Corso di Chimica Supramolecolare

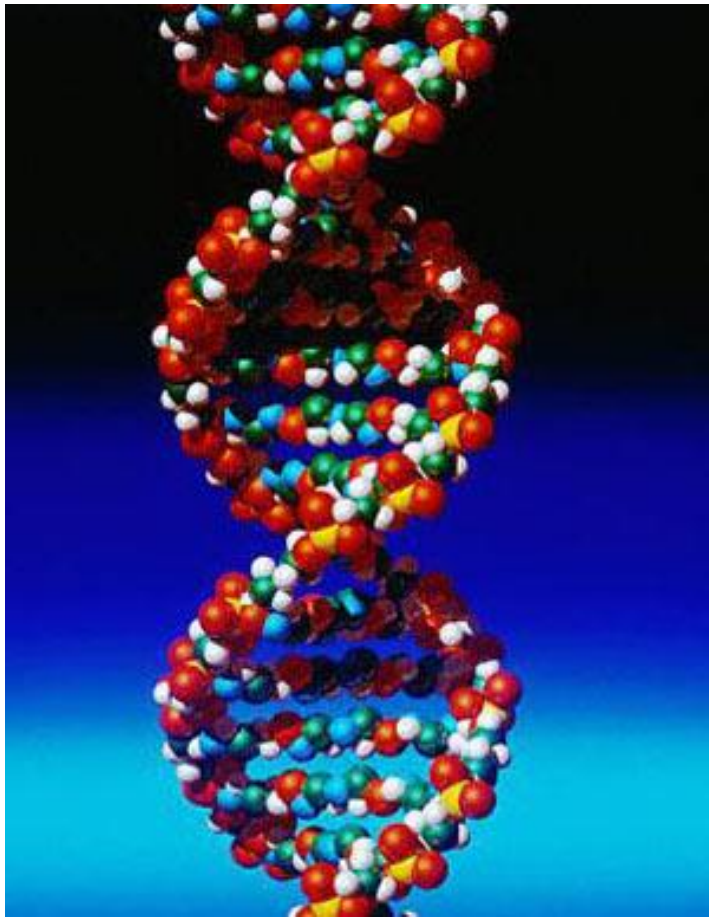
(LM in Chimica @units)

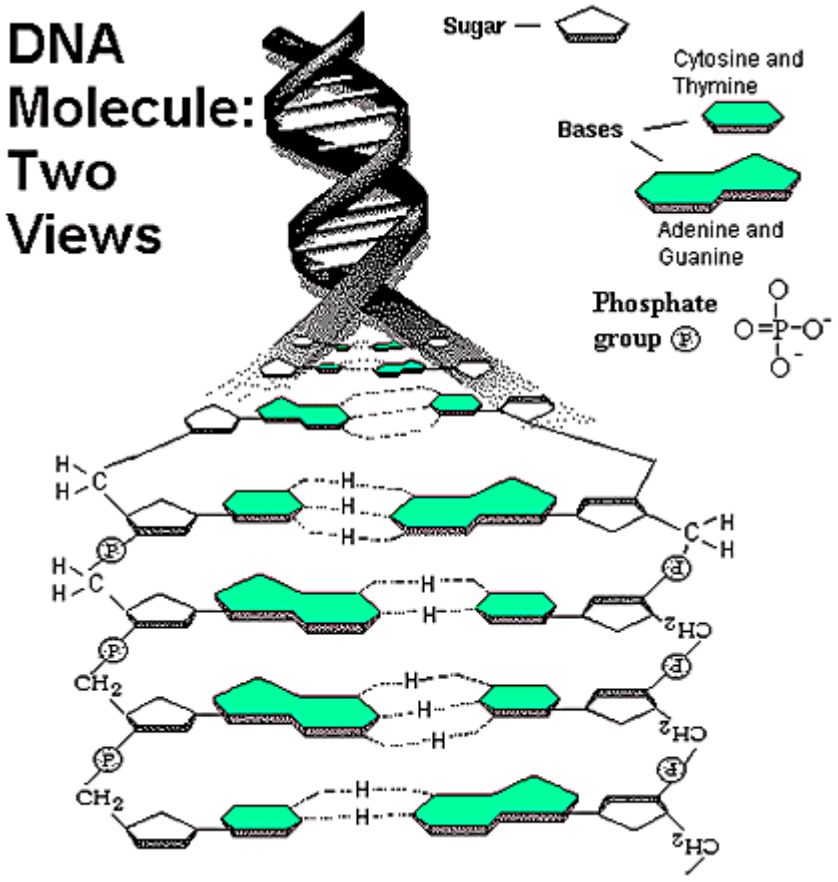
AA 2019/2020

Prof. E. Iengo
eiengo@units.it

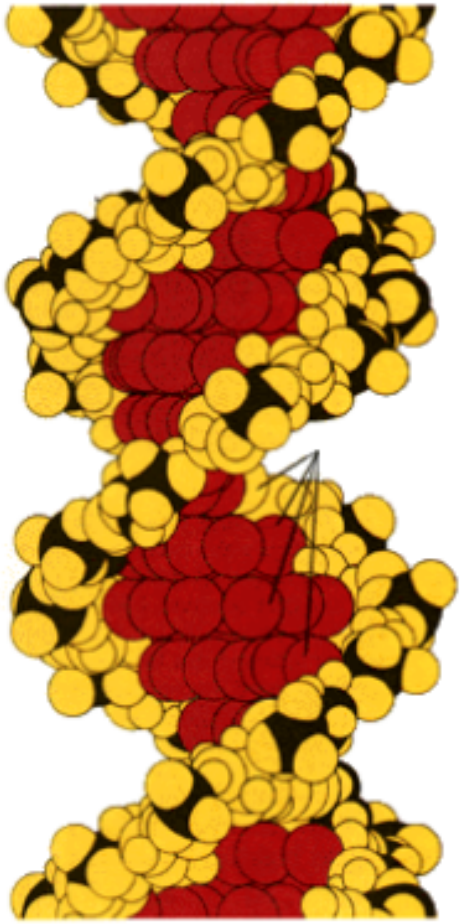
The original inspiration: Supramolecular systems in Nature

DNA





Information Storage



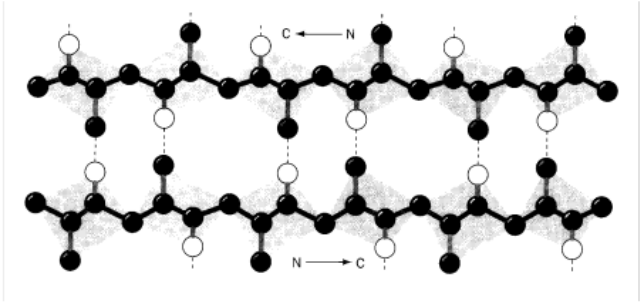
Watson & Crick 1953

The ultimate supramolecular material?

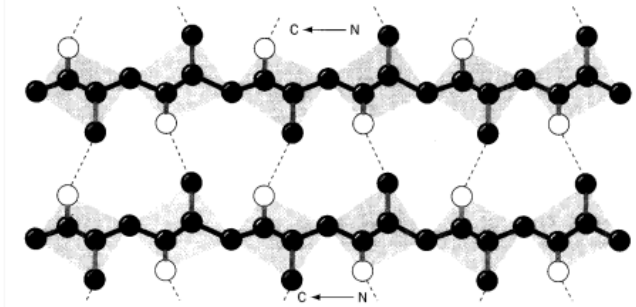
- Encodes gigabytes of data
- Can Self-Replicate
- Built-in Error Correction
- Is the basis of life

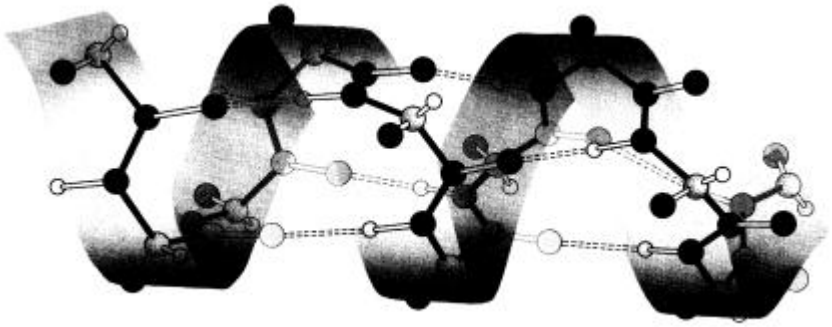
The original inspiration:
Supramolecular systems in Nature

PROTEINS



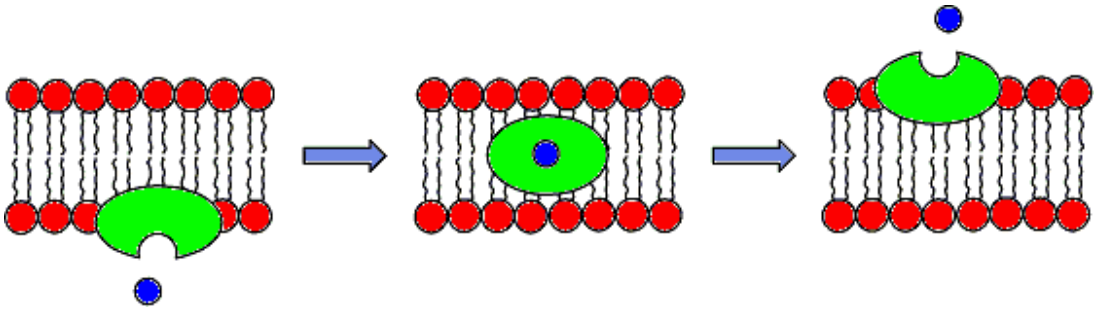
(a)





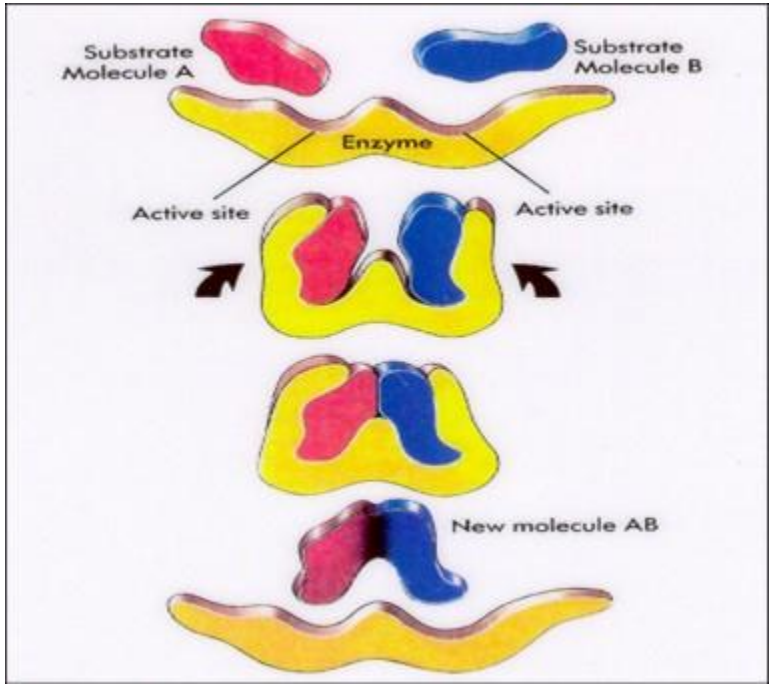
The original inspiration: Supramolecular systems in Nature

MEMBRANES and TRANSMEMBRANE CARRIERS



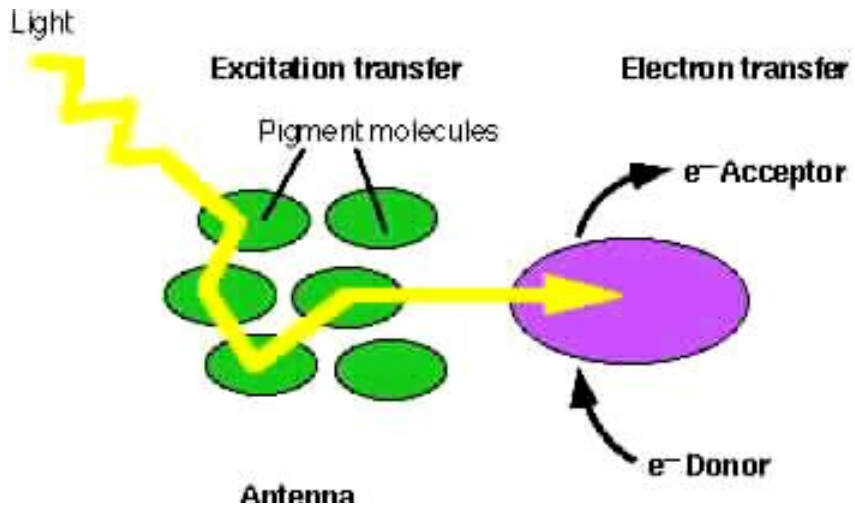
The original inspiration: Supramolecular systems in Nature

