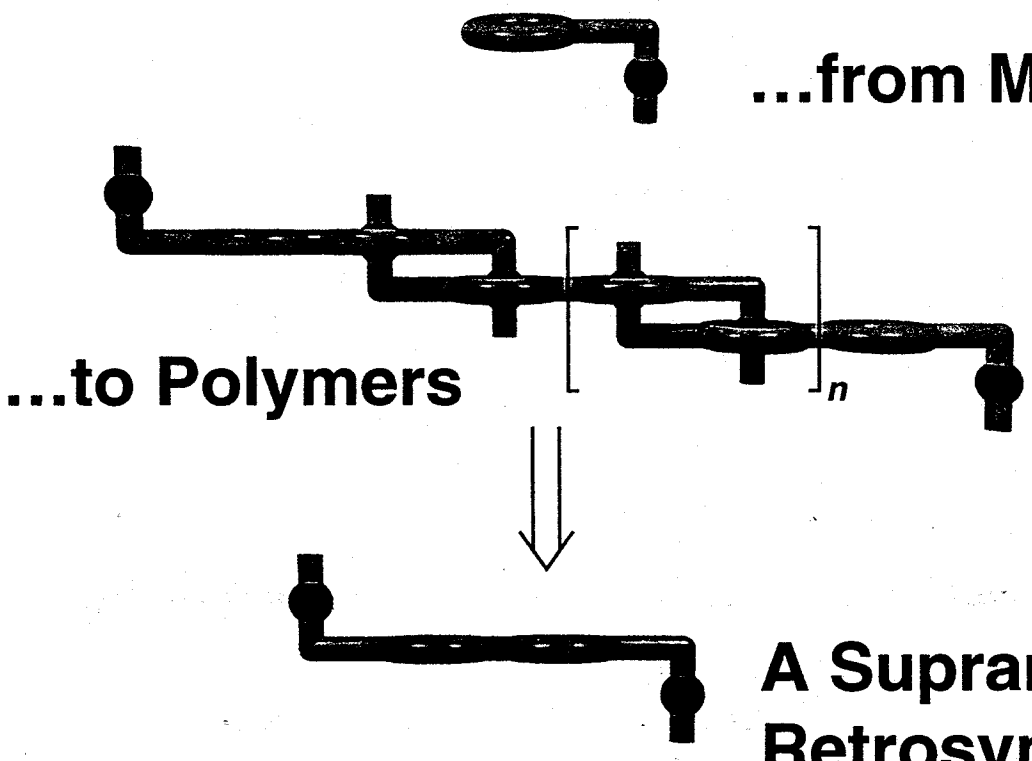


Stereochemical Consequences of Dimerization

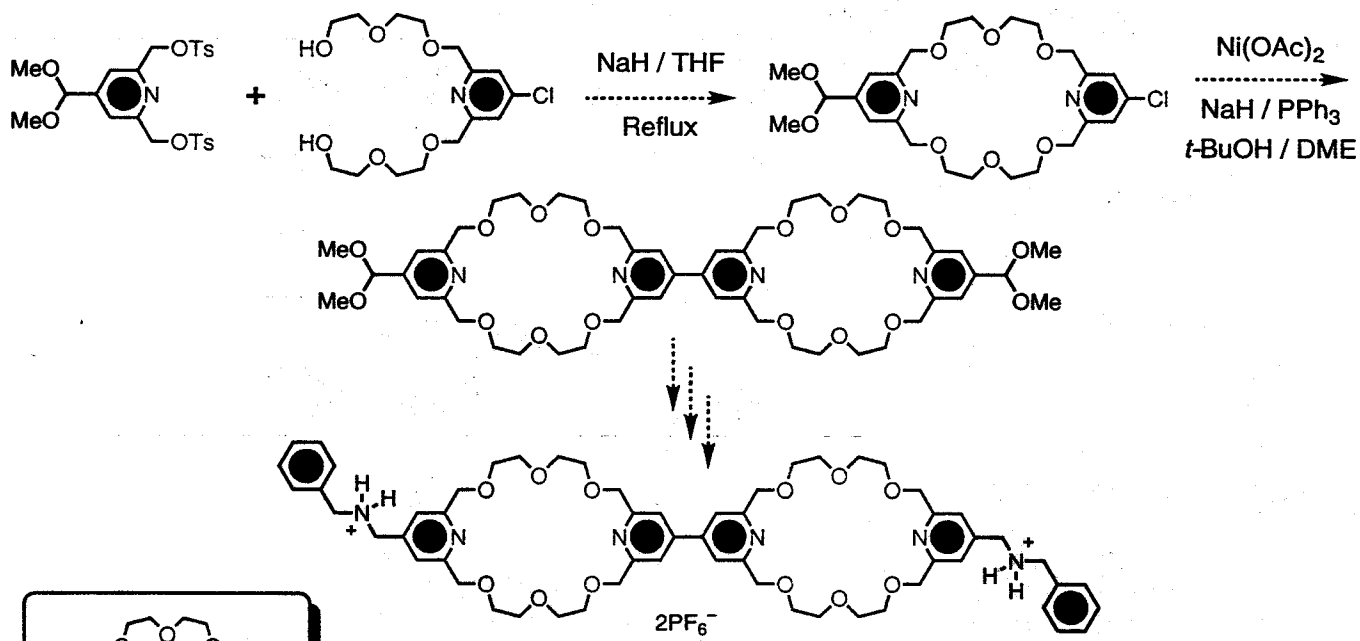


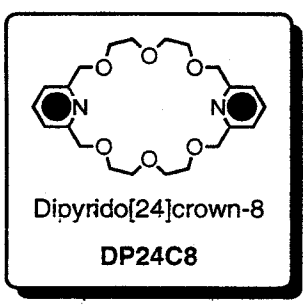
X-Ray crystallographic analysis revealed the crystals to be racemic (*i.e.*, containing equal amounts of **A** and **C**)

A Possible Route...



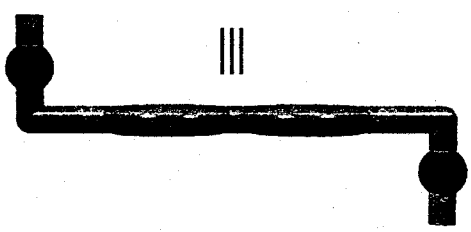
Proposed Synthesis of a New Daisy Chain Monomer





Dipyrido[24]crown-8

DP24C8



No symmetry complications upon formation of dimeric structures

Noncovalent Synthesis of Rotaxane-Like Species

Slippage

Thermodynamic Control

Assembly

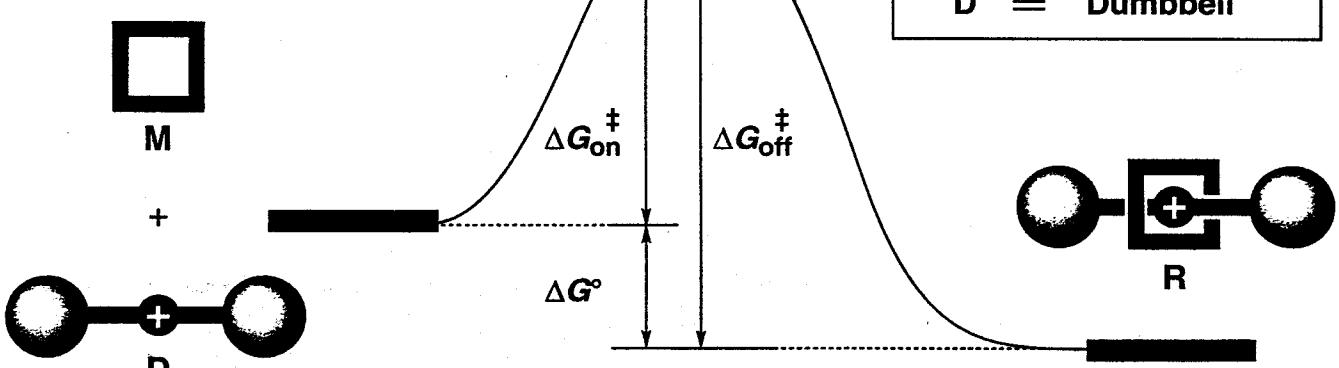
k_{on}

k_{off}

Disassembly

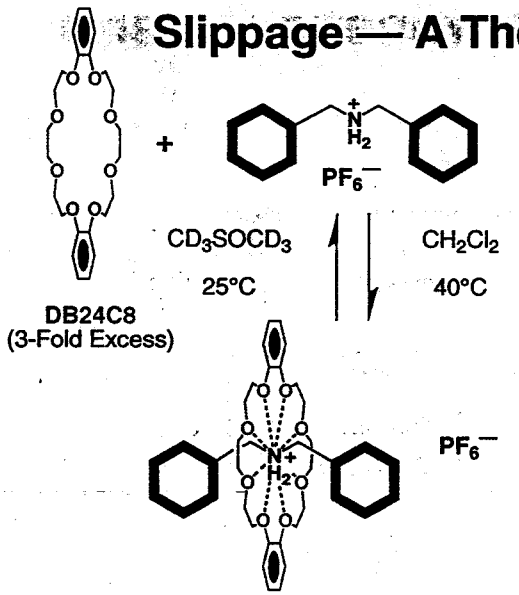
$$K_a = \frac{[R]}{[M][D]} = \frac{k_{on}}{k_{off}}$$

R ≡ Rotaxane
M ≡ Macrocycle
D ≡ Dumbbell



J. Am. Chem. Soc. **1998**, *120*, 2297-2307

Slippage — A Thermodynamically-Controlled Process



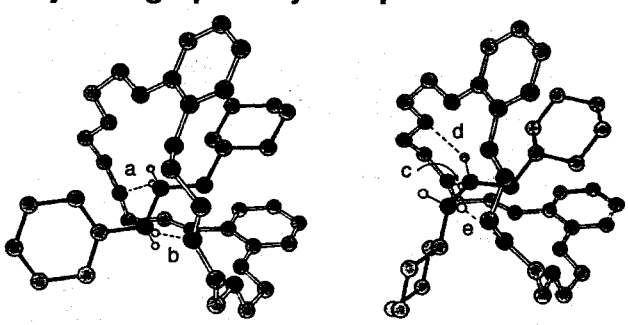
Days	Dumbbell (%)	Rotaxane (%)
0	100.0	0.0
4	63.5	36.5
8	43.5	56.5
12	30.6	69.4
16	18.6	81.4
20	11.0	89.0
24	7.5	92.5
28	4.6	95.4
32	3.3	96.7
36	2.2	97.8

X-Ray Crystal Structure ⇒

[N⁺—H •••• O] a c d
[C—H •••• O] b e

One *c*-C_6H_{11} sandwiched between two catechol rings

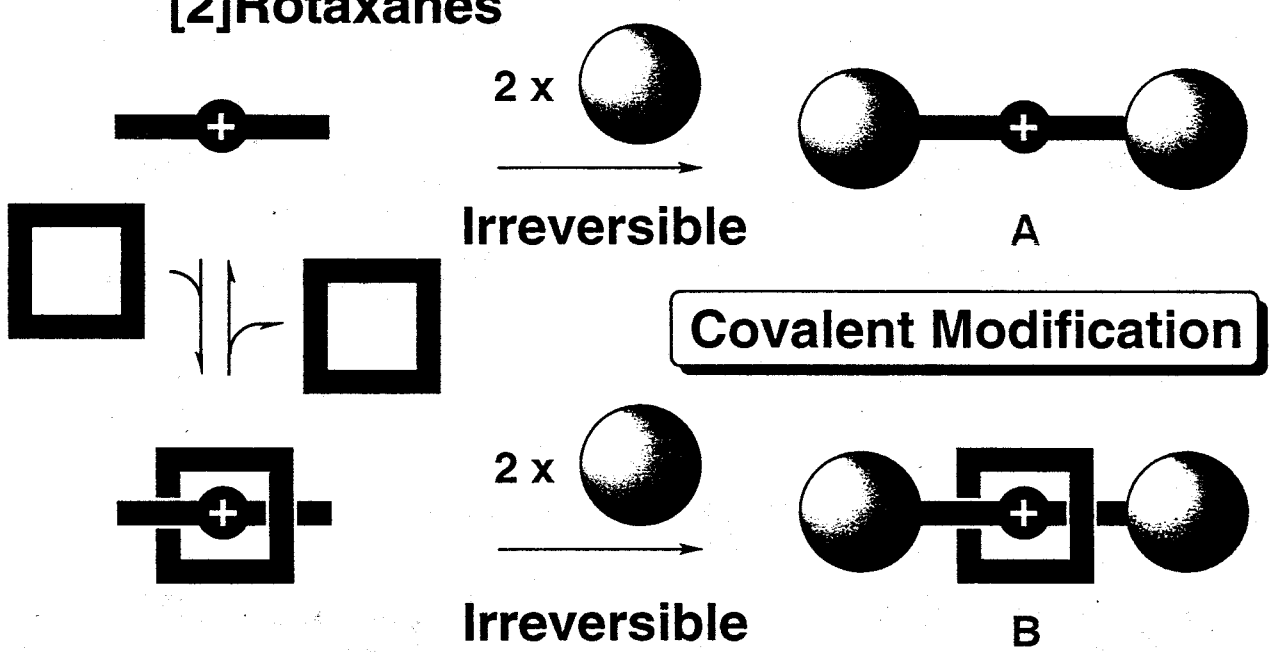
Two Crystallographically-Independent "Molecules"



J. Am. Chem. Soc. **1998**, *120*, 2297-2307

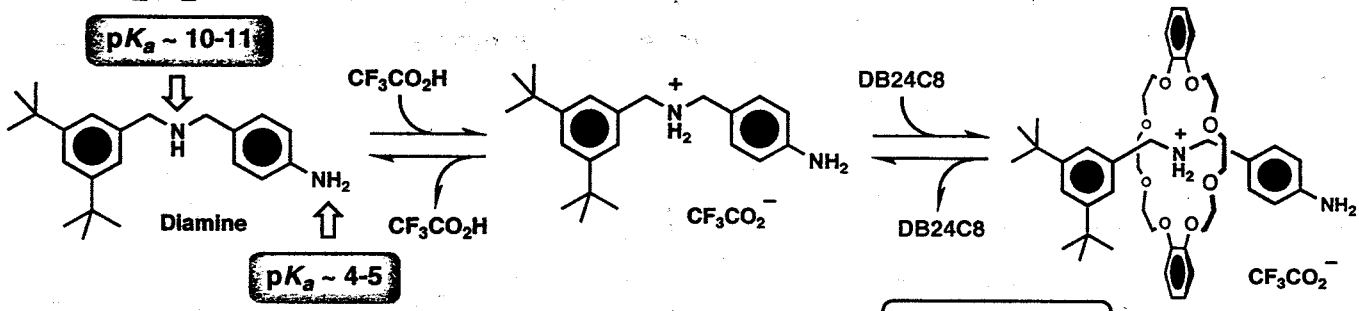
Supramolecular Assistance to the Covalent Synthesis of [2]Rotaxanes

Kinetic Control

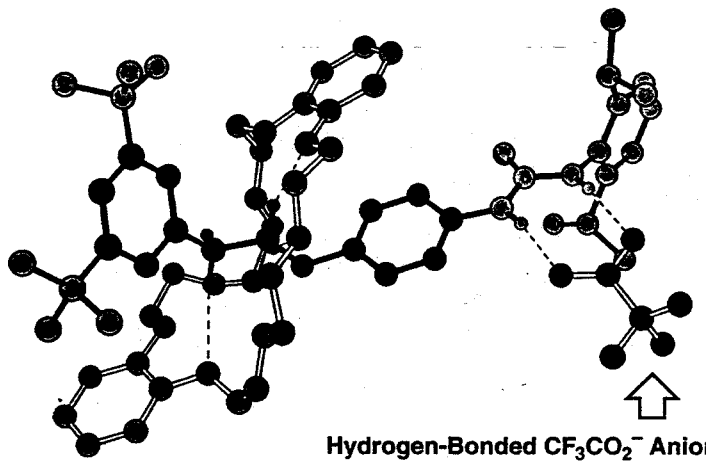


- **If complexation/decomplexation is fast relative to Covalent Modification, then the ratio of A:B is proportional to the difference in the activation free energies of the transition states leading to A and B.**

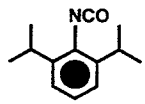
A [2]Rotaxane Formed Under Kinetic Control



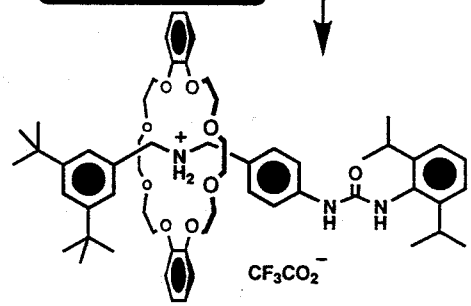
X-Ray Crystal Structure of the [2]Rotaxane



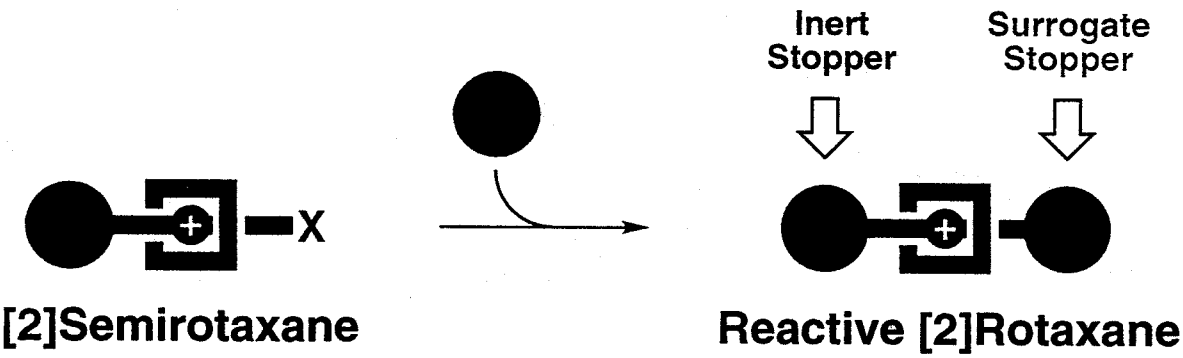
CH_2Cl_2	
Diamine	1
CF_3CO_2H	1
DB24C8	3
Isocyanate	5
RT / 4 Days	