ENZYMES

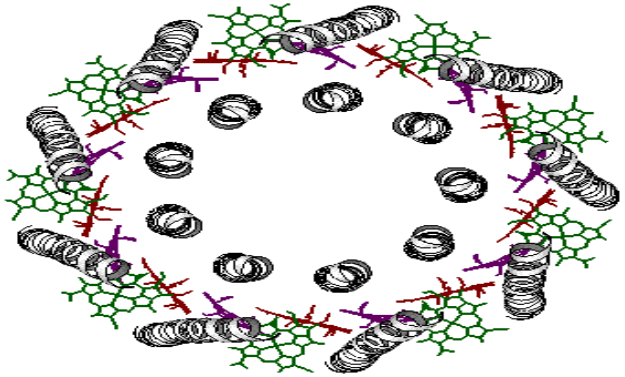


The original inspiration: Supramolecular systems in Nature

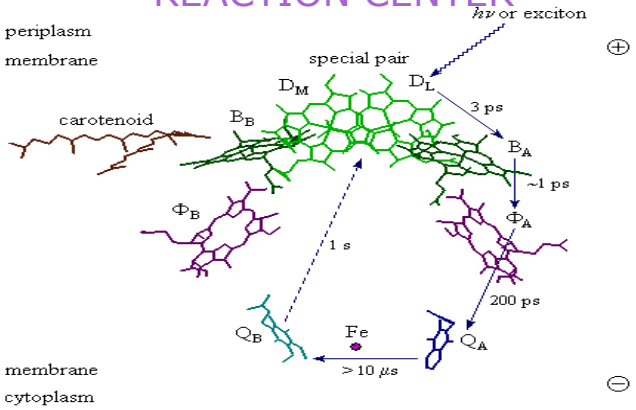
THE PHOTOSYNTHETIC APPARATUS



ANTENNA UNITS

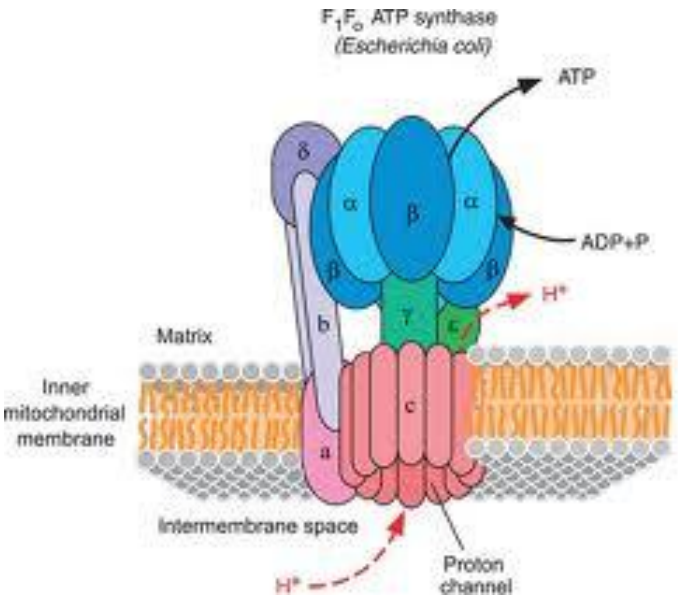


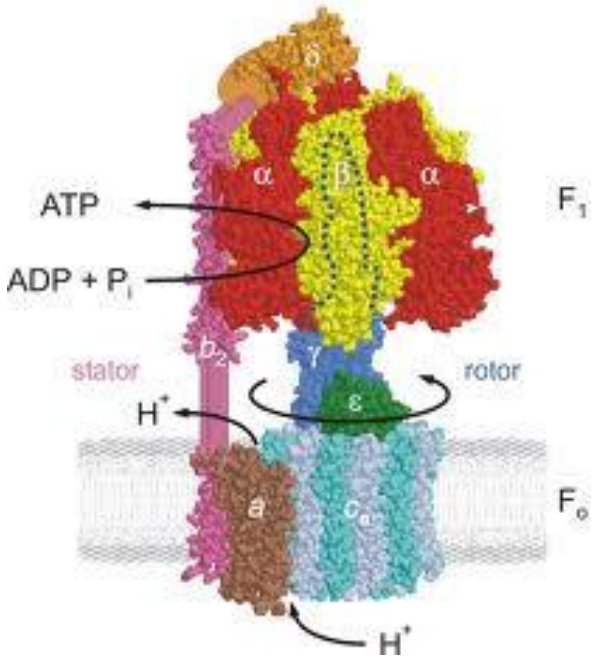
REACTION CENTER

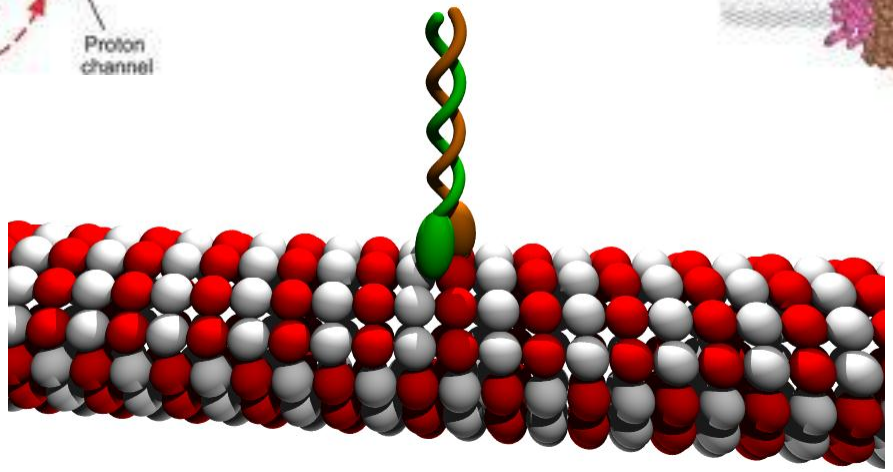


The original inspiration: Supramolecular systems in Nature

ATP Synthase and KINESIN

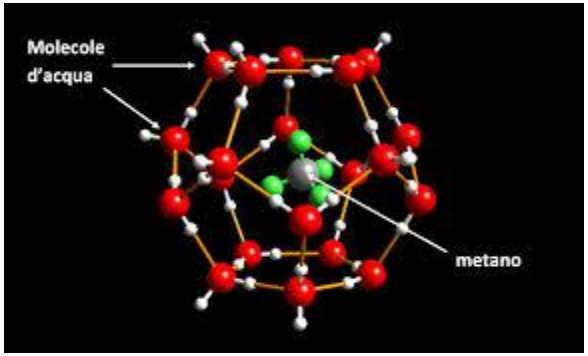






The original inspiration: Supramolecular systems in Nature

METHANE CLATHRATE (Siberian craters)



Supramolecular Chemistry - definitions

- the chemistry beyond the molecules: molecules are already formed

- the chemistry of molecular assemblies and of the intermolecular bond: association of molecules

- the chemistry of the non covalent bond: weak interactions

Bottom-up approach

Nano objects

Smart and functional materials

Supramolecular Chemistry - vocabulary

Host-Guest, Self-assembly, Supramolecular Assembly, Design, Control, Non covalent Interactions, Electrostatic Int., Anion-Π Int., Solvent effects,…

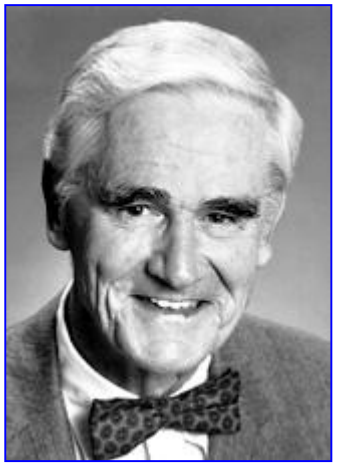
Molecular machines, containers, nanoscale flasks, nanoassemblies, supramolecular architectures, cages, trasporters, molecular magnets, nanoparticles, nanoballs, channels, tubes,…

Macrocycles, Cucubiturils, Helicates, Rotaxanes, Catenanes, Dendrimers..

Functional and complex nanomaterials and devices (smart materials, MOFs, polymers, gels, SAMs..)

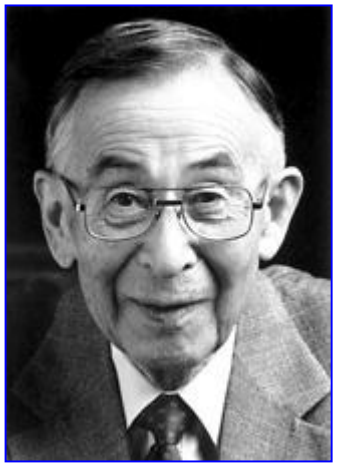
Imaging, Sensing, Recognition, Catalysis, Switching, …

Nobel Prize in Chemistry, 1987



Donald J. Cram

Jean-Marie Lehn



Charles J. Pedersen

«for their development and use of molecules with structure-specific interactions of high selectivity»

http://nobelprize.org/nobel_prizes/chemistry/laureates/1987/

The Nobel Prize in Chemistry, 2016

J-P. Sauvage

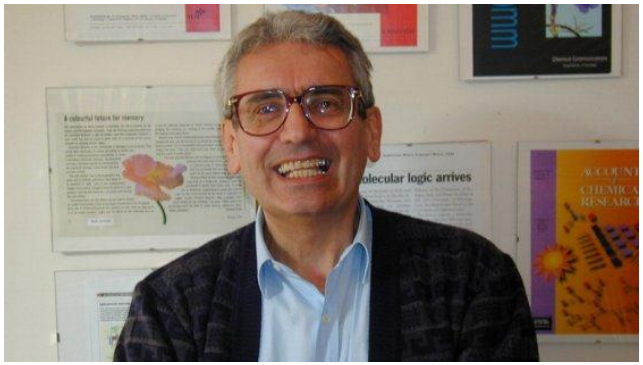
Sir J. F. Stoddart

B. L. Feringa

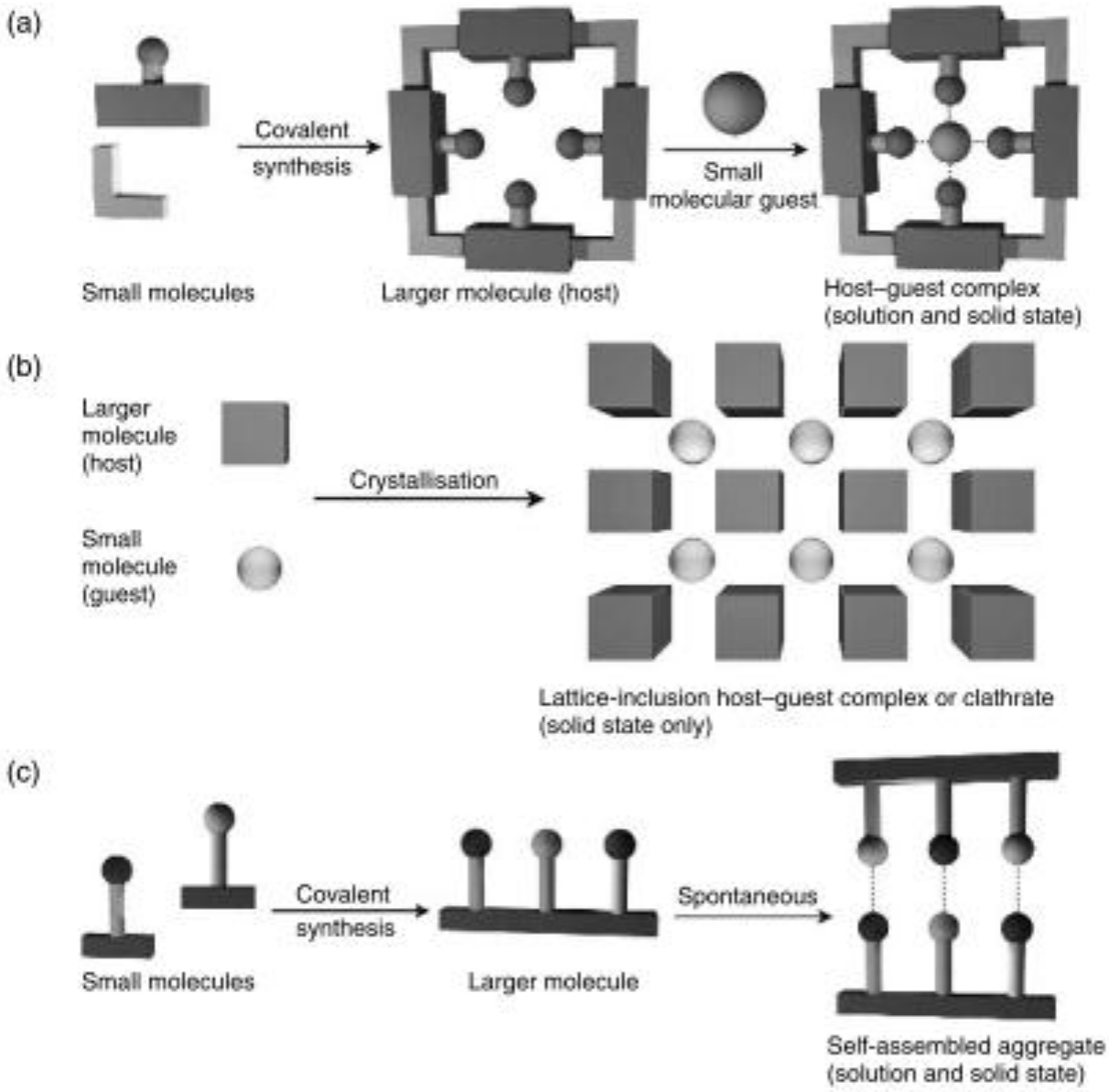
"for the design and synthesis of molecular machines"

https://www.nobelprize.org/nobel_prizes/chemistry/laureates/2016/

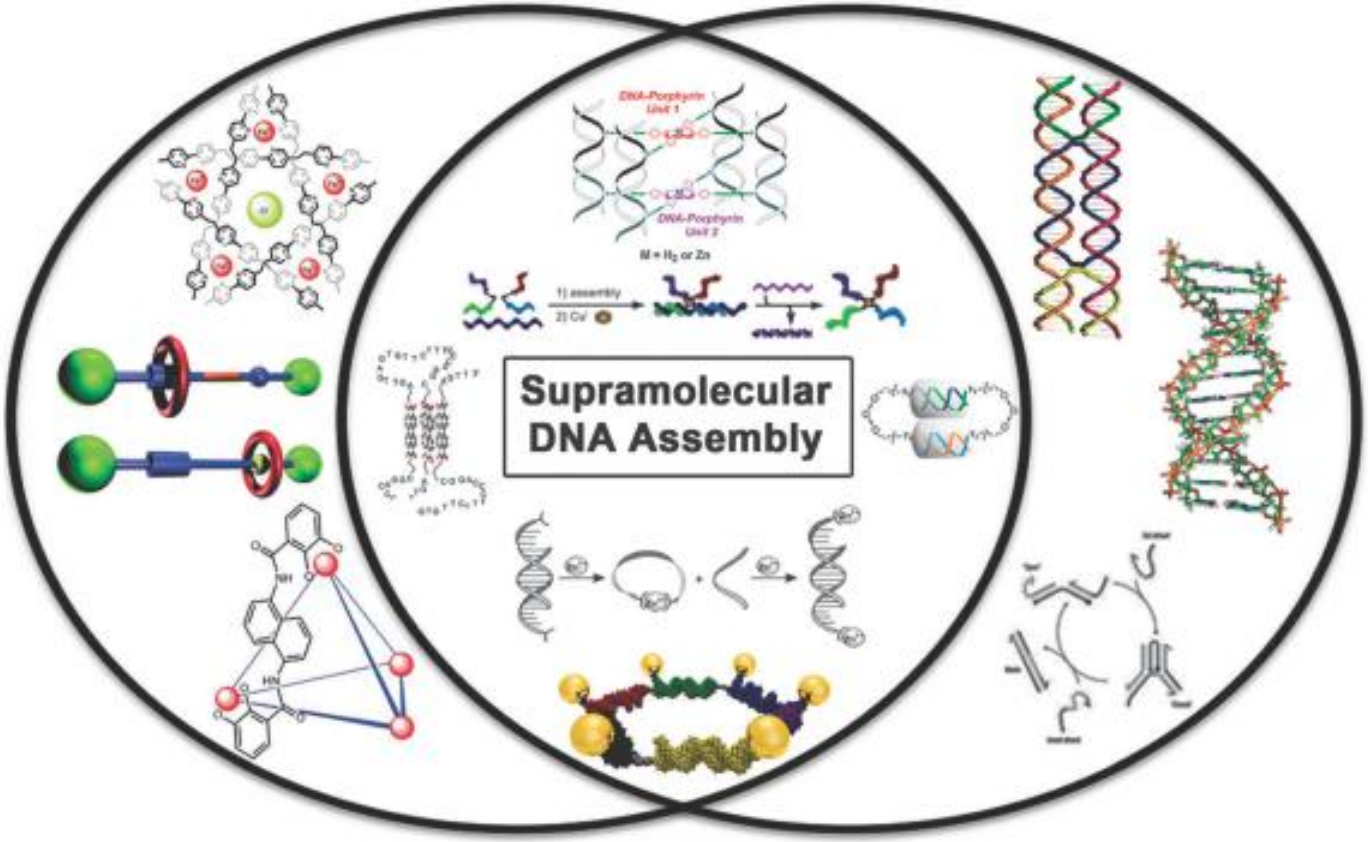
Chimica, il Nobel mancato



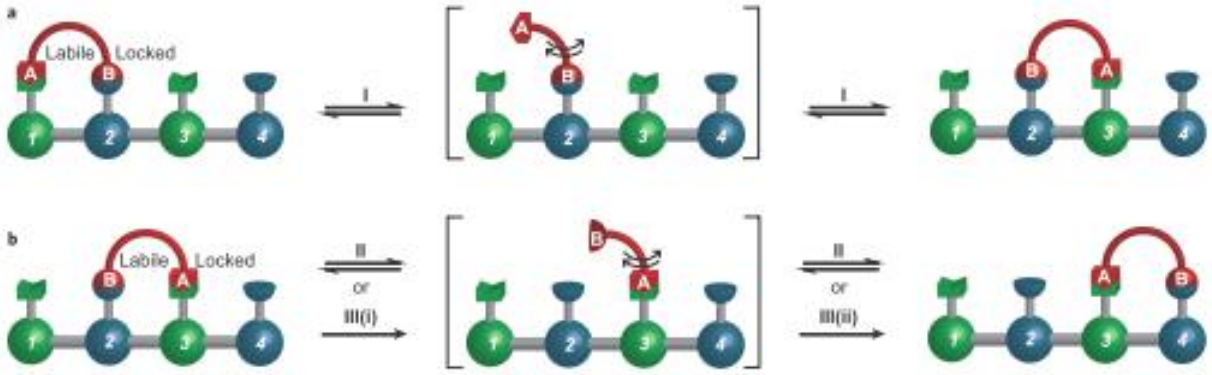
Prof. Vincenzo Balzani, docente emerito dell‘Università di Bologna


(a)
Covalent
synthesis
Small
molecular guest
Small molecules
Larger molecule (host)
Host–guest complex
(solution and solid state)
(b)
Larger
molecule
(host)
Small
molecule
(guest)
Crystallisation
Lattice-inclusion host–guest complex or clathrate
(solid state only)
(c)
Covalent
synthesis
Spontaneous
Small molecules
Larger molecule
Self-assembled aggregate
(solution and solid state)

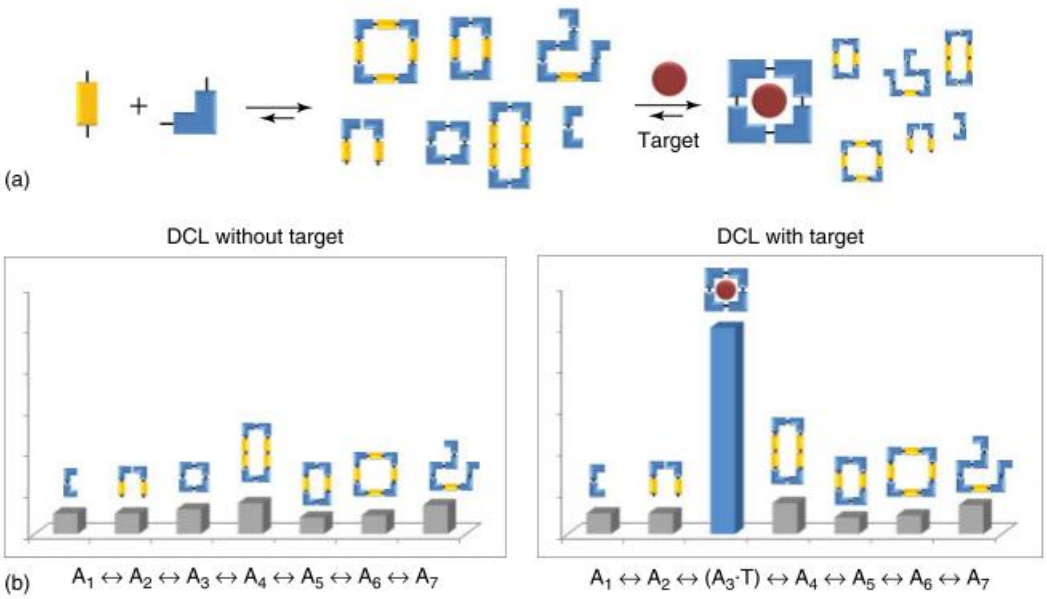
The bridge:
Supramolecular ARTIFICIAL and NATURAL systems