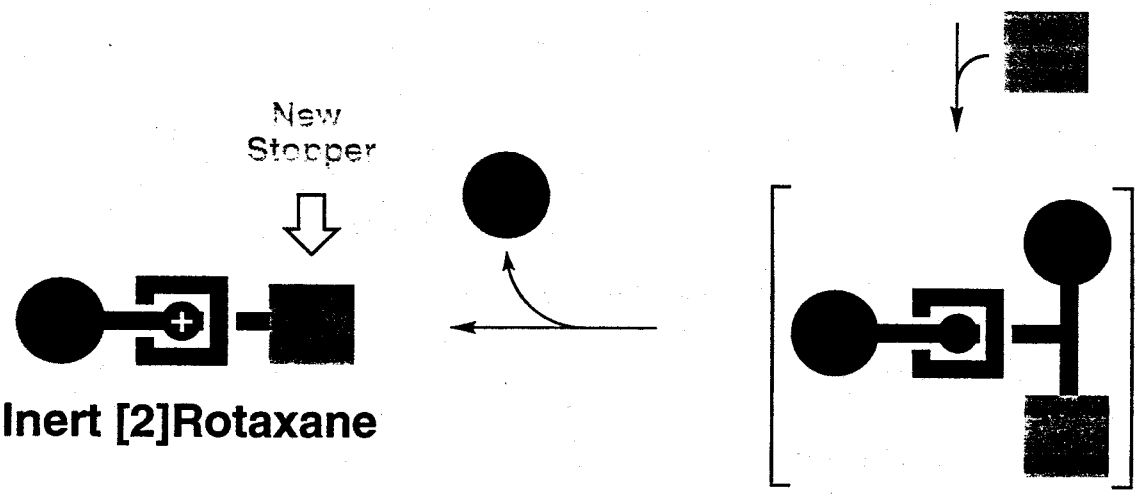


64 %

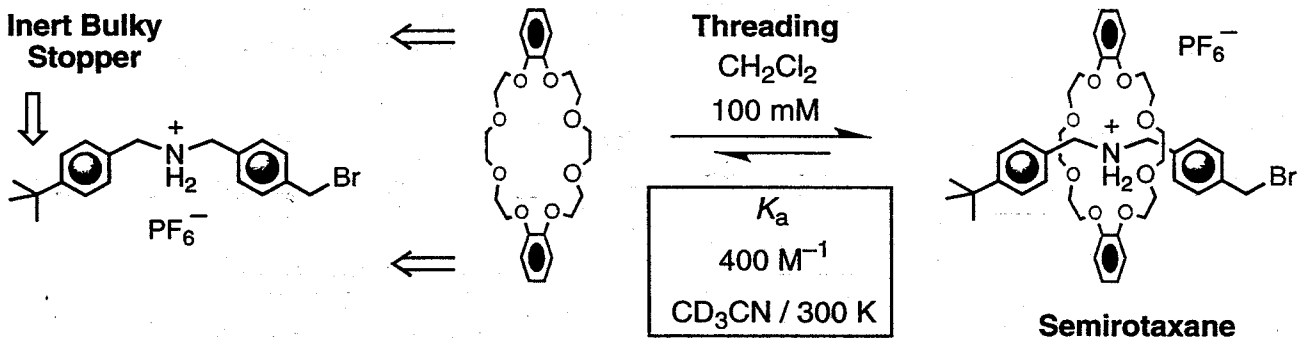


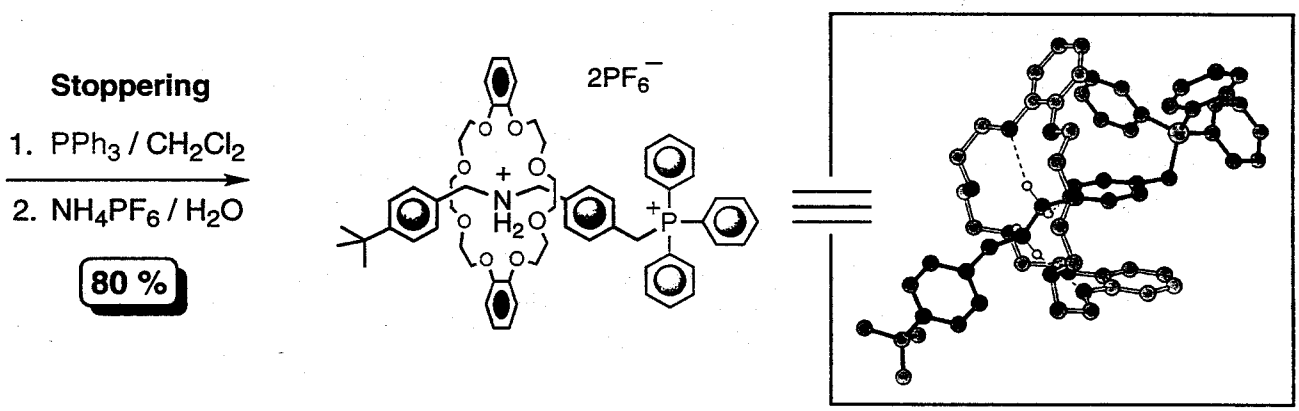
Exchanging the Stoppers in [2]Rotaxanes





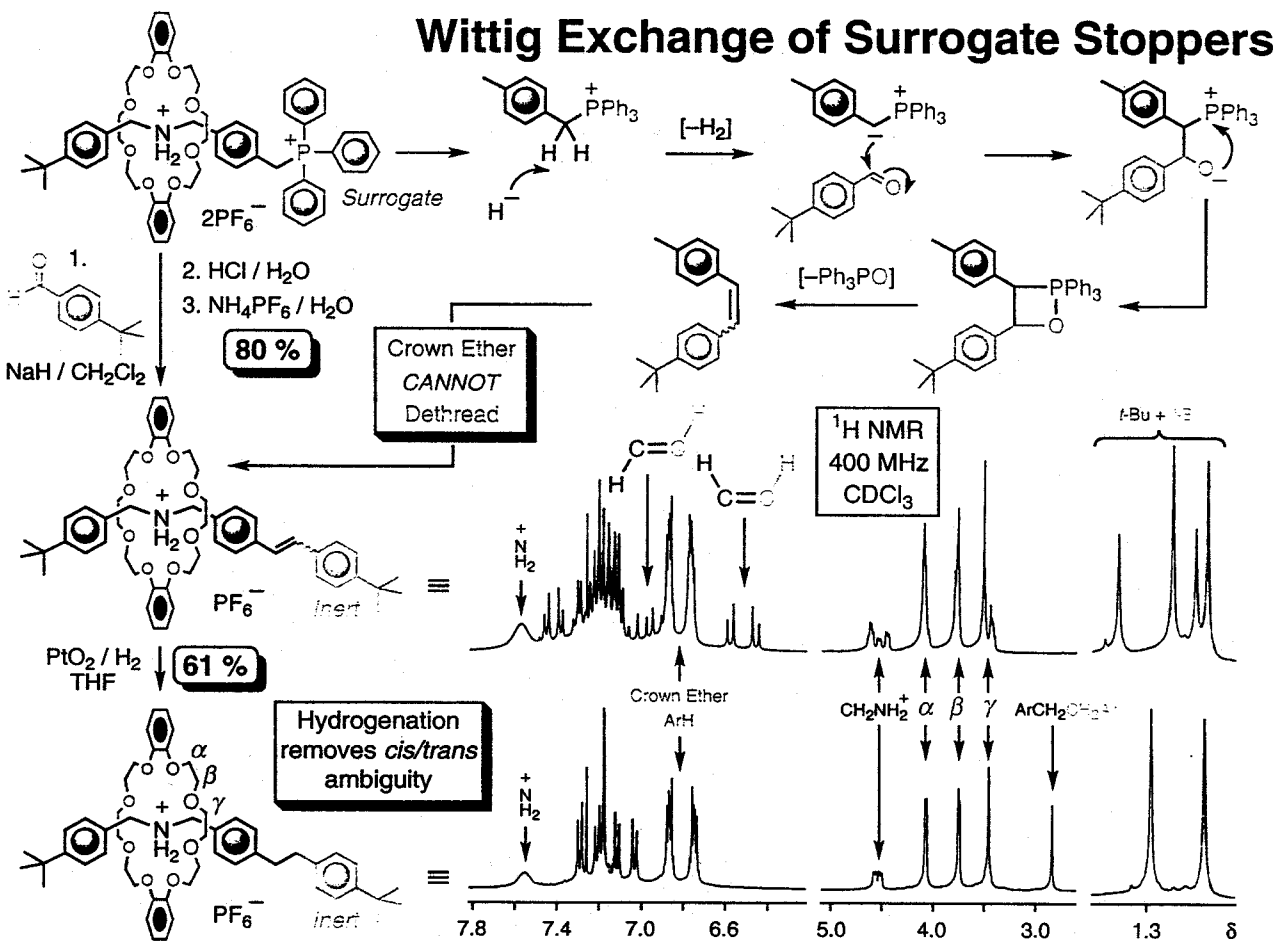
Template-Directed Synthesis of...



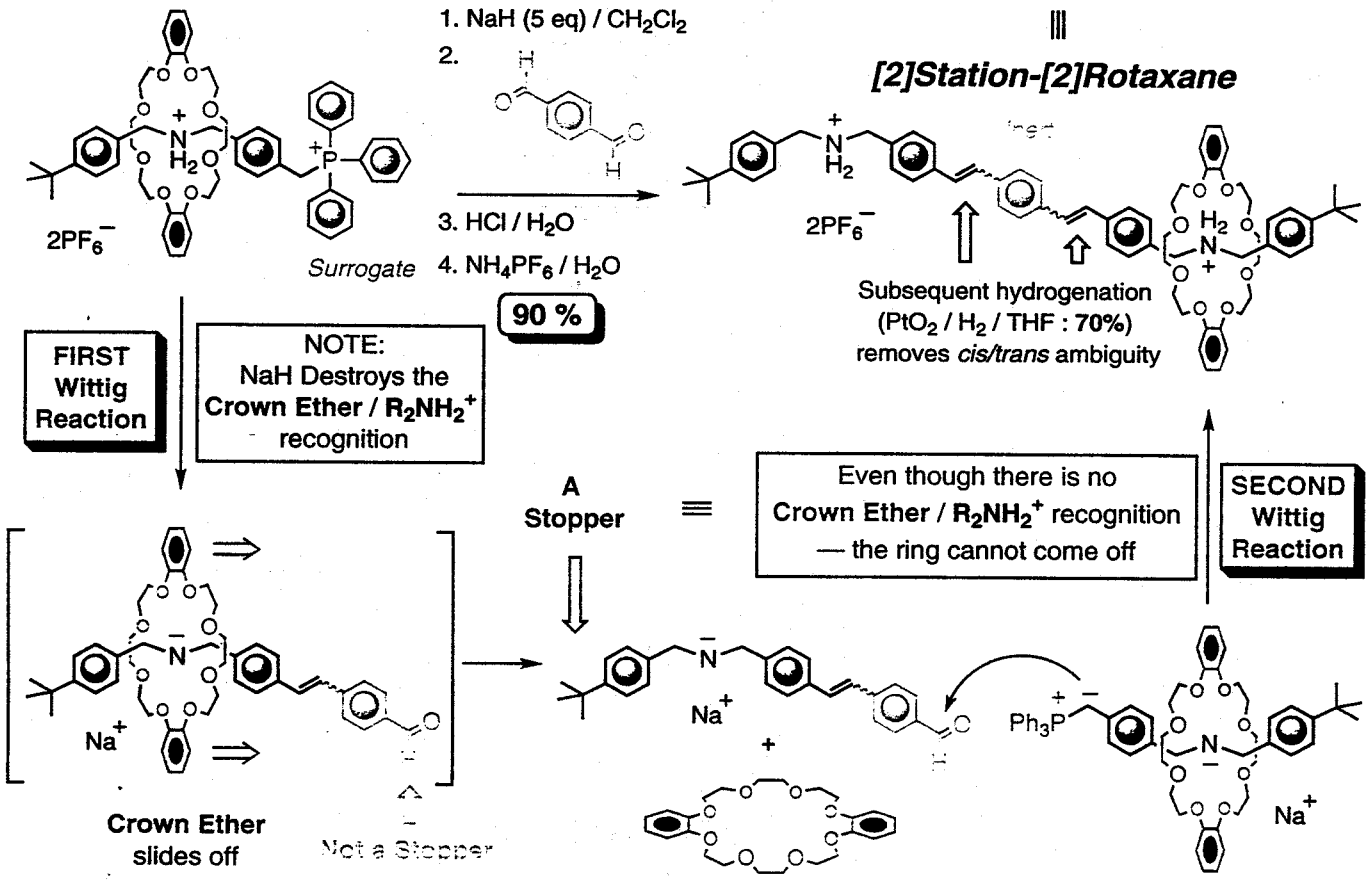


...a Phosphonium [2]Rotaxane

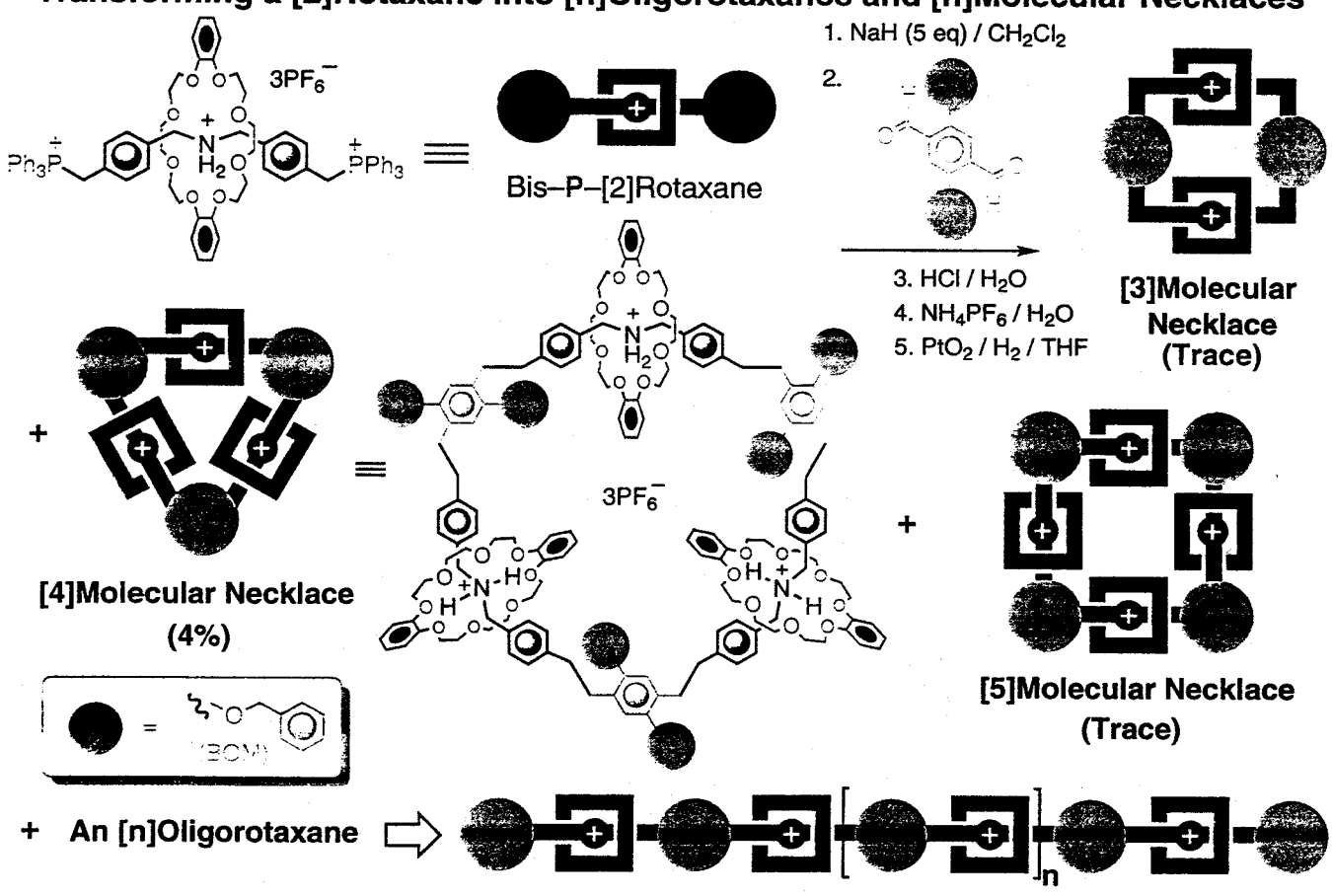
Wittig Exchange of Surrogate Stoppers



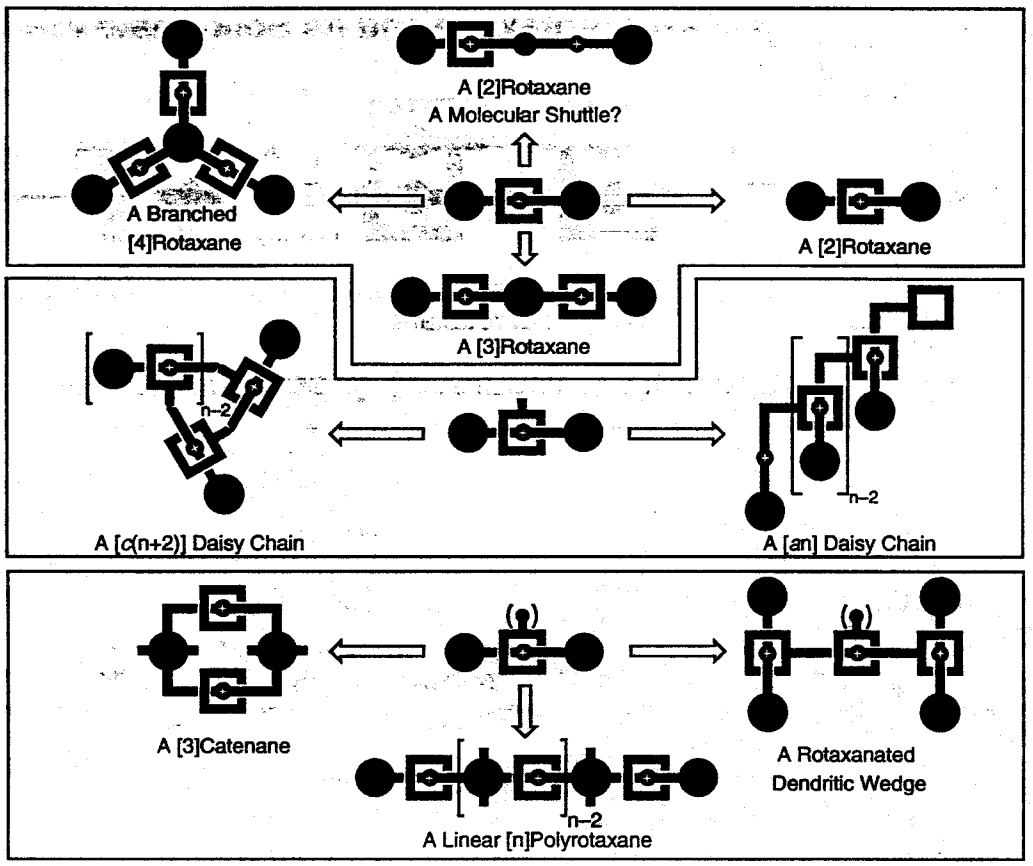
A Highly Specific Synthesis of a Molecular Shuttle