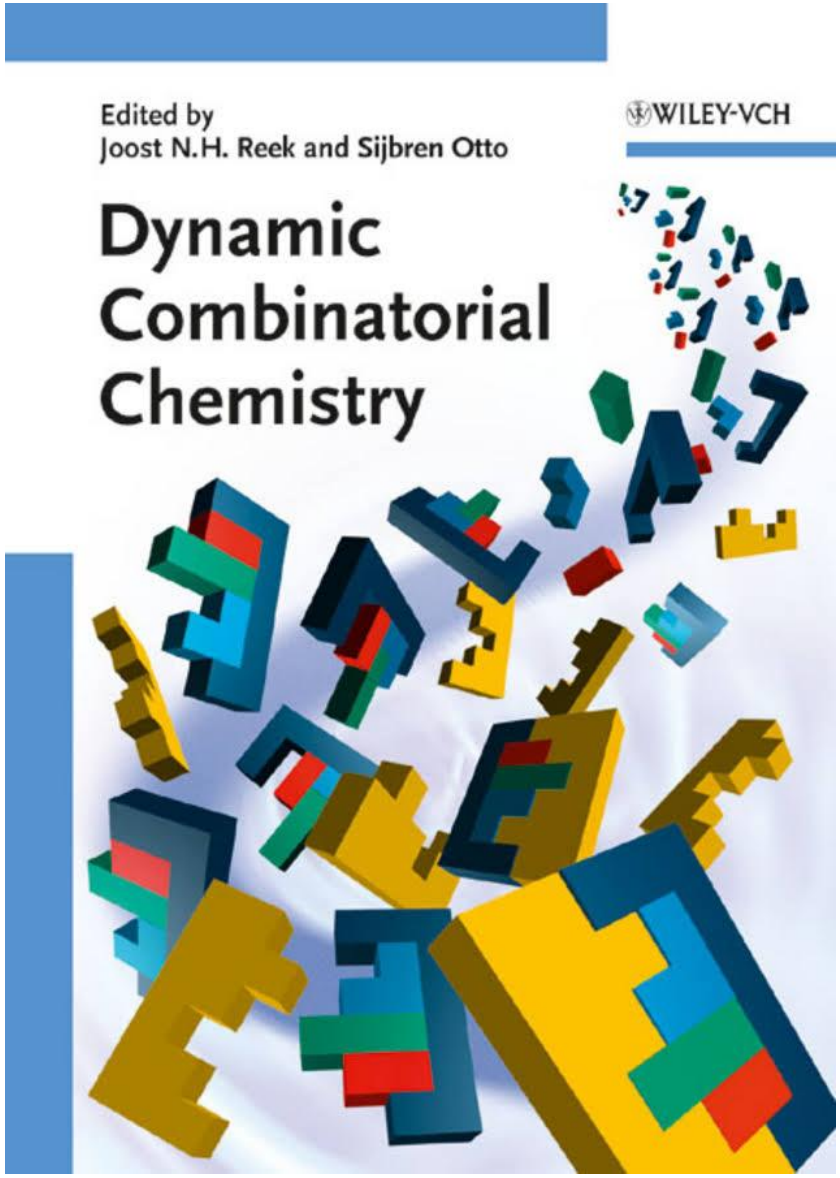


A synthetic molecule that CAN WALK DOWN A TRACK

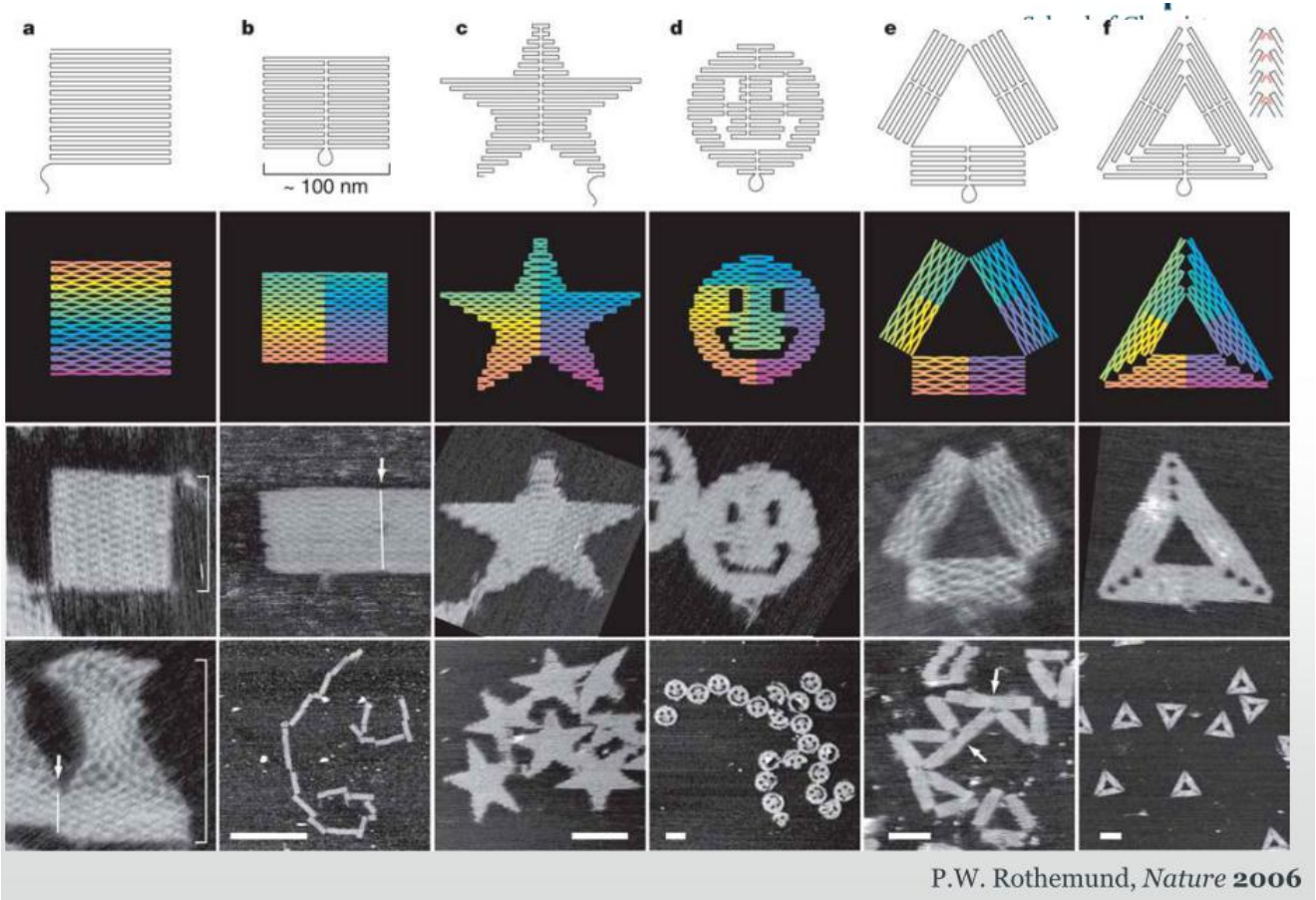


DYNAMIC COMBINATORIAL LIBRARIES

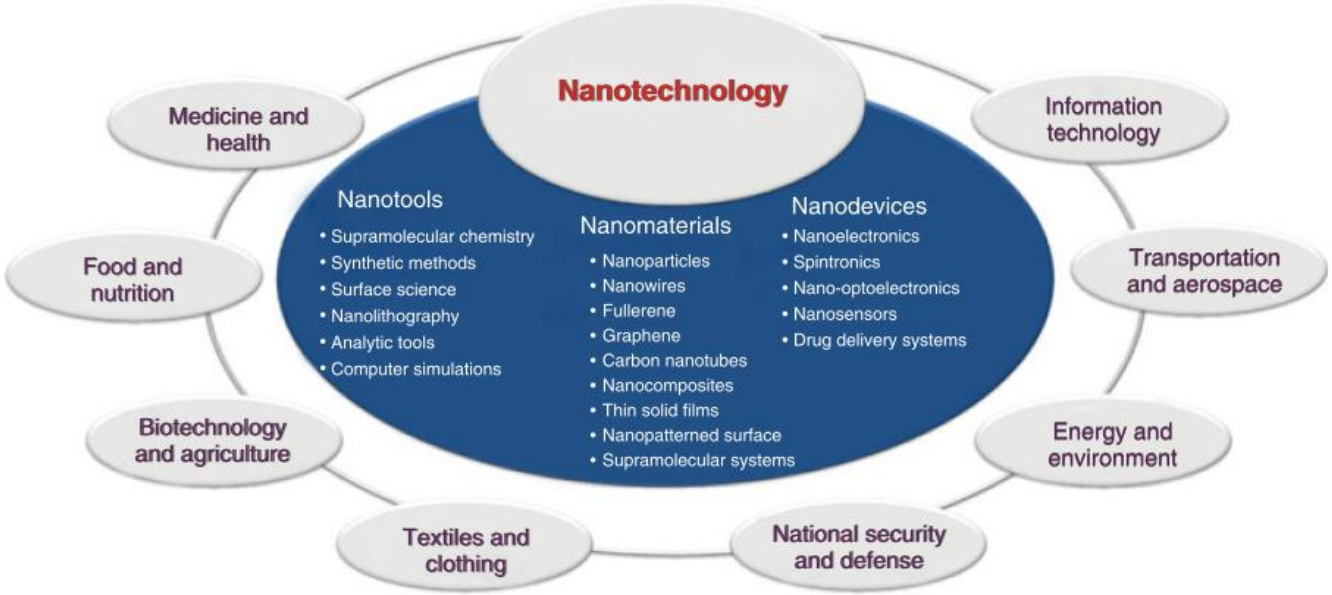



Edited by
Joost N.H. Reek and Sijbren Otto
WILEY-VCH
Dynamic
Combinatorial
Chemistry

Folding DNA to create NANOSCALE SHAPES AND PATTERNS



From Supramolecular Chemistry to Nanotechnology



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2. J. W. Steed, J. L. Atwood *Supramolecular Chemistry*, J. Wiley & Sons, UK, **2000**.

3. J. W. Steed, D. R. Turner, K. J. Wallace *Core Concepts in Chemistry and Nanochemistry*, Wiley, Chichester, **2007**.

4. H.-J. Schneider, A. Yatsimirsky *Principles and Methods in Supramolecular Chemistry*, J. Wiley & Sons, UK, **2000**.

5. L. F. Lindoy, I. M. Atkinson *Self-Assembly in Supramolecular Chemistry*, in *Monograms in Supramolecular Chemistry*, J. F. Stoddart ed., Royal Society of Chemistry, UK, **2000**.

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9. P. W. N. M. Van Leeuwen Supramolecular Catalysis, Wiley-VCH, Weinheim (Germany), **2008**.

10. J.-P. Sauvage (Ed.) Perspectives in Supramolecular Chemistry, Wiley-VCH, Weinheim (Germany), **2007**.

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Core Concepts in Supramolecular Chemistry and Nanochemistry

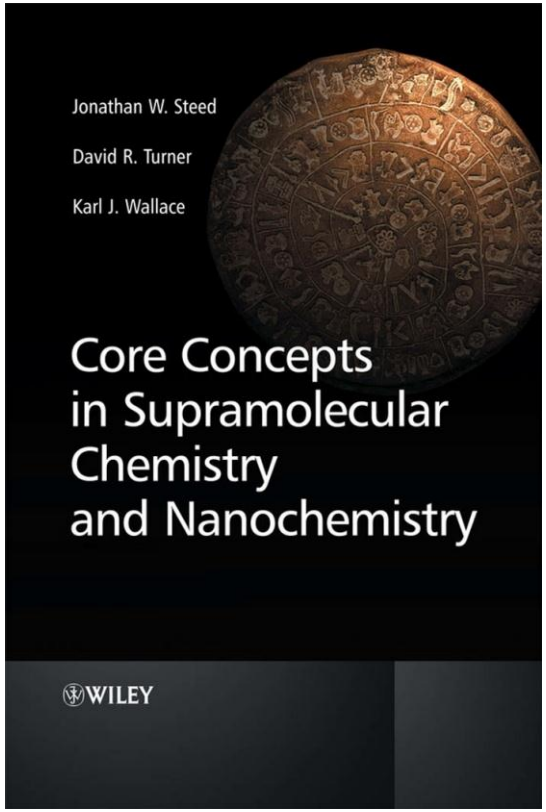
Jonathan W. Steed,
Durham University, UK

David R. Turner,
Monash University, Australia

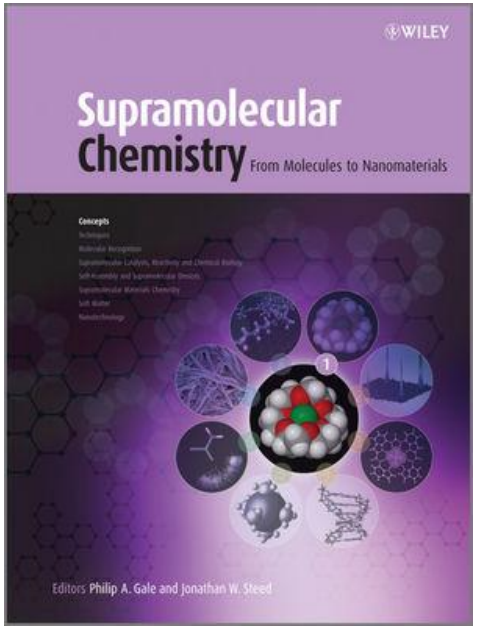
Karl J. Wallace,
University of Southern Mississippi, USA

BICENTENNIAL 1807 WILEY 2007 BICENTENNIAL

John Wiley & Sons, Ltd



Bibliography



Supramolecular Chemistry: From Molecules to Nanomaterials, 8 Volume Set
Jonathan W. Steed (Editor-in-Chief), Philip A. Gale (Editor-in-Chief), Wiley.