Transforming a [2]Rotaxane into [n]Oligorotaxanes and [n]Molecular Necklaces



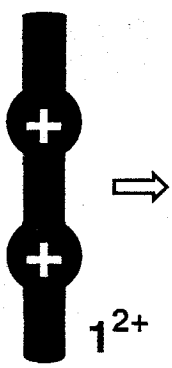
Some of the New Interlocked Architectures within Reach



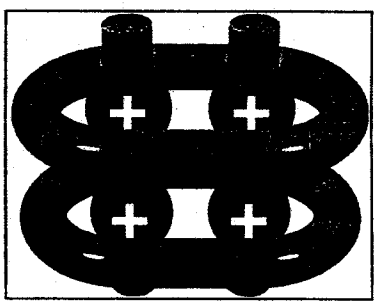
Solid-State Superstructure of $[BPP34C10(1)_2]^{4+}$

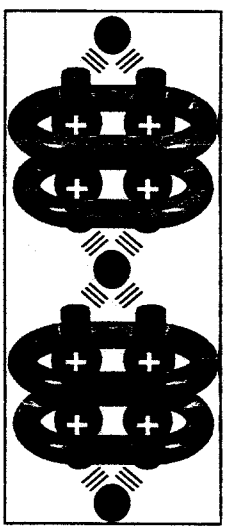
BPP34C10

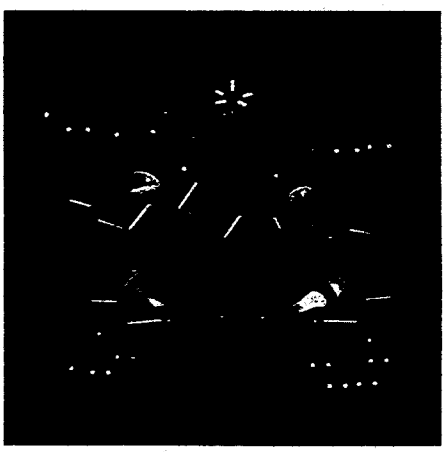
● ≡ PF_6^-

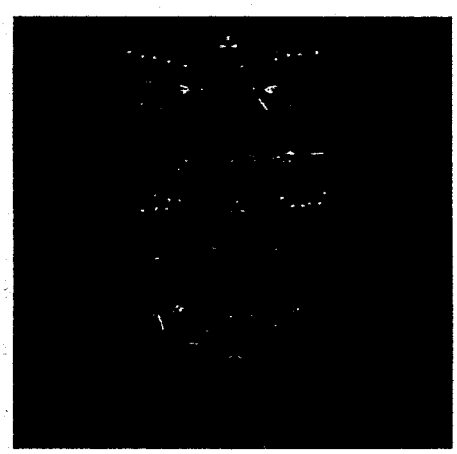


1^{2+}



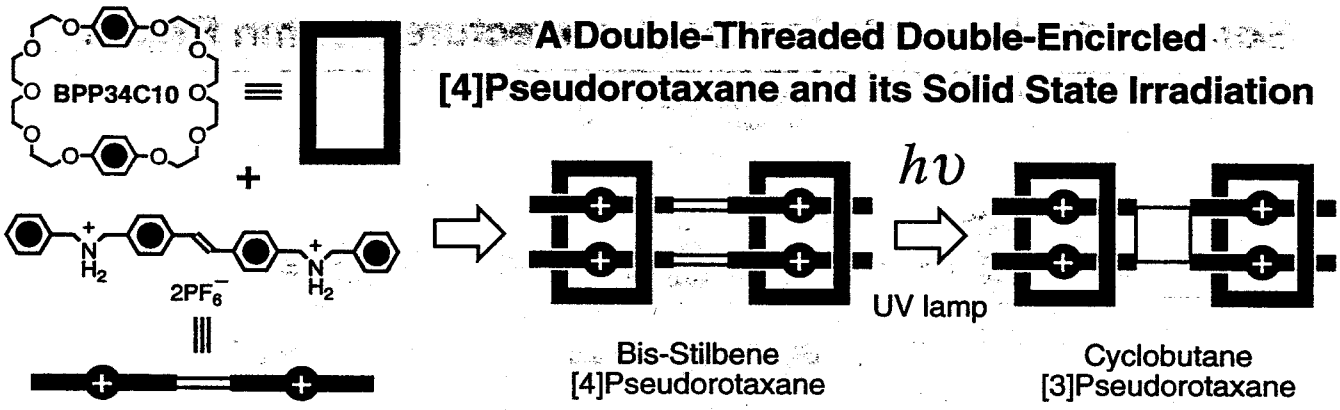




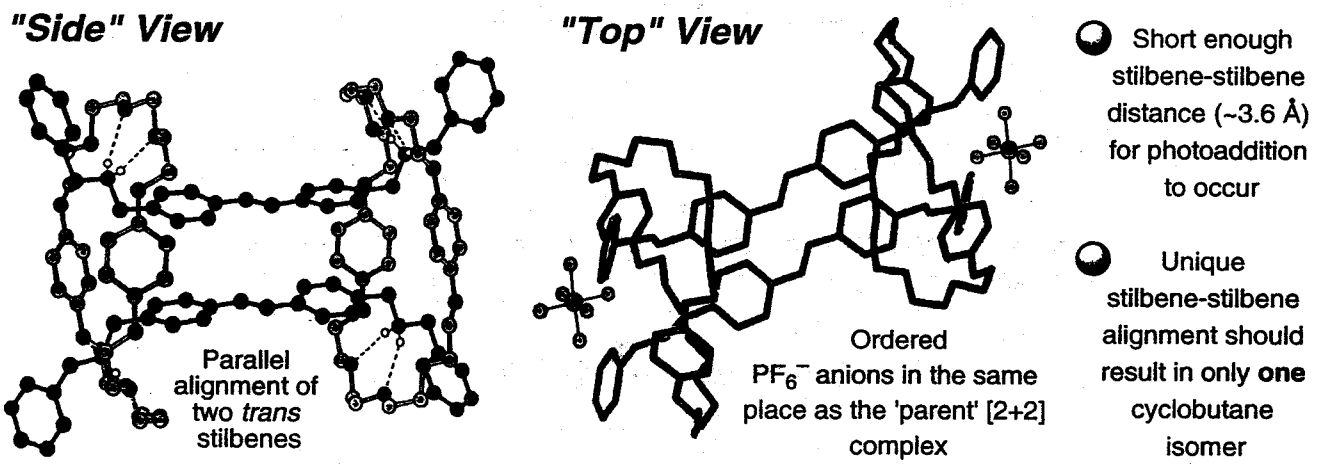


The PF_6^- Anions are responsible for the One-Dimensional Array

A Double-Threaded Double-Encircled [4]Pseudorotaxane and its Solid State Irradiation

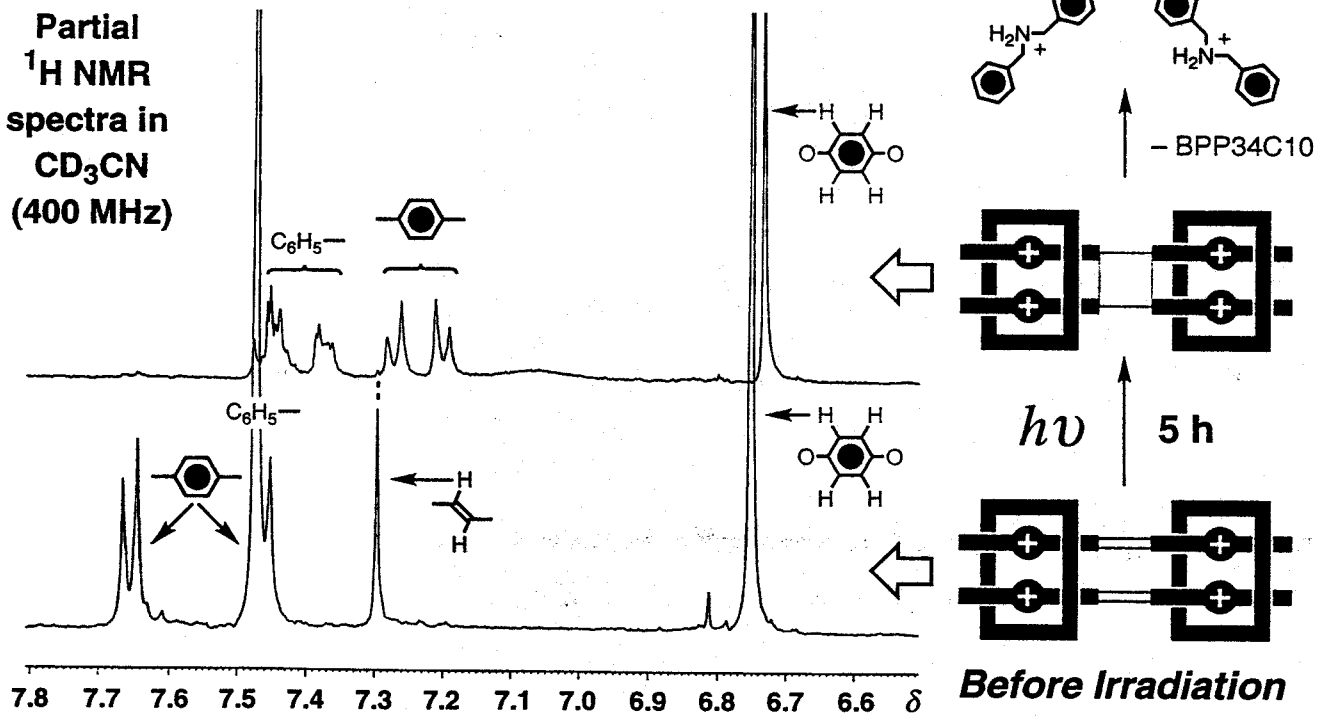


Solid-State Superstructure of the Precursor [4]Pseudorotaxane

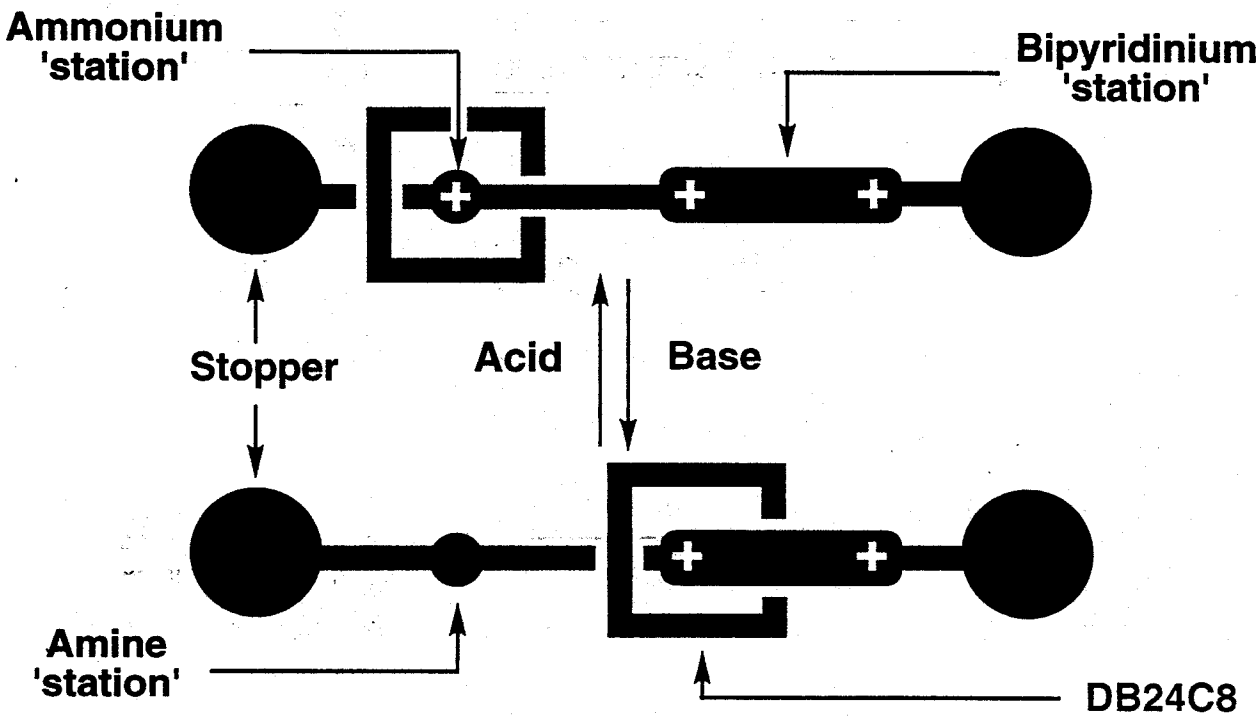


Solution Phase ^{1}H NMR Characterization of Crystals Before and After UV-Irradiation