Programma

Interazioni non covalenti

Recettori 1

cationi/anioni/molecole neutre

Metodi Analitici

Recettori 2

Cavitandi/Contenitori molecolari

- Covalenti

-Auto-assemblati (legami H, legami M, legami covalenti dinamici)

-Applicazioni: isolamento di intermedi instabili; reattività nello spazio confinato; catalisi

Programma

Chimica Topologica

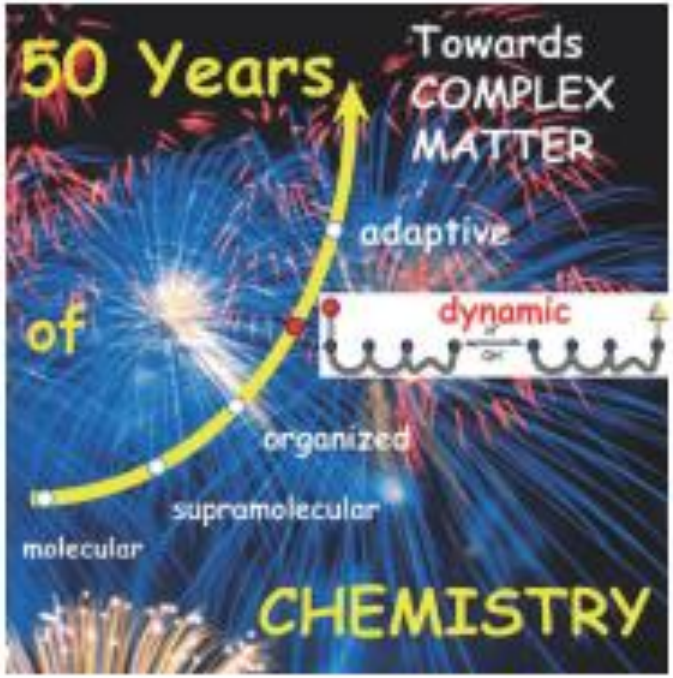
Elicati/Catenani/Rotaxani/Nodi

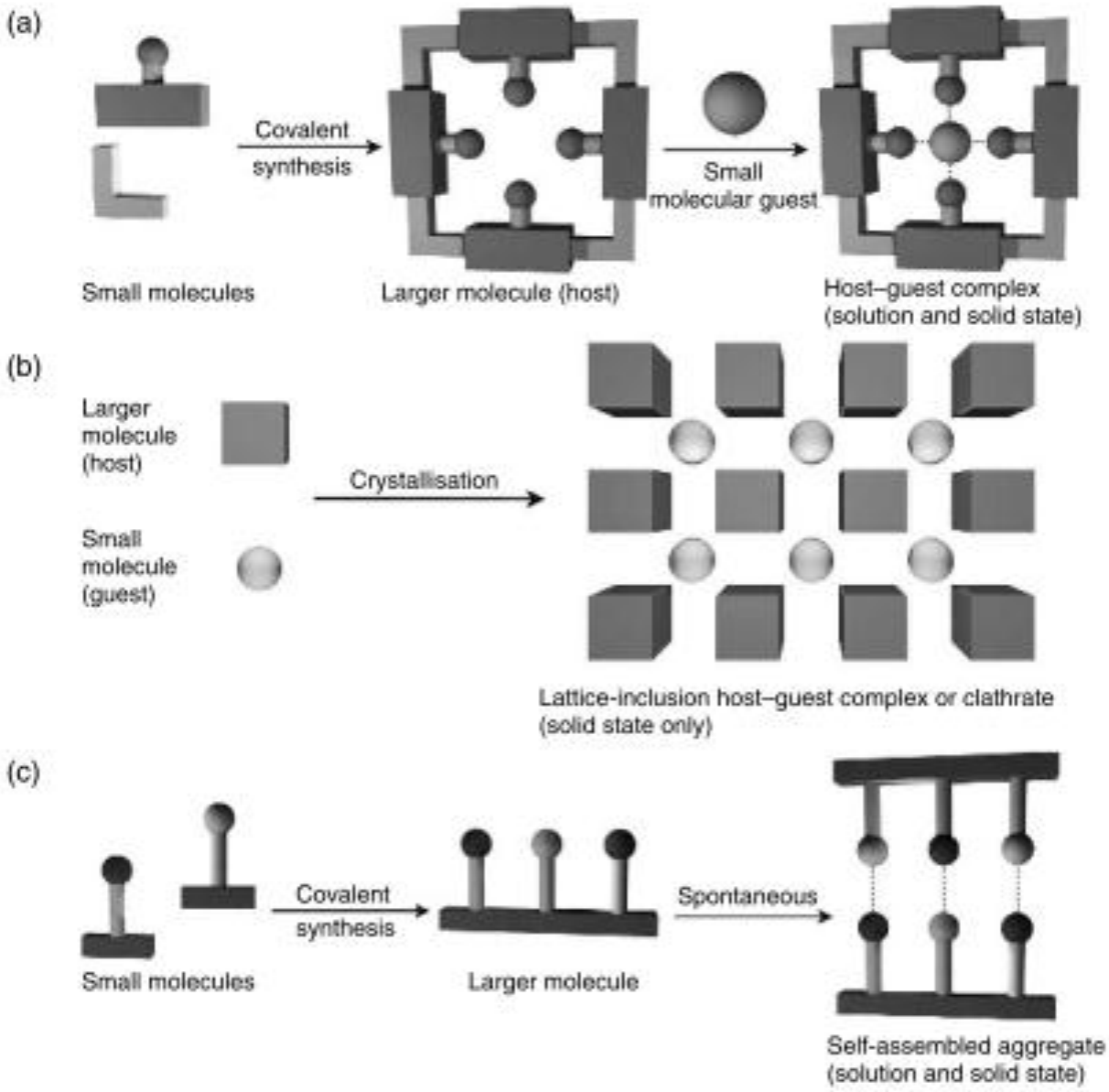
Dispositivi e Macchine molecolari

Determinazione delle Costanti di Associazione
(Prof. P. Tecilla 4h)

Sensori **Dynamic Combinatorial Chemistry**

(Prof. P. Pengo 3h)

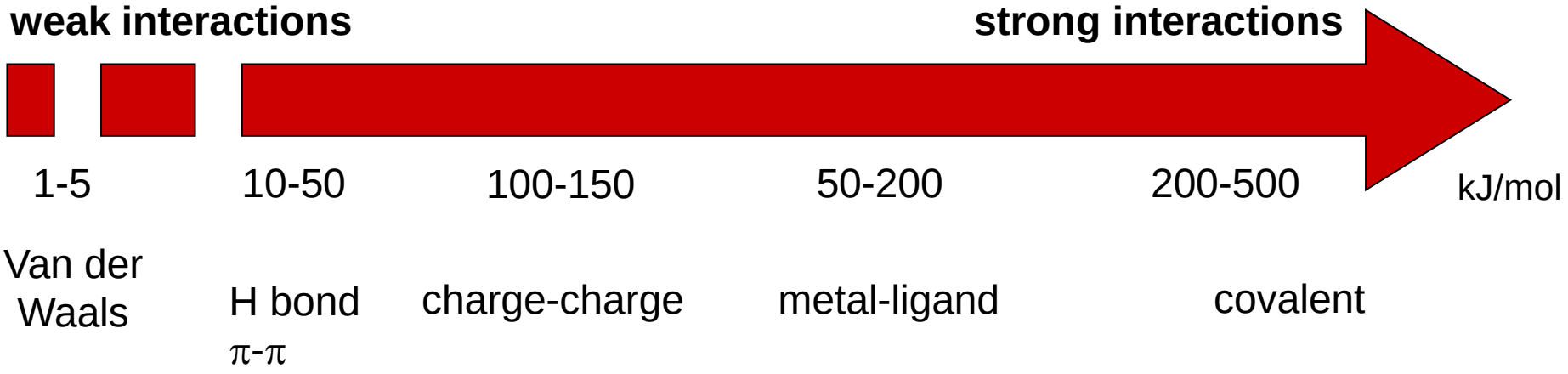

50 Years
of
Towards
COMPLEX
MATTER
adaptive
dynamic
organized
supramolecular
molecular
CHEMISTRY


(a)
Covalent
synthesis
Small
molecular guest
Small molecules
Larger molecule (host)
Host–guest complex
(solution and solid state)
(b)
Larger
molecule
(host)
Small
molecule
(guest)
Crystallisation
Lattice-inclusion host–guest complex or clathrate
(solid state only)
(c)
Covalent
synthesis
Spontaneous
Small molecules
Larger molecule
Self-assembled aggregate
(solution and solid state)

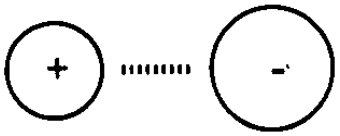
Weak (Reversible) Intermolecular Interactions

- Electrostatic
- π-π
- Cation-π/ Anion-π/CH-π
- H Bonding
- Halogen Bonding
- Metal-Ligand Coordination
- Reversible Covalent Bonding
- Chelate Effect
- Macrocyclic Effect
- Hydrophobic Effect

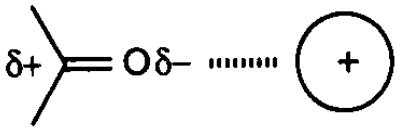
Weak Intermolecular Interactions



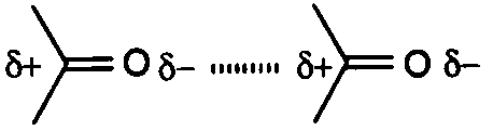
Electrostatic Interactions



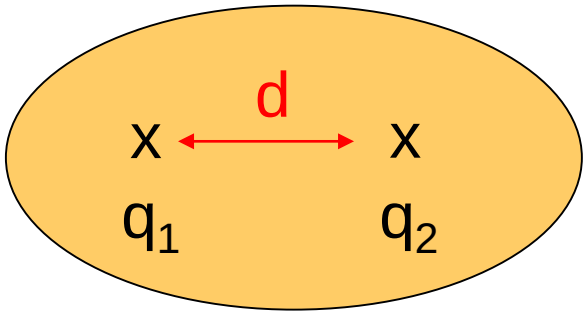
Charge-Charge Interactions 100-350 kJ/mol



Dipole-Charge Interactions 50-200 kJ/mol



Dipole-Dipole Interactions 5-50 kJ/mol



$$W = \frac{1}{4\pi\varepsilon_0}\frac{q_1 q_2}{\varepsilon d} \text{ (J)}$$

vacuum permittivity

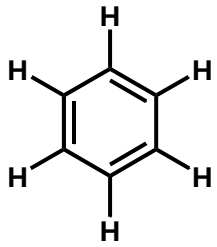
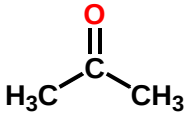
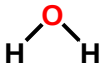
dielectric constant (nature of solvant)

ε(vacuum) = 1

apolar medium ⇔ ε small (~ 2)

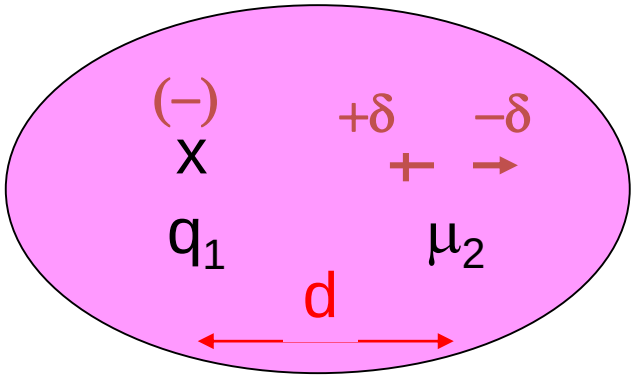
polar medium ⇔ ε big (H_2O ~ 80)

dielectric constant of the solvant

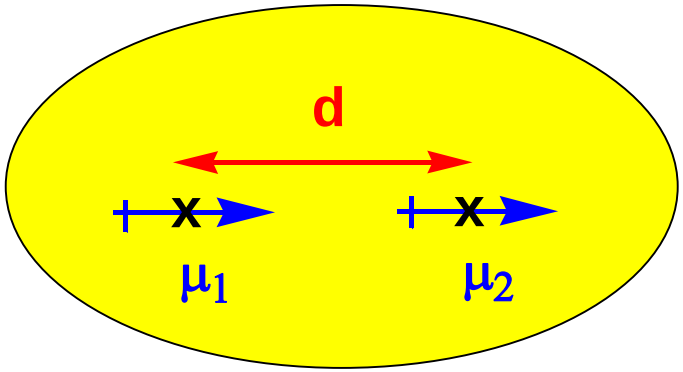
		ε	
Benzene		2,3	apolar
Acetone		20,7	
Ethanol	CH_3CH_2OH	24,3	
water		78,5	polar

ε = 78.5 d = 0.5 nm => W = 3.75 kJ.mol^{-1}

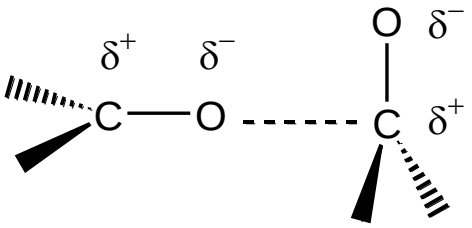
ε = 2 d = 0.5 nm => W = 140 kJ.mol^{-1}

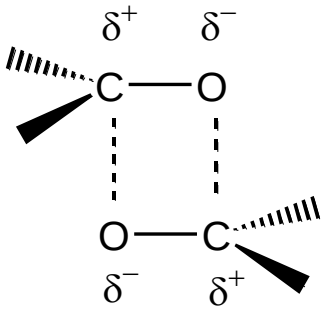


$$W = - C^{te} \times \frac{|q|\mu_2}{\varepsilon d^2}$$

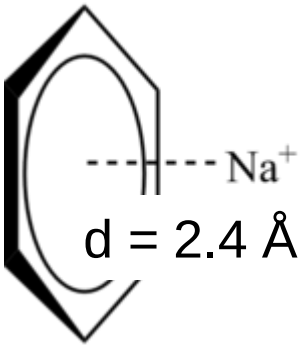


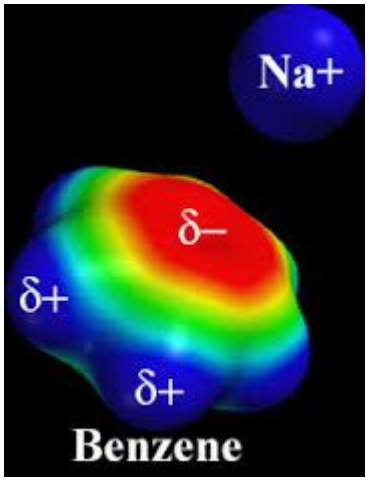
$$W = - C^{te} \frac{\mu_1 \mu_2}{\varepsilon d^3}$$

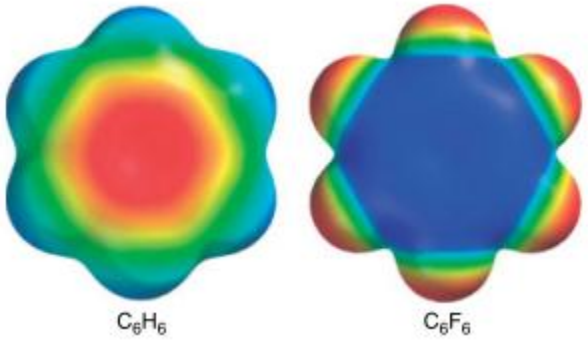




Cation-π Interactions

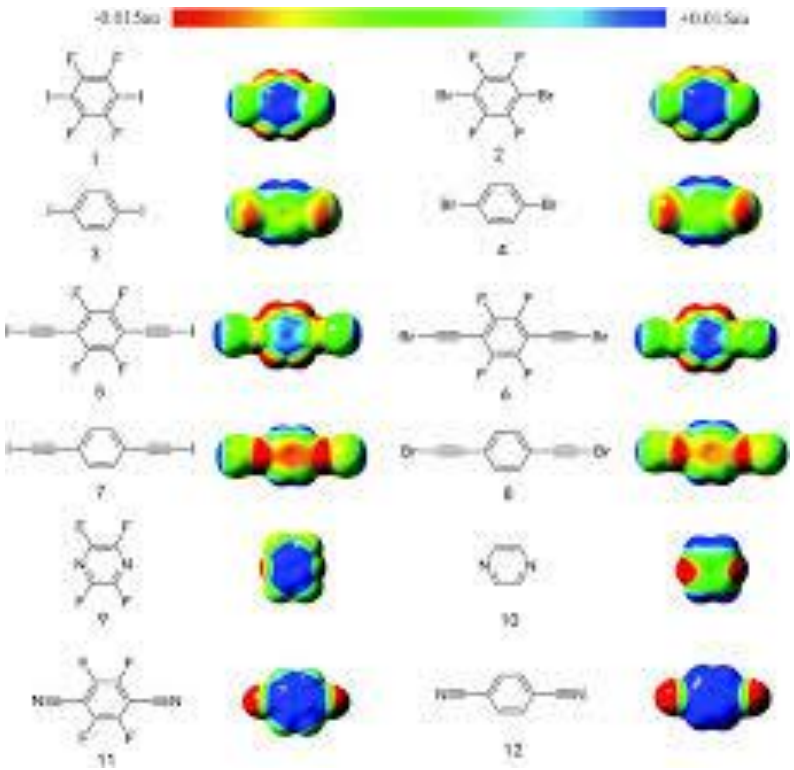




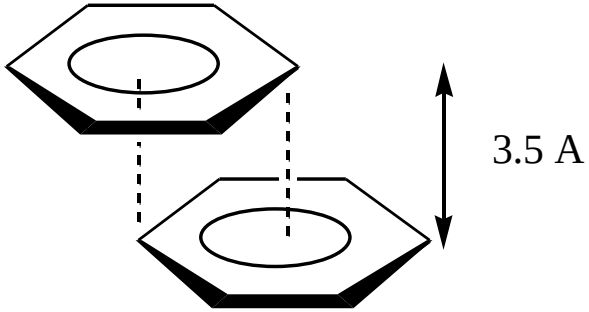


Anion-π Interactions

Proposed by three research groups of theoreticians independently in 2002 based on their theoretical calculations, anion −π interactions are defined as attractive interactions between negatively charged species and electron-deficient aromatic rings.
Typical anion−π interaction indicates the attraction of an anion species to the centroid of an aromatic ring.
In comparison to a plethora of theoretical calculations of anion−π interactions, experimental studies on these intriguing noncovalent bond interactions are limited.



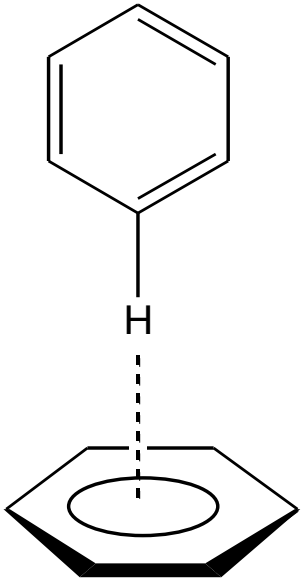
π-π Interactions up to 50 kJ/mol

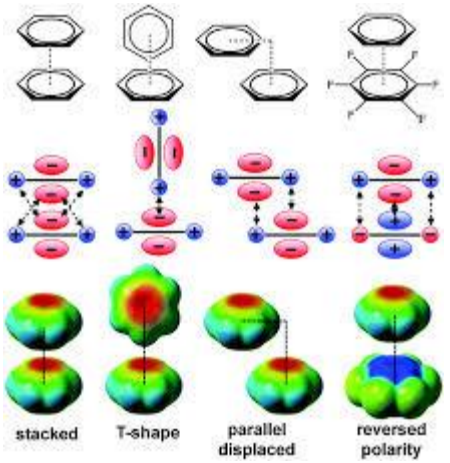


face to face

3.5 A

edge to face

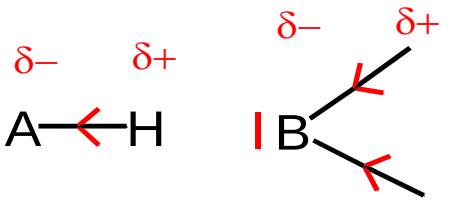




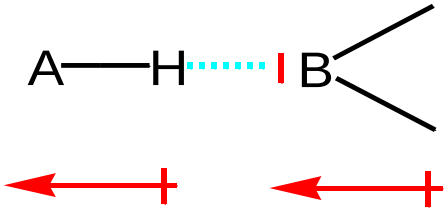
C.A. Hunter and J.K.M. Sanders, ***The Nature of π - π interactions***, *J. Am. Chem. Soc.,* **1990**, *112*, 5525;

E.-I. Kim, S. Paliwal and C.S. Wilcox, ***Measurements of molecular electrostatic field effects in edge-to-face aromatic interactions and CH- π interactions with implications for protein folding and molecular recognition***, *J. Am. Chem. Soc*., **1998**, *120*, 11192.

H Bond 4-120 kJ/mol



A, B electronegative or electrondeficient atoms



permanent dipoles

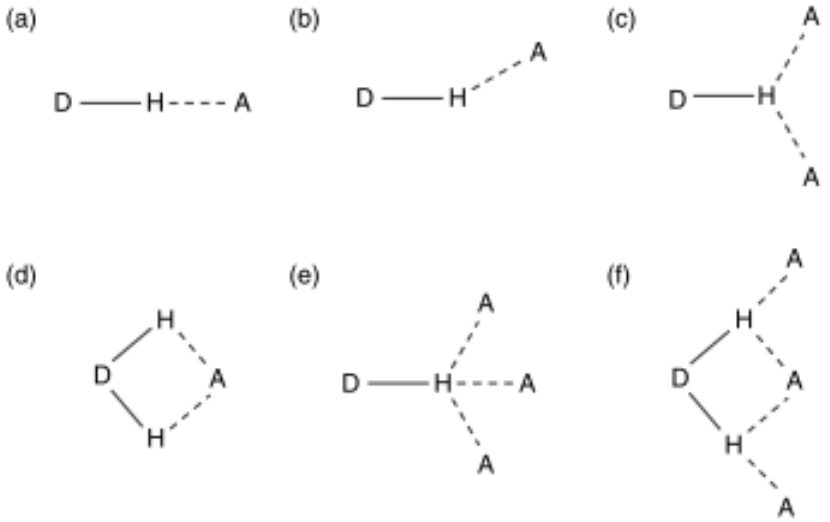


Table 1.5 Properties of hydrogen bonded interactions.

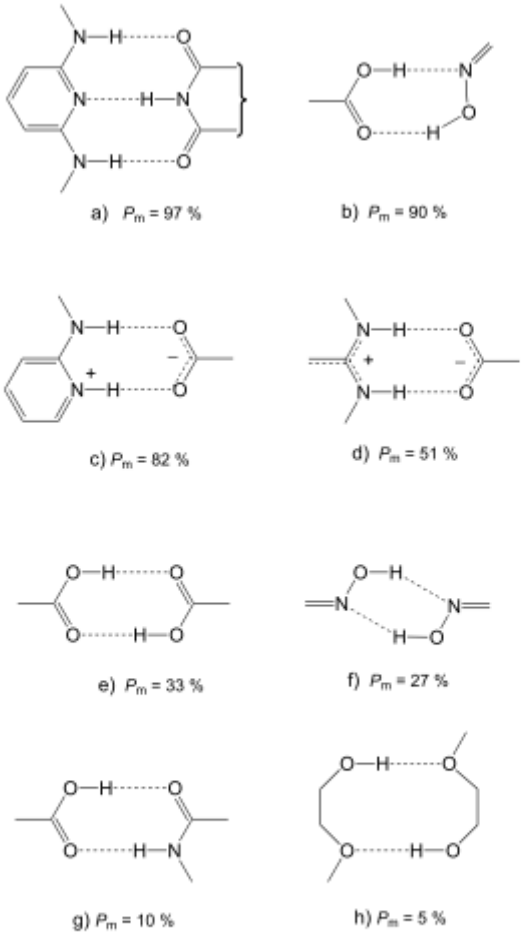
	Strong	Moderate	Weak
A–H···B interaction	Mainly covalent	Mainly electrostatic	Electrostatic
Bond energy ($kJ\,mol^{-1}$)	60–120	16–60	<12
Bond lengths (Å)			
H···B	1.2–1.5	1.5–2.2	2.2–3.2
A···B	2.2–2.5	2.5–3.2	3.2–4.0
Bond angles (°)	175–180	130–180	90–150
Relative IR vibration shift (stretching symmetrical mode, cm^{-1})	25%	10–25%	<10%
^1H NMR chemical shift downfield (ppm)	14–22	<14	?
Examples	Gas phase dimers with strong acids/bases Proton sponge HF complexes	Acids Alcohols Biological molecules	Minor components of bifurcated bonds C–H hydrogen bonds O–H···π hydrogen bonds

G.A. Jeffrey, ***An Introduction to Hydrogen Bonding,*** Oxford University Press: Oxford, **1997**.

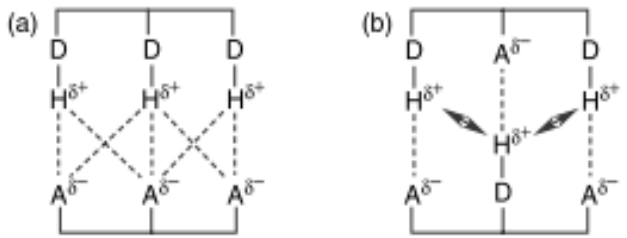
The Hydrogen Bond in the Solid State

Thomas Steiner*

Angew. Chem. Int. Ed. **2002**, *41*, 48 – 76



Scheme 17. Eight examples of intermolecular hydrogen bond motifs with their probability of formation (P_m) in crystals.[122] Notice that P_m of the carboxy – oxime heterodimer (b) is much higher than that of the carboxylic acid (e) and oxime homodimers (f).