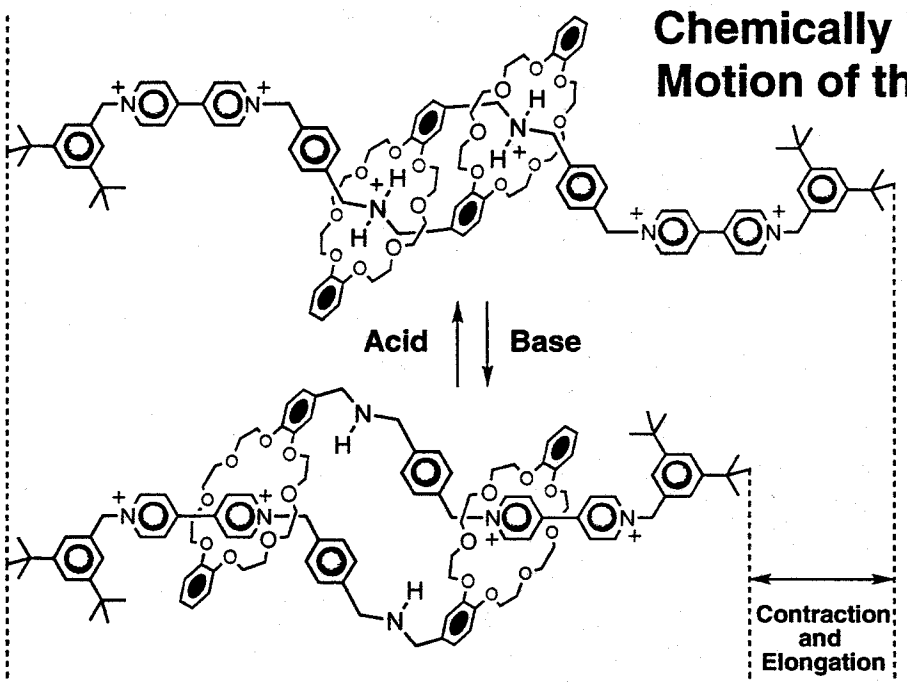
- *Note: No Solid State Photodimerization is observed in the absence of BPP34C10*



A Reversible pH-Controlled Molecular Switch



Chemically Induced Reversible Motion of the Molecular Muscle



Addition of Base
(i-Pr_2NEt or Bu_3N)

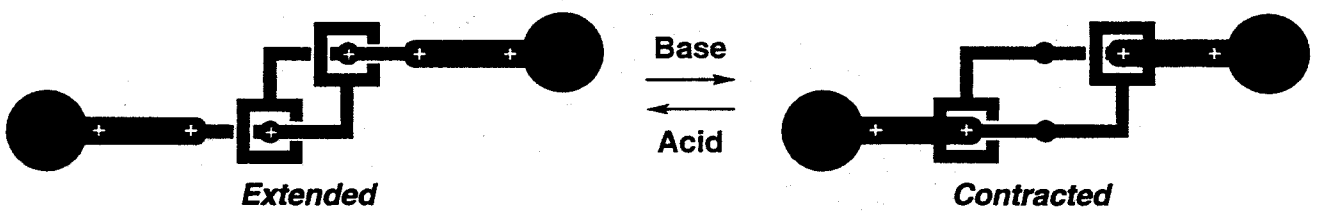
⇩

Contraction

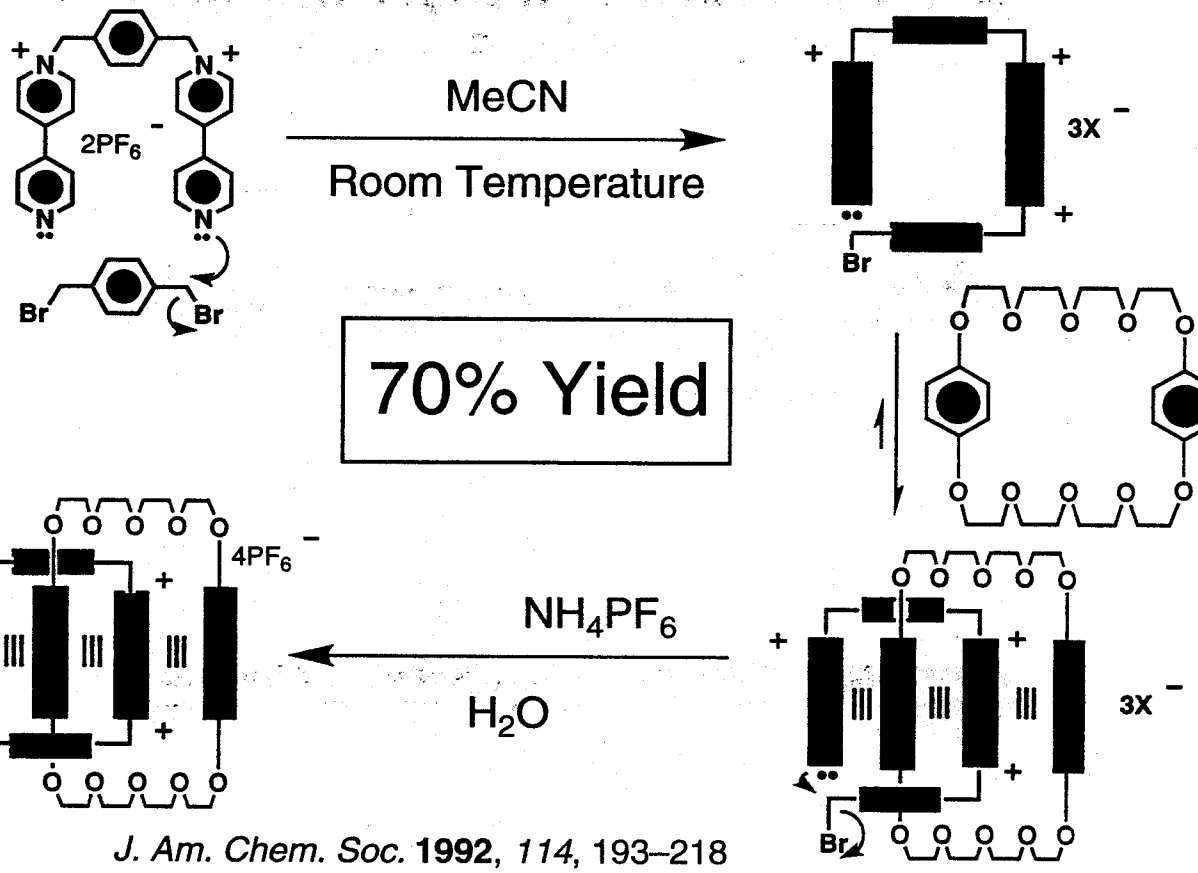
Addition of Acid
(CF_3CO_2H or TfOH)

⇩

Elongation

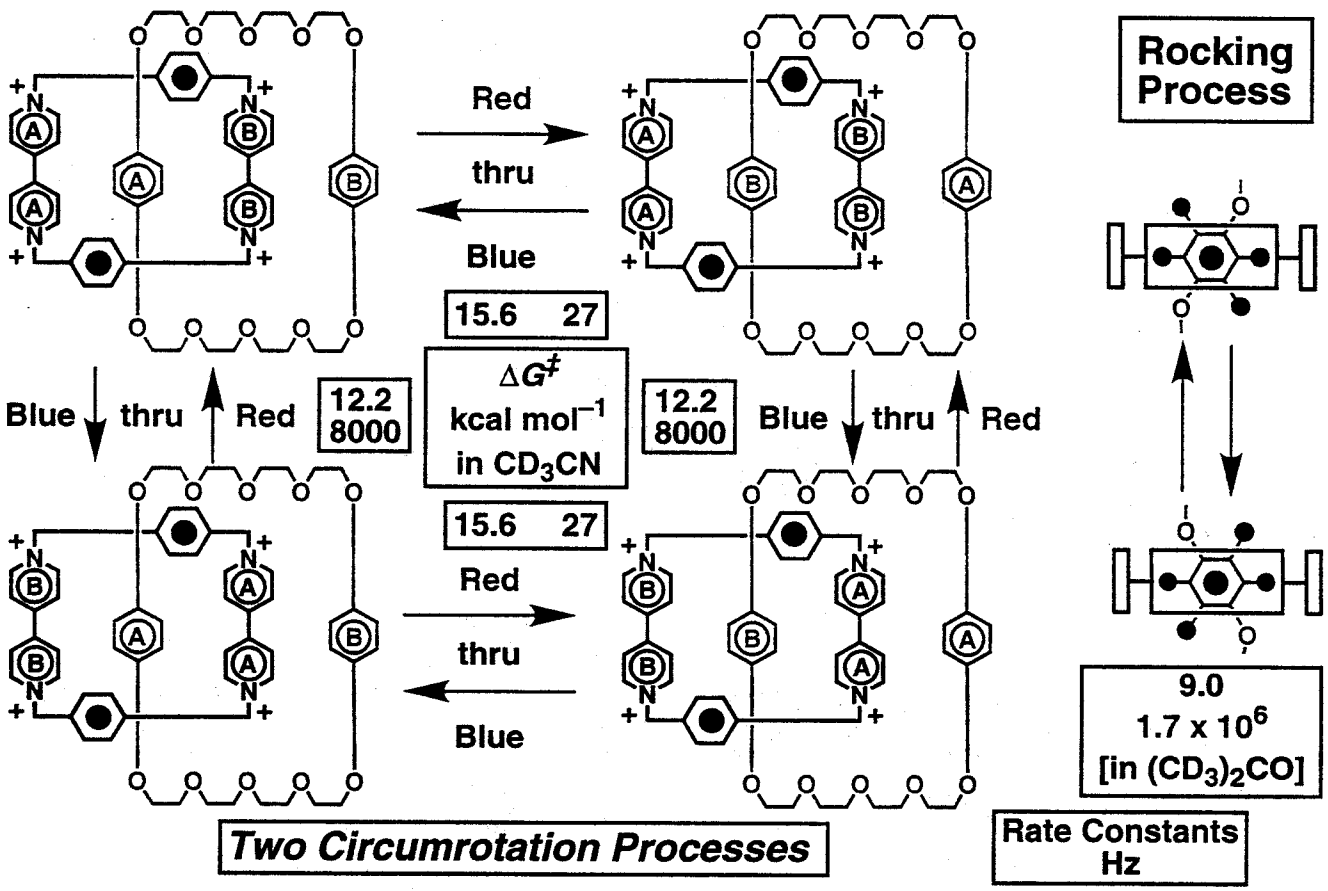


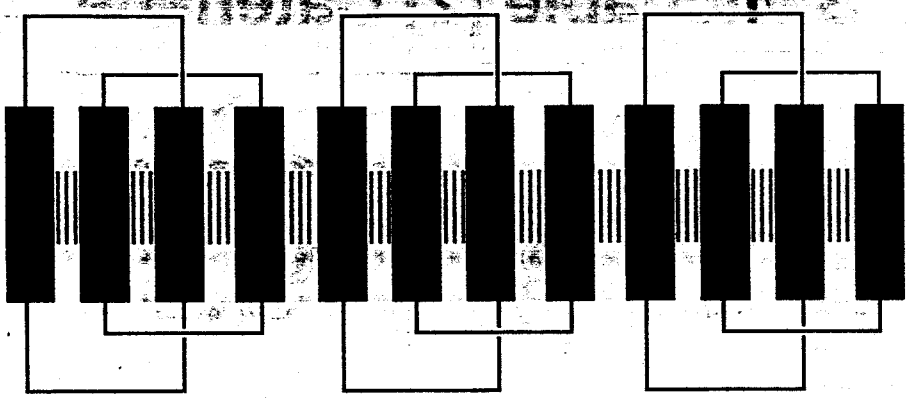
A [2]Catenane Made to Order



J. Am. Chem. Soc. **1992**, *114*, 193–218

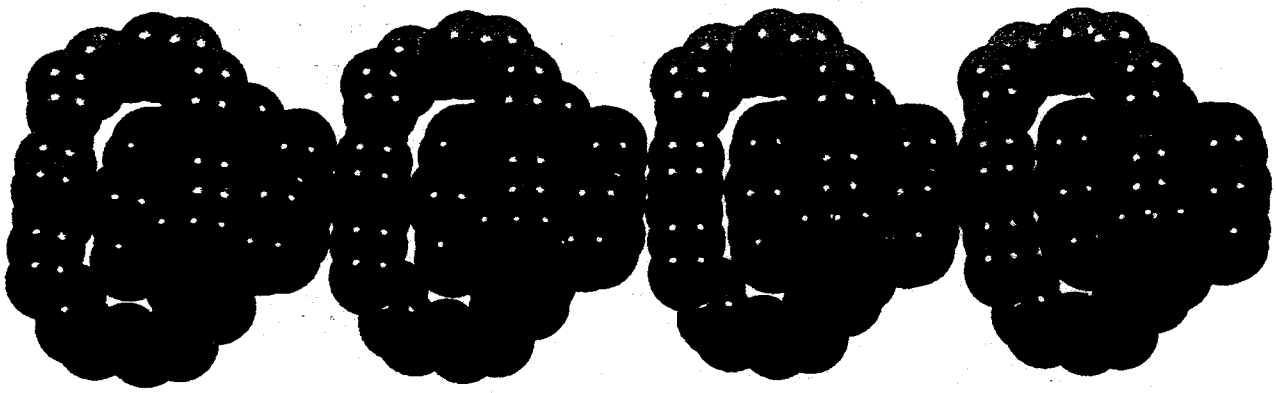
The [2]Catenane — A Basis for Building Molecular Switches