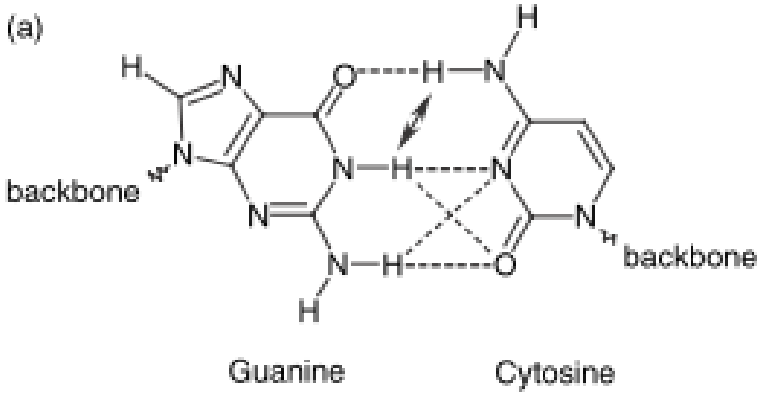


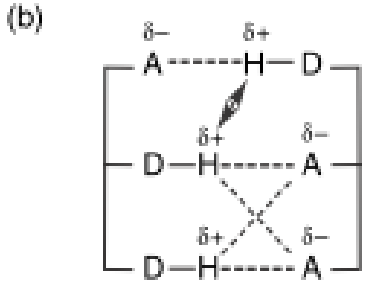
D Donor

A Acceptor

Attractive interaction

Repulsive interaction





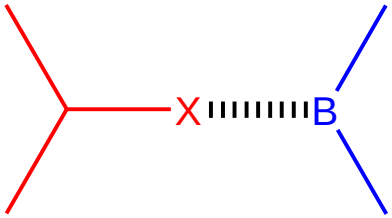
Halogen Bond

In 2009 the International Union of Pure and Applied Chemistry (IUPAC) started a project (project no. 2009-032-1-100) having the aim “ to take a comprehensive look at intermolecular interactions involving halogens as electrophilic species and classify them”
http://www.halogenbonding.eu/
http://www.iupac.org/web/ins/2009-032-1-100

An IUPAC recommendation defining these interactions as halogen bonds was issued in 2013 when the project was concluded: This definition states that

“ A halogen bond occurs when there is evidence of a net attractive interaction between an electrophilic region associated with a halogen atom in a molecular entity and a nucleophilic region in another, or the same, molecular entity. ”

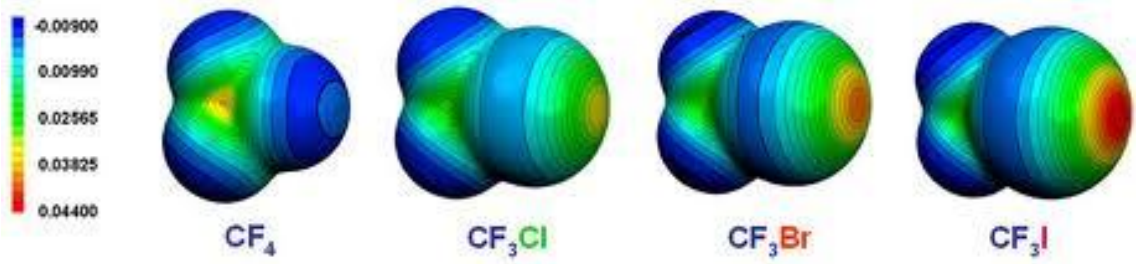
Halogen Bond



B : Lewis base (neutral or anionic)

X : electron-poor halogen atom

- Very directional (180°, but also other geometries)
- As strong as H-bond
- Often encountered in solid state, more rarely in solution



molecule	atom	bond producing a σ-hole
H_3C-F	F	C−F
H_3C-Cl	Cl	C−Cl
H_3C-Br	Br	C−Br
H_3C-I	I	C−I
F_3C-F	F	C−F
F_3C-Cl	Cl	C−Cl
F_3C-Br	Br	C−Br
F_3C-I	I	C−I
NC−F	F	C−F
NC−Cl	Cl	C−Cl
NC−Br	Br	C−Br
NC−I	I	C−I
		Dihalogens
F−F	F	F−F
Cl−Cl	Cl	Cl−Cl
Br−Br	Br	Br−Br
		Focus on Bromine
Br—C≡C—Br	Br	C−Br
H_3Si-Br	Br	C−Br
F_3Si-Br	Br	Si−Br
H_3Ge-Br	Br	Ge−Br
H_2N-Br	Br	N−Br
F_2N-Br	Br	N−Br
H_2P-Br	Br	P−Br
F_2P-Br	Br	P−Br
HO−Br	Br	O−Br
FO−Br	Br	O−Br
HS−Br	Br	S−Br
FS−Br	Br	S−Br
F−Br	Br	F−Br
Cl−Br	Br	Cl−Br

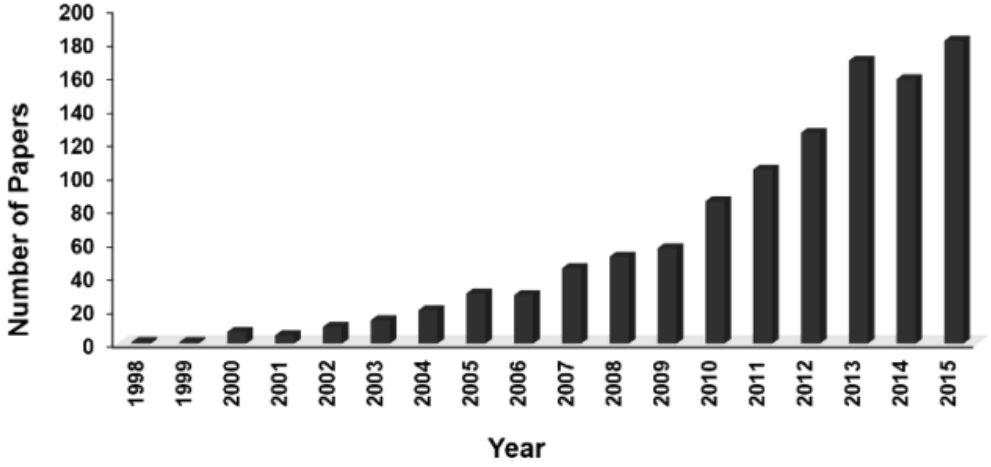


Figure 5. Number of papers per year having "halogen bonding" in the title and/or abstract (source SciFinder, search performed in November 2015).

CHEMICAL REVIEWS

Review

pubs.acs.org/CR

DOI: 10.1021/acs.chemrev.5b00484

The Halogen Bond

Gabriella Cavallo,[†] Pierangelo Metrangolo,*[,†,‡] Roberto Milani,[‡] Tullio Pilati,[†] Arri Priimagi,[§] Giuseppe Resnati,*[,†] and Giancarlo Terraneo[†]

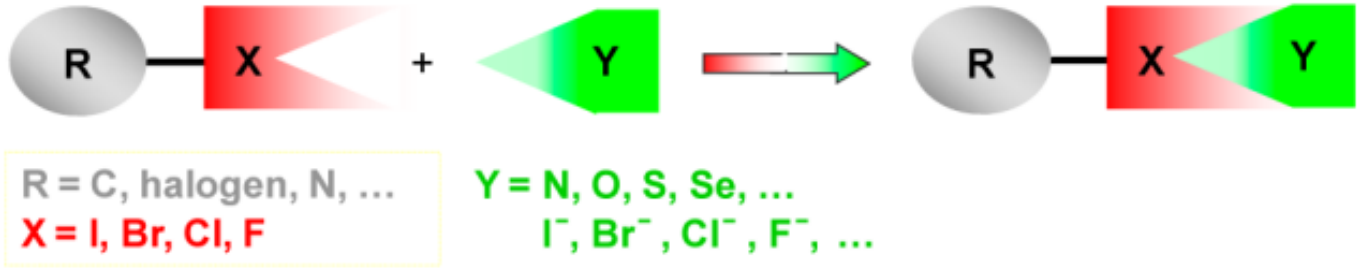


Figure 1. Schematic representation of the halogen bond.

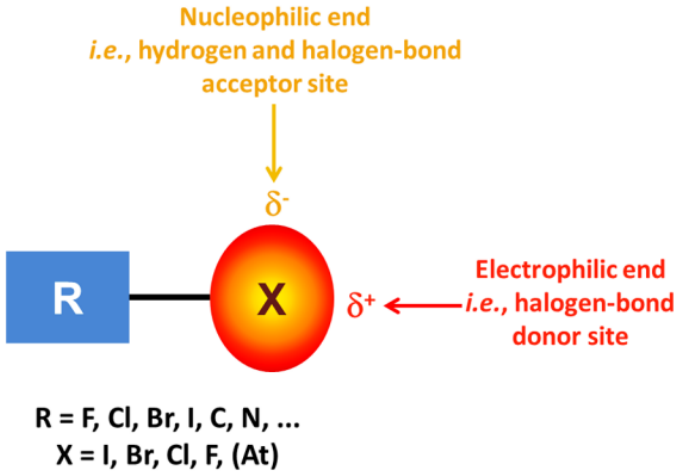
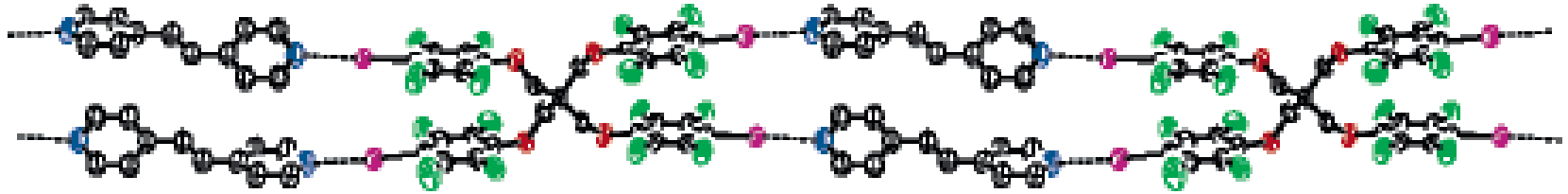
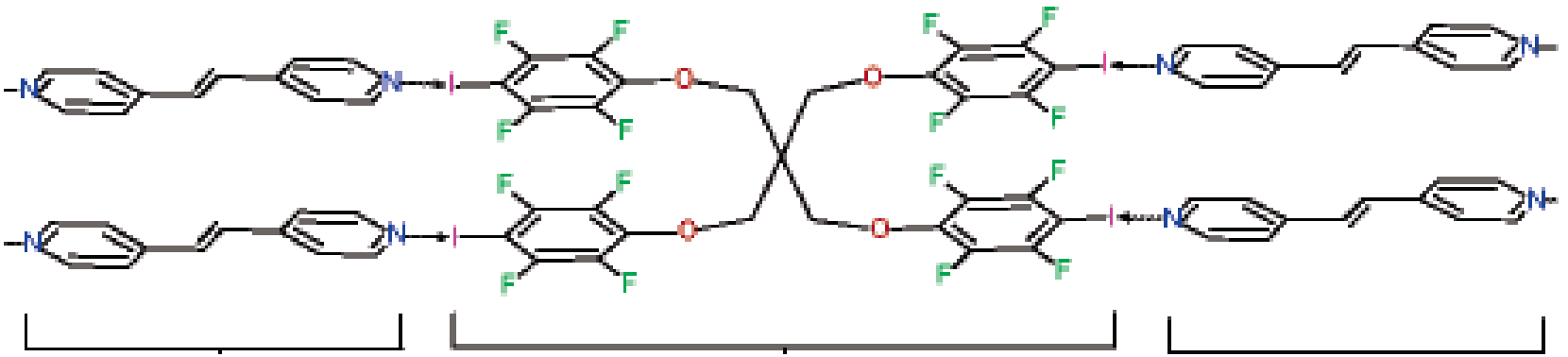
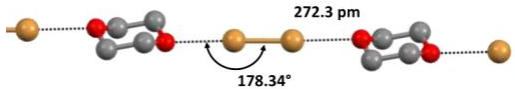


Figure 21. Schematic representation of the anisotropic distribution of the electron density around covalently bound halogen atoms and the pattern of the resulting interactions.