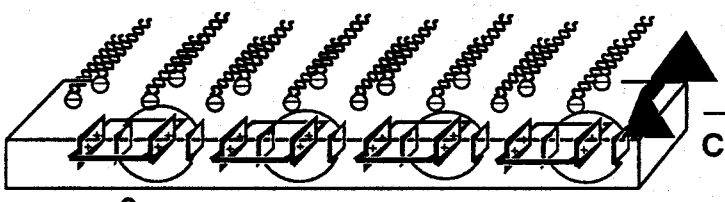


A Continuous *Donor-Acceptor* Stack is Observed in the Crystal Lattice of the [2]Catenane...

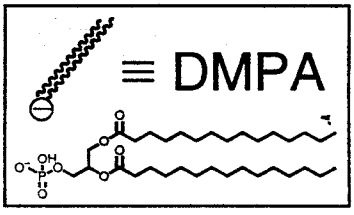
D A D A D A D A D A D A



...and at Interfaces



Barrier movement – Compression



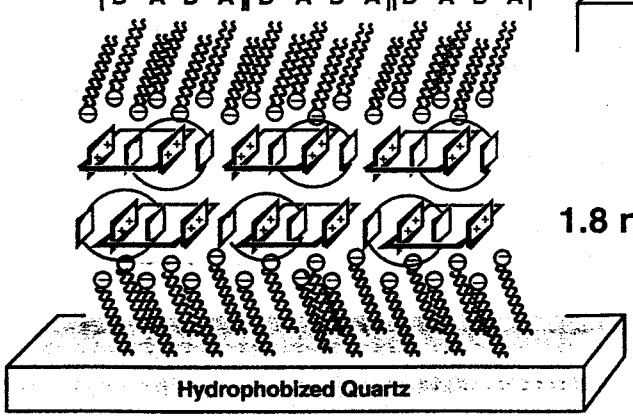
2.3 nm^2 per Molecular Aggregate (4:1)

Langmuir Films

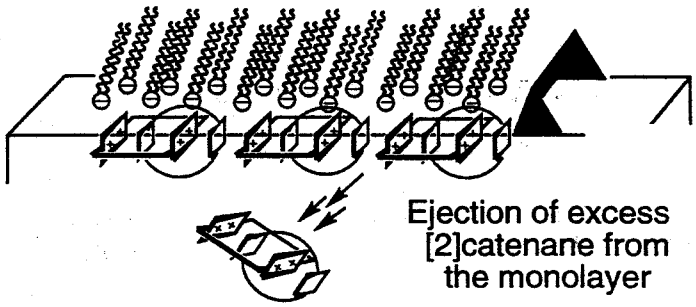
Langmuir-Blodgett Bilayer

|A D A D‖A D A D‖A D A D|

|D A D A‖D A D A‖D A D A|



|A D A D‖A D A D‖A D A D|



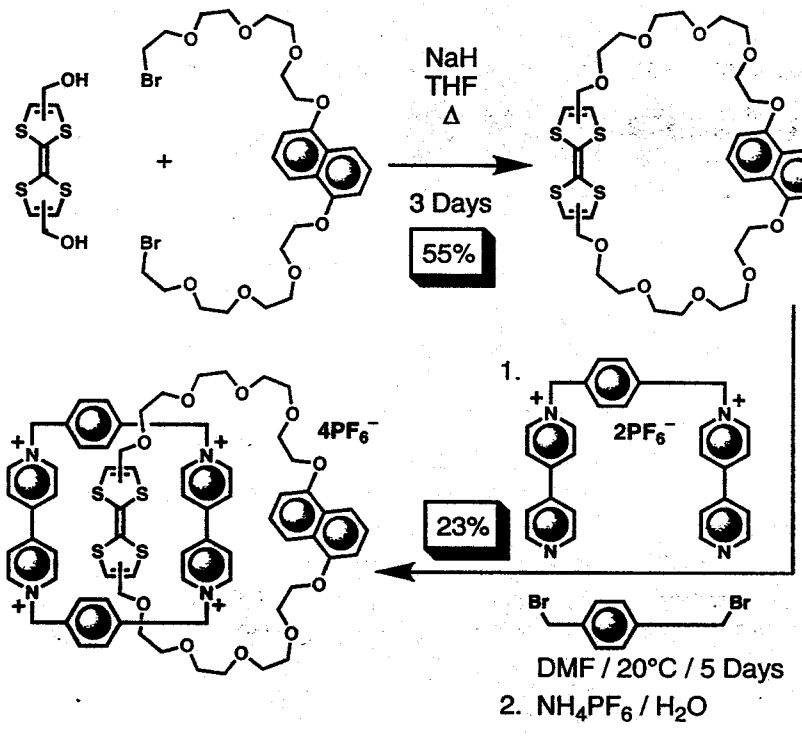
Ejection of excess [2]catenane from the monolayer

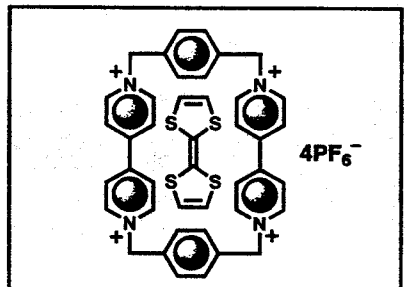
1.8 nm^2 per Molecular Aggregate (5 to 6:1)

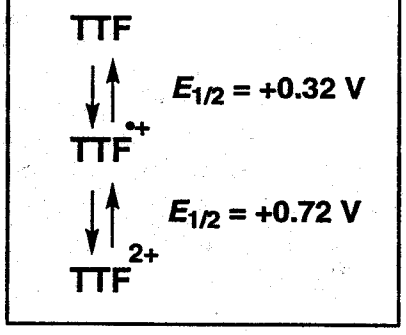
Langmuir-Blodgett Multilayer

Langmuir **2000**, *16*, 1924–1930

Chemically and Electrochemically Switchable [2] Catenane

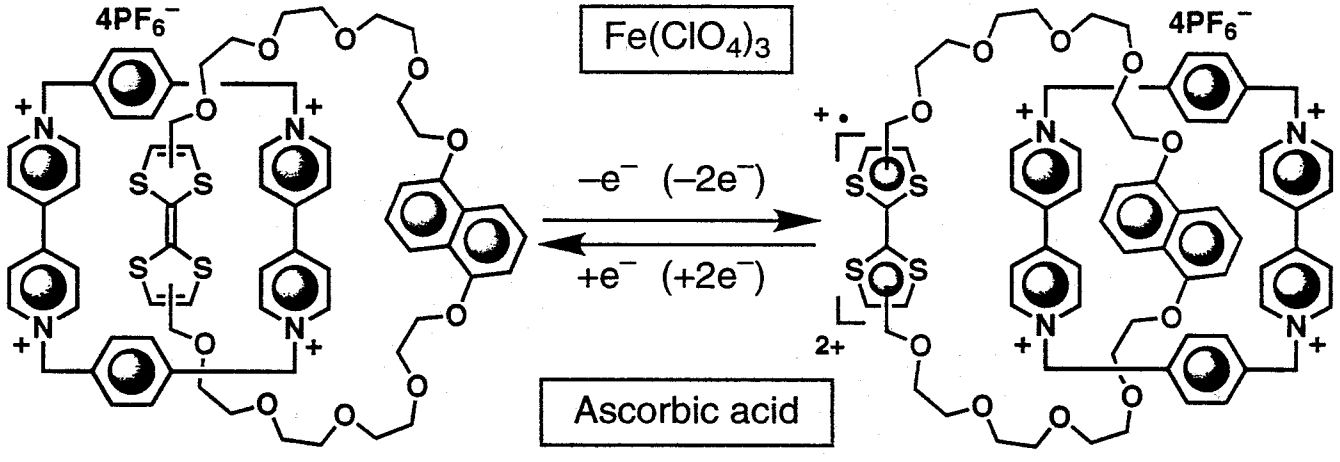






Angew. Chem. Int. Ed. **1998**, *37*, 333–337

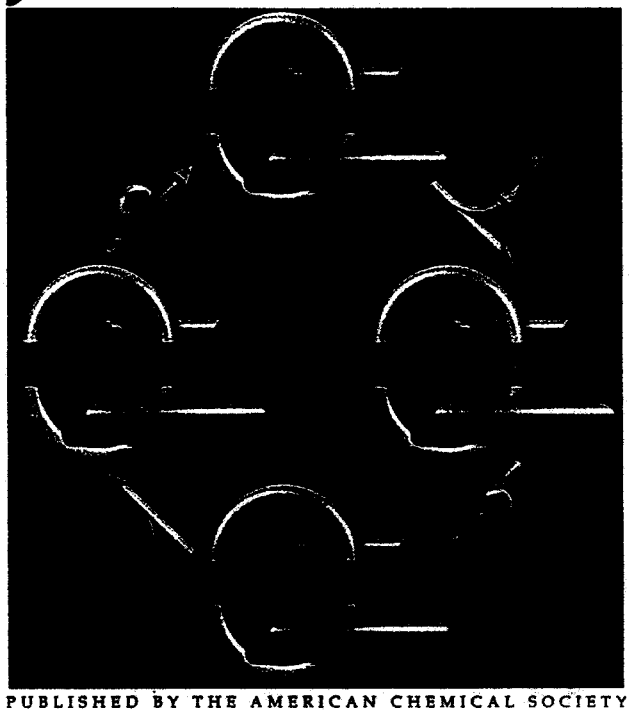
A Redox-Controlled [2]Catenane



Dark green **Maroon**

- **The catenane can be switched by either chemical or electrochemical means**

JOC
http://pubs.acs.org/joc
The Journal of Organic Chemistry
VOLUME 65 NUMBER 7 APRIL 7, 2000



PUBLISHED BY THE AMERICAN CHEMICAL SOCIETY

Controlling Circumrotation in the TTF [2]Catenane

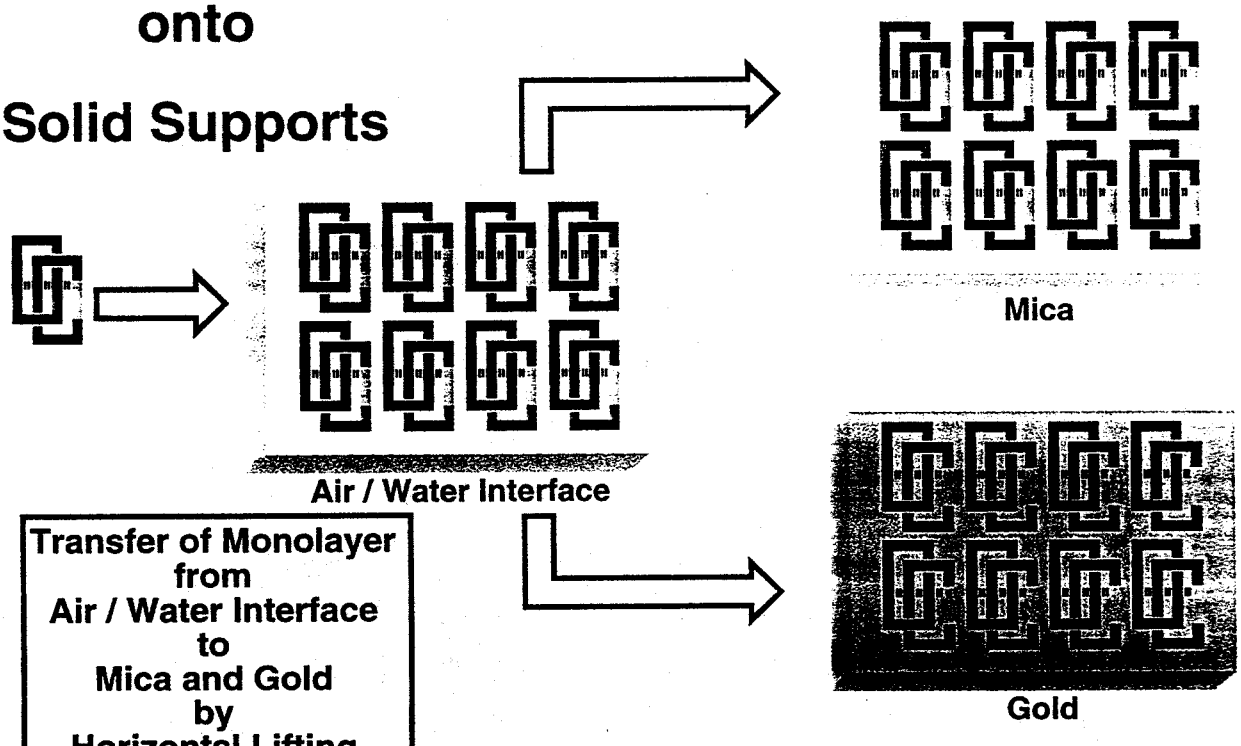
Stimulus

Electrochemical
or
Chemical
with
Oxidizing and Reducing Agents

Readout

Color Change
or
Visible Absorption Spectrum

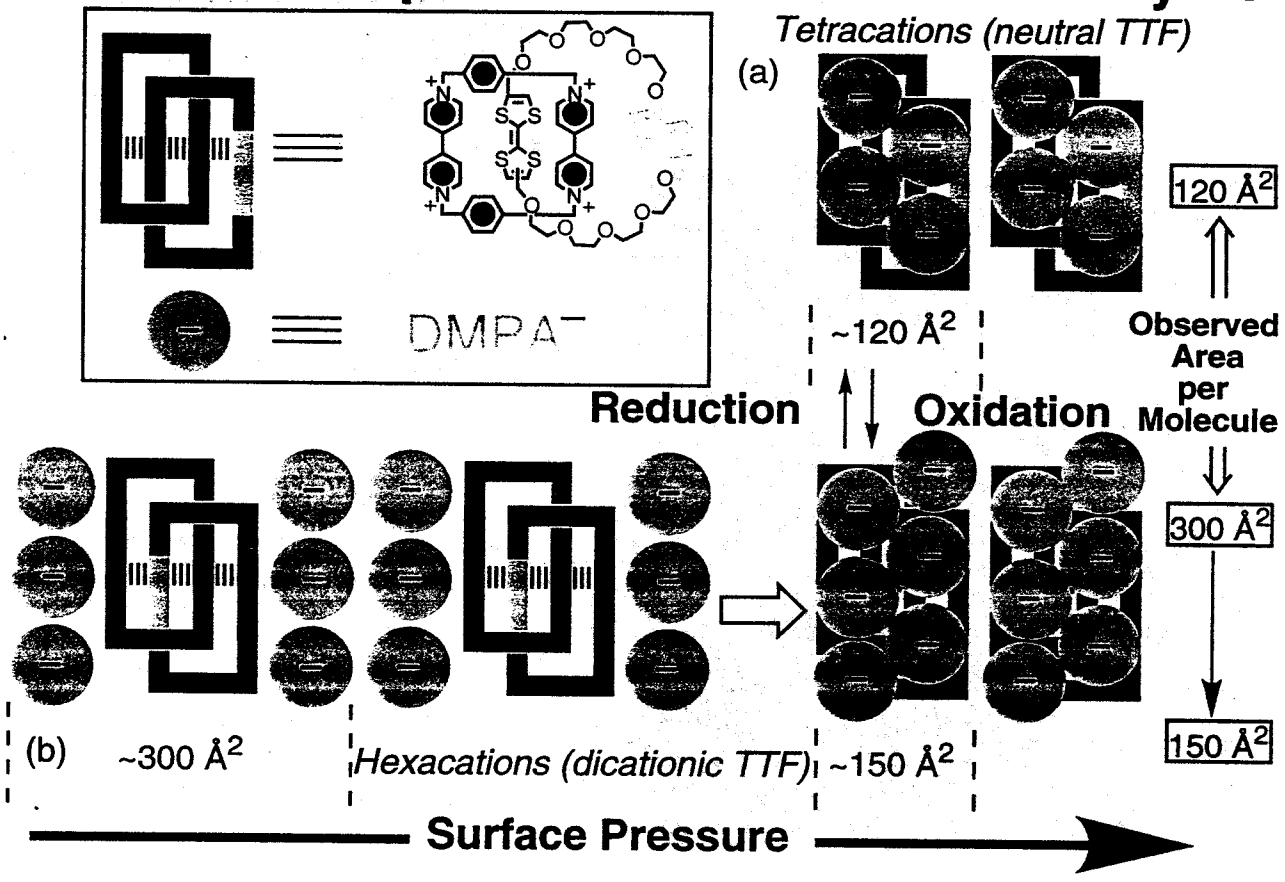
Depositing Switchable [2]Catenane Monolayers onto Solid Supports



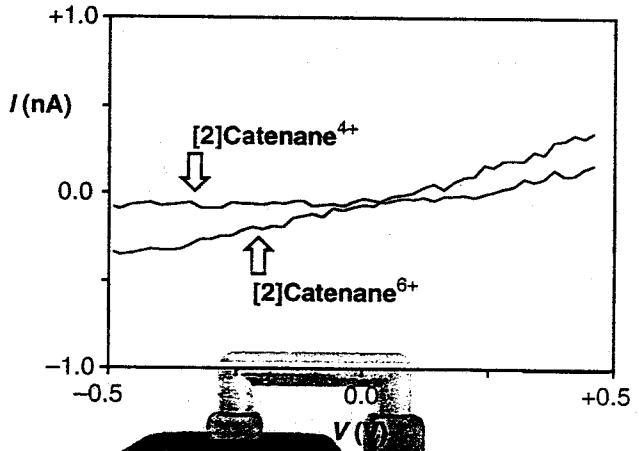
Transfer of Monolayer
from
Air / Water Interface
to
Mica and Gold
by
Horizontal Lifting
Technique

Adv. Mater. **2000**, *12*, XXXX–XXXX

Schematic Representations of the Monolayers



Current / Voltage Response of Monolayers of the [2]Catenane on a Gold Surface

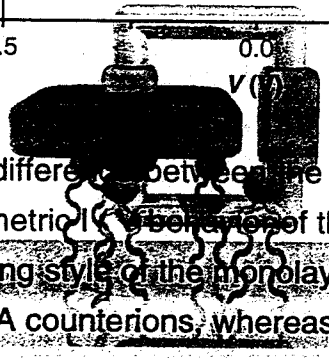


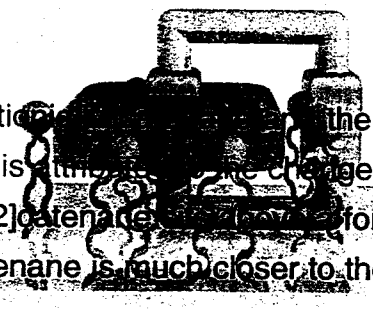
Experimental Conditions:

STM Tip fixed in center of image

V Ramped between +0.8 and –0.8 V 64 times over a total period of 280 μs.

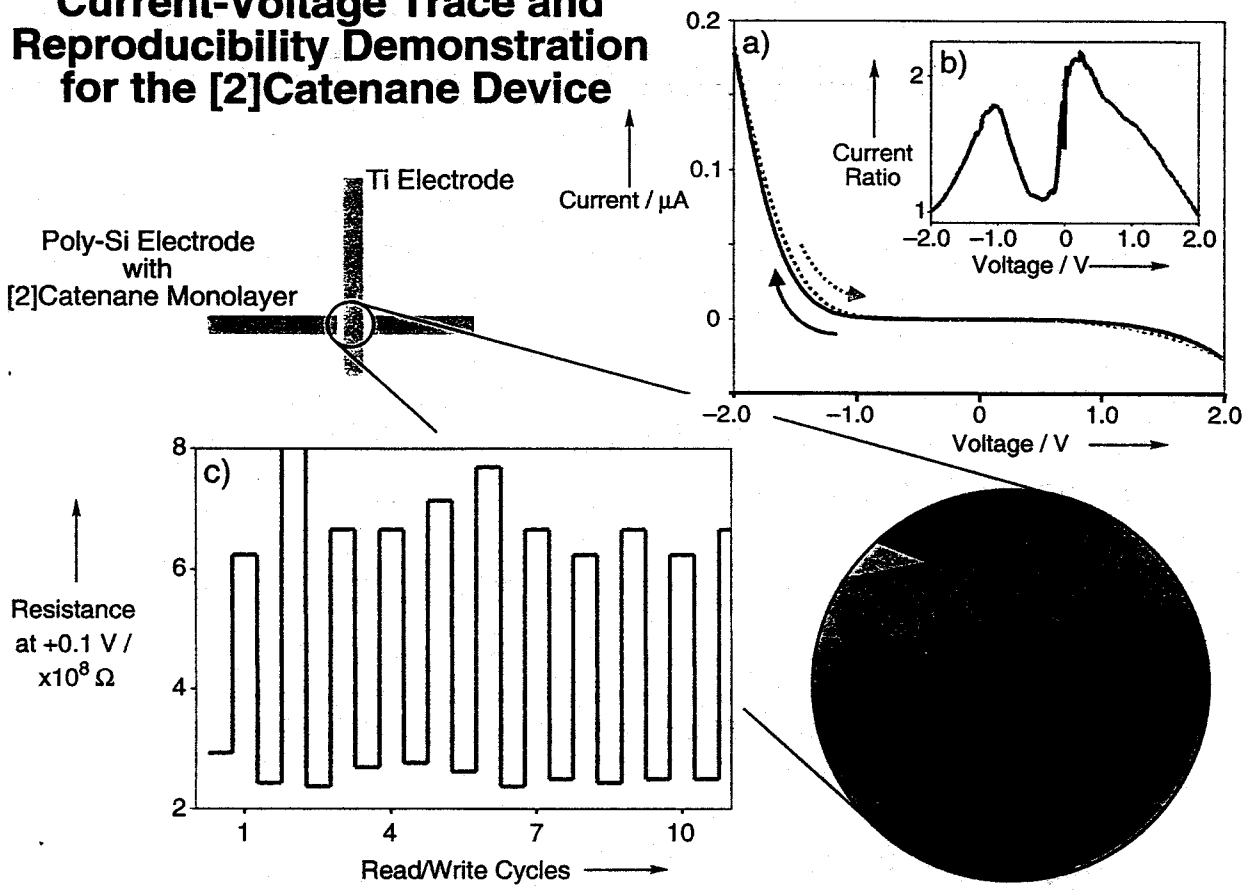
Current recorded and displayed as a function of Voltage

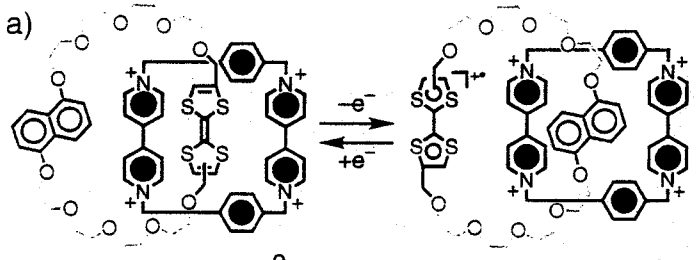


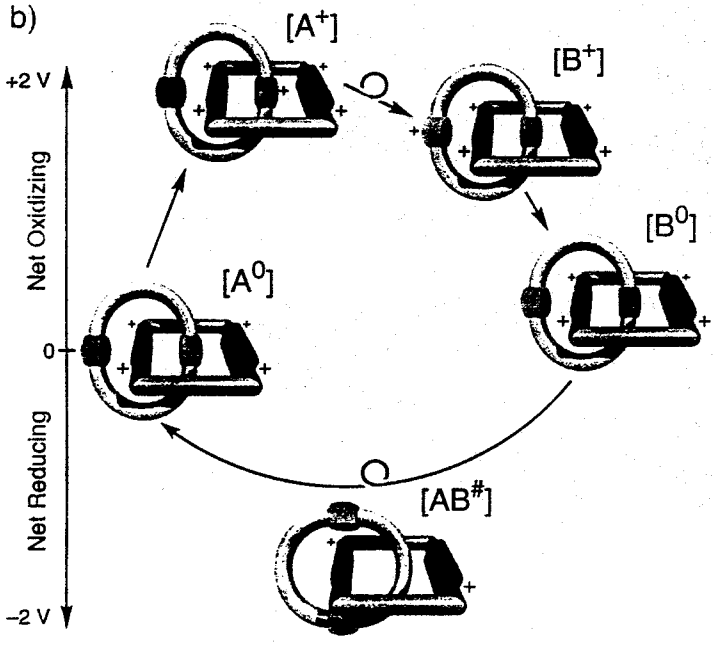


The differ[illegible]between the flat trace for the tetracatio[illegible] the linear symmetric I(V) behavior of the hexacationic species is attributed to a change in the packing style of the monolayers. The tetracationic [2]catenane [illegible] forest of DMPA counterions, whereas the hexacationic [2]catenane is much closer to the gold surface, and is surrounded by its counterions.

Current-Voltage Trace and Reproducibility Demonstration for the [2]Catenane Device







Proposed Mechanism for the Operation of the Device

- [A^0] Ground state / Switch open

READ JUNCTION RESISTANCE AT + 0.1 V

- +2 V Bias across junction creates [A^+] which undergoes circumrotation to give [B]$^+$
- Reduction of [B^+] generates [B^0]
- [B^0] is the closed state of the device

READ JUNCTION RESISTANCE AT + 0.1 V

- Partial reduction (at −2 V) is necessary to regenerate [A^0] by an activated process.

THUS

While the [A^+] to [B^+] circumrotational process is **voltage activated**, the regeneration of [A^0] from [B^0] is **thermally and voltage activated.**

Molecular-Based Memory Devices

- An electronically addressable, reconfigurable, molecular-based, solid-state switching device capable of ambient operation has been fabricated.

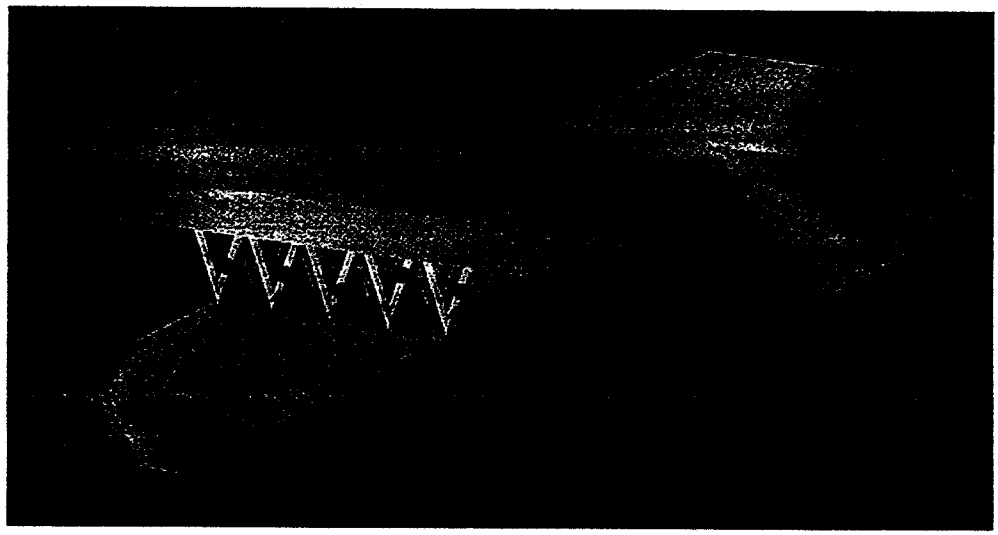
- The device utilizes a single monolayer of redox-controllable [2]catenane molecules anchored with phospholipid counterions and sandwiched between two electrodes.

- The device exhibited robust operation under ambient conditions and could be cycled many times.

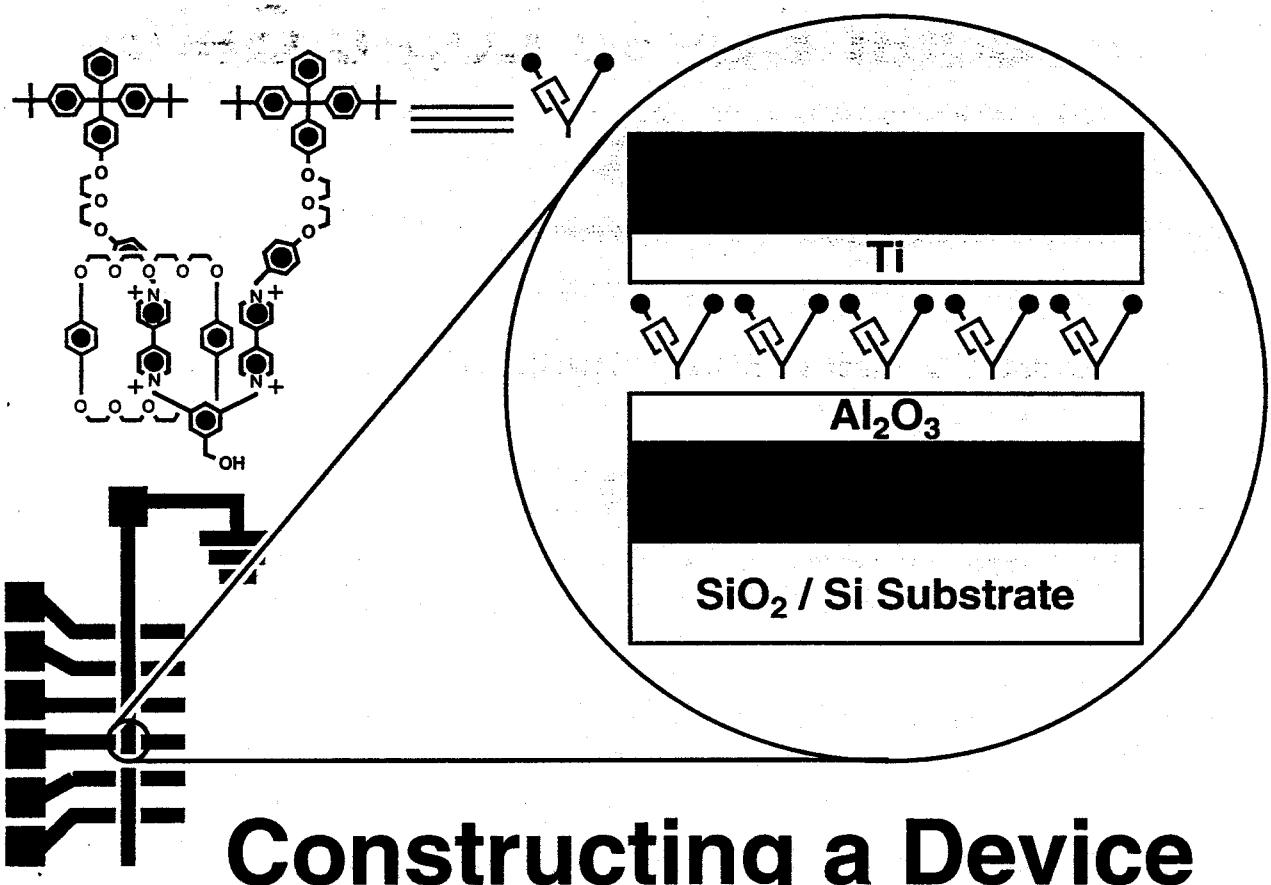
- The change in the junction resistance between the closed and open states of the device is approximately a factor of 2 —

IMPLYING THAT THEY MAY BE USEFUL AS MEMORY DEVICES

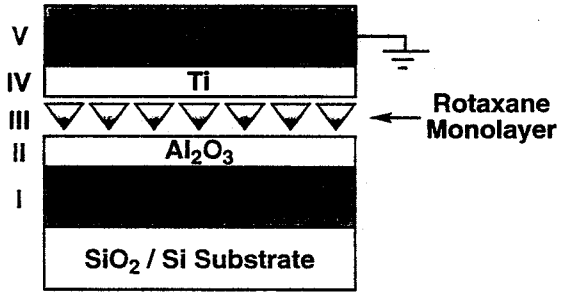
Electronically-Configurable Molecular-Based Logic Gates



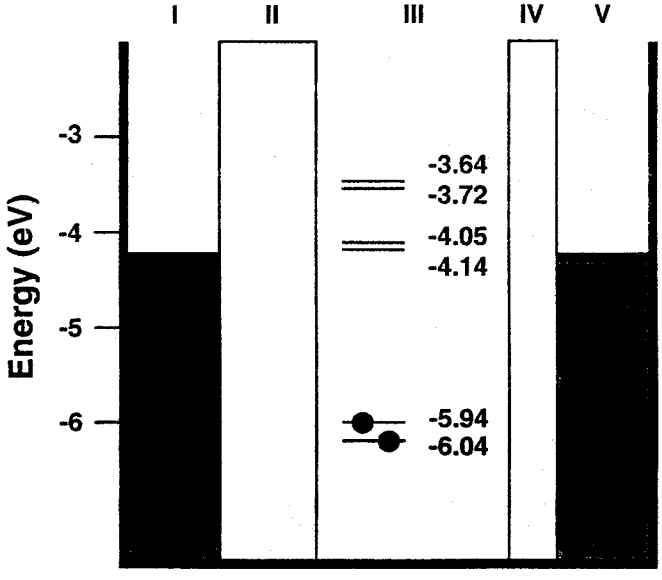
Science **1999**, *285*, 391–394

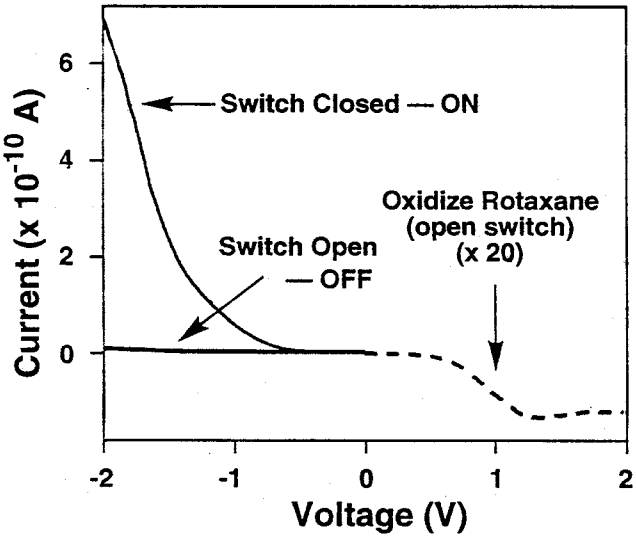


Constructing a Device



Turning Off Any Given Switch is Irreversible





Molecular Based Logic Gates

- Logic gates have been fabricated from an array of configurable switches — each consisting of a monolayer of redox-active molecules sandwiched between metal electrodes.
- The switches can be read by monitoring current flow at reducing voltages.
- In the closed state, current flow is dominated by resonant tunneling through the electronic states of the molecules.
- The switches are irreversibly opened by applying an oxidizing voltage across the device.
- Several devices have been configured together to produce AND and OR logic gates.

Take Home Messages

- Synthesis does not begin and end with the making and breaking of covalent bonds.
- Synthetic supramolecular chemistry is in its infancy.
- Dynamic covalent chemistry provides a thermodynamic means of making interlocked molecules.
- Interlocked molecules beyond catenanes and rotaxanes are on the horizon.
- Slippage is an appeling way of assembling rotaxanes.
- Reactions done under kinetic control can be used to interconvert interlocked molecules and incorporate them into large assemblies.
- Solid-state superstructures of complex systems are far from being predictable.
- Supramolecular polymers that incorporate intertwining as well as noncovalent bonding are not far off.

- Molecular shuttles, switches, and muscles have been demonstrated in solution.

- Catenanes and rotaxanes can be self-organized as monolayers at the air-water interface and transferred onto solid supports.

- A molecule-based solid-state electronically-reconfigurable switch has been demonstrated.

- Mechanochemical processes observed in solutions of catenanes and rotaxanes are transferrable with modifications into device situations.

- Electronically-configurable molecular-based logic gates have been fabricated into a device.

- Chemistry provides the means to transfer concepts between the life sciences and materials science.

Artificial Molecular Machines

"Just as dyes came to the fore and brightened up our lives in the 19th century and drugs came onto the scene and made our lives more bearable in the 20th century, so the 21st century will be dominated by devices that will transform our lives beyond our wildest dreams."

Balzani — Credi — Raymo — Stoddart

Angew.Chem. Int. Ed. **2000**, *39*, 3348-3391