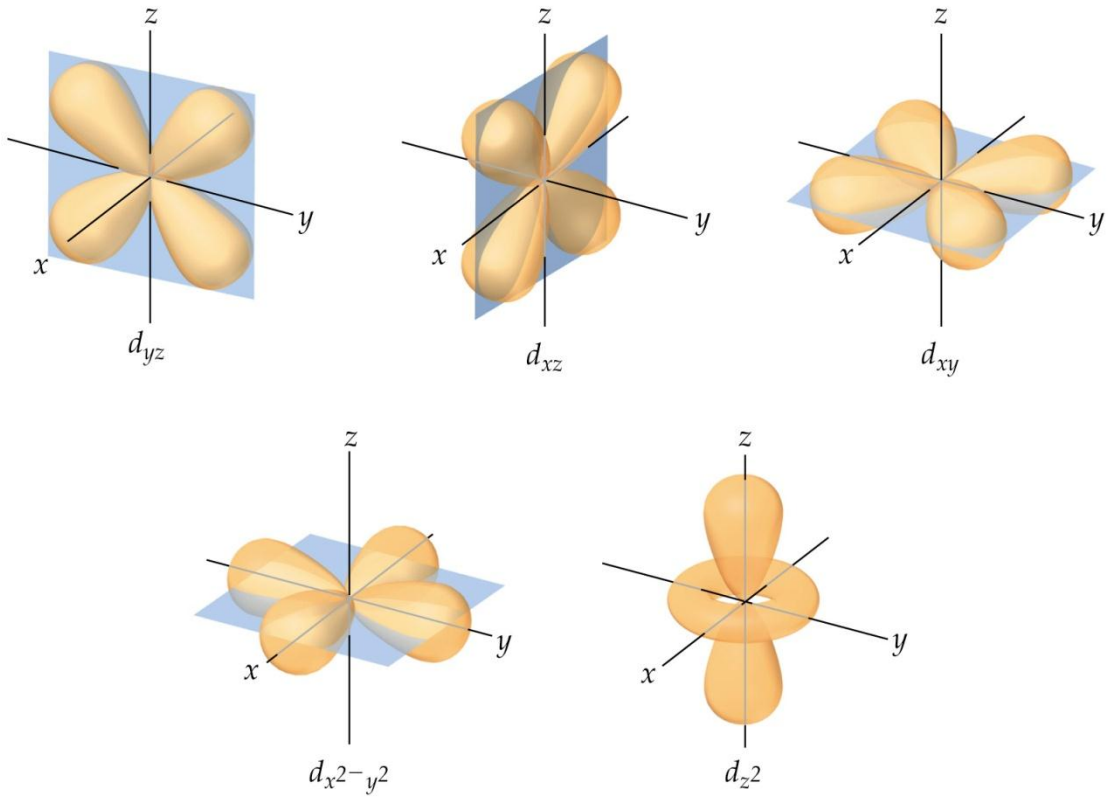


14

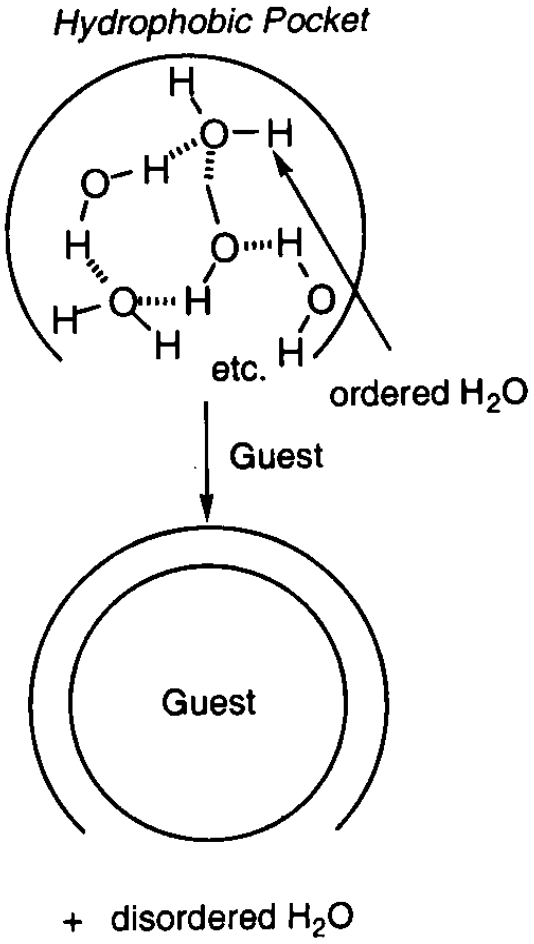


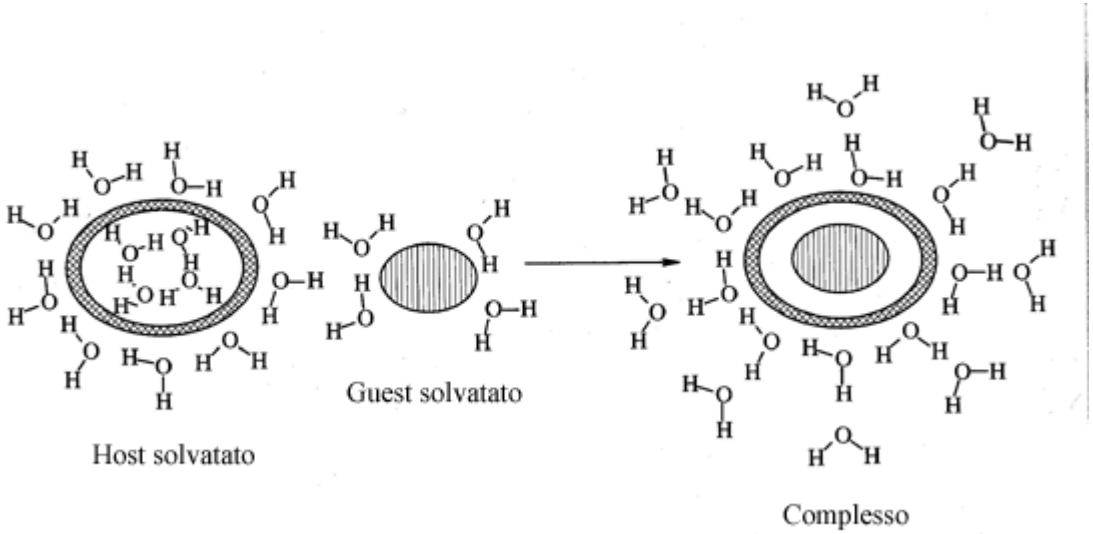


Metal-Ligand Interaction



Hydrophobic Effect





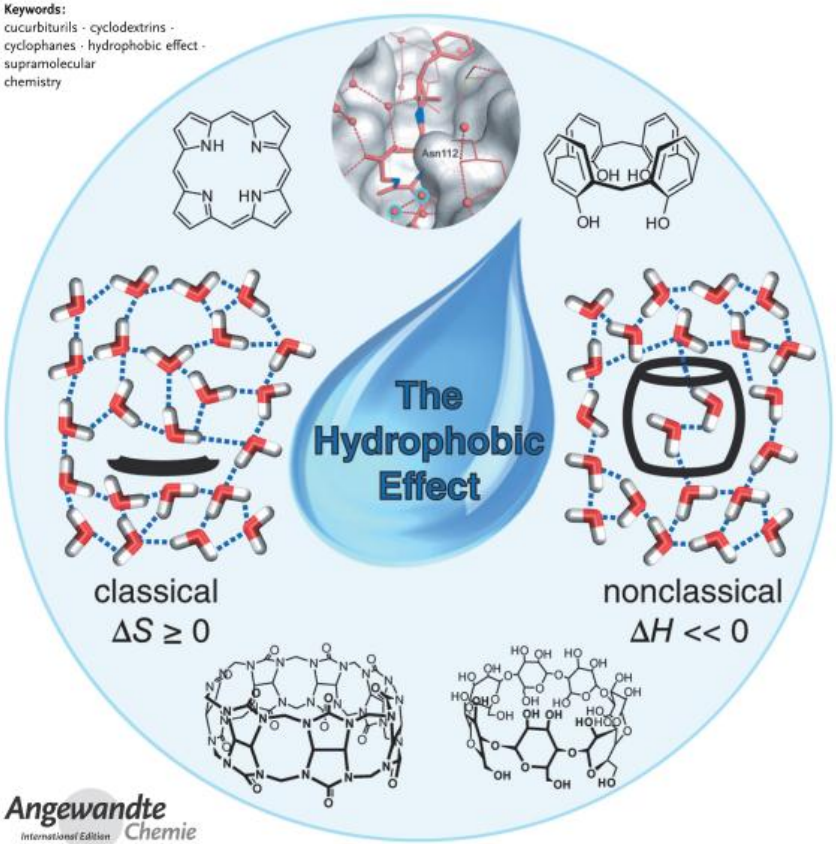
Hydrophobic Effect

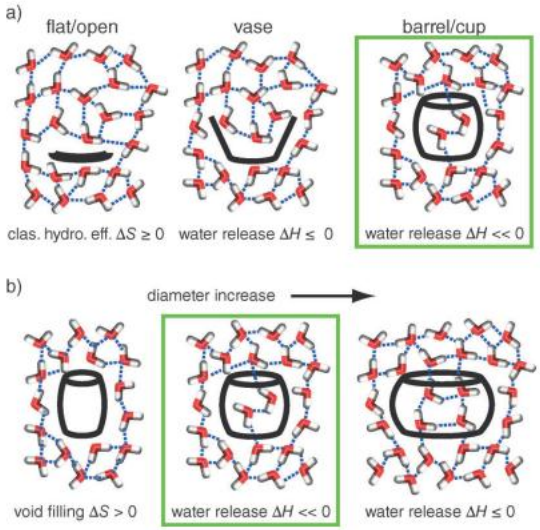
DOI: 10.1002/anie.201310958

The Hydrophobic Effect Revisited—Studies with Supramolecular Complexes Imply High-Energy Water as a Noncovalent Driving Force

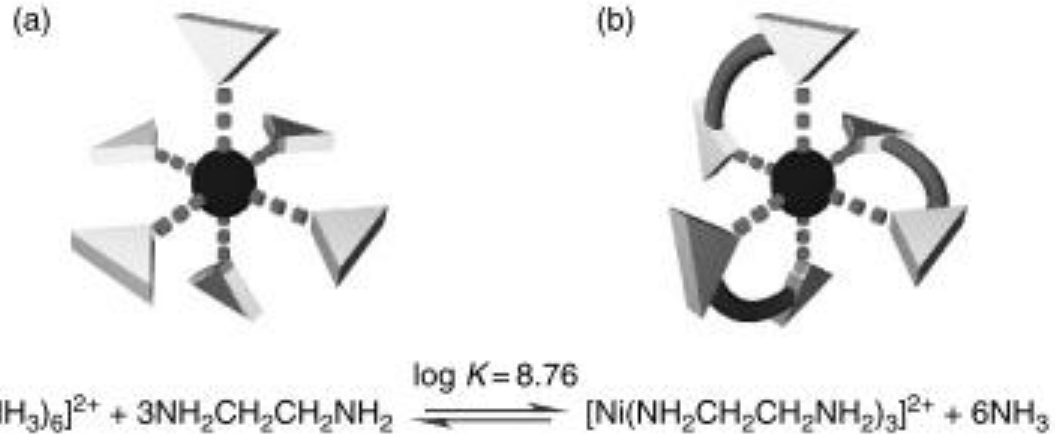
Frank Biedermann, Werner M. Nau,* and Hans-Jörg Schneider**

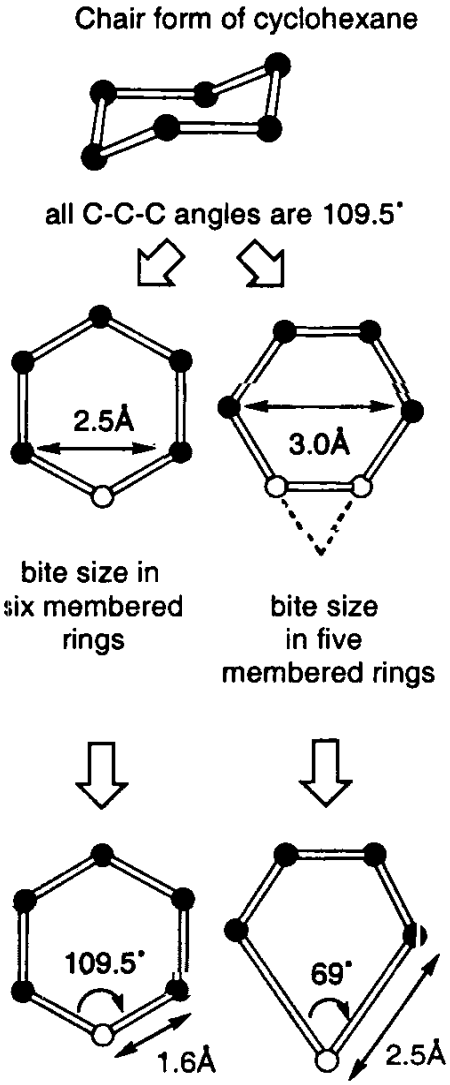
Keywords:
cucurbiturils · cyclodextrins · cyclophanes · hydrophobic effect · supramolecular chemistry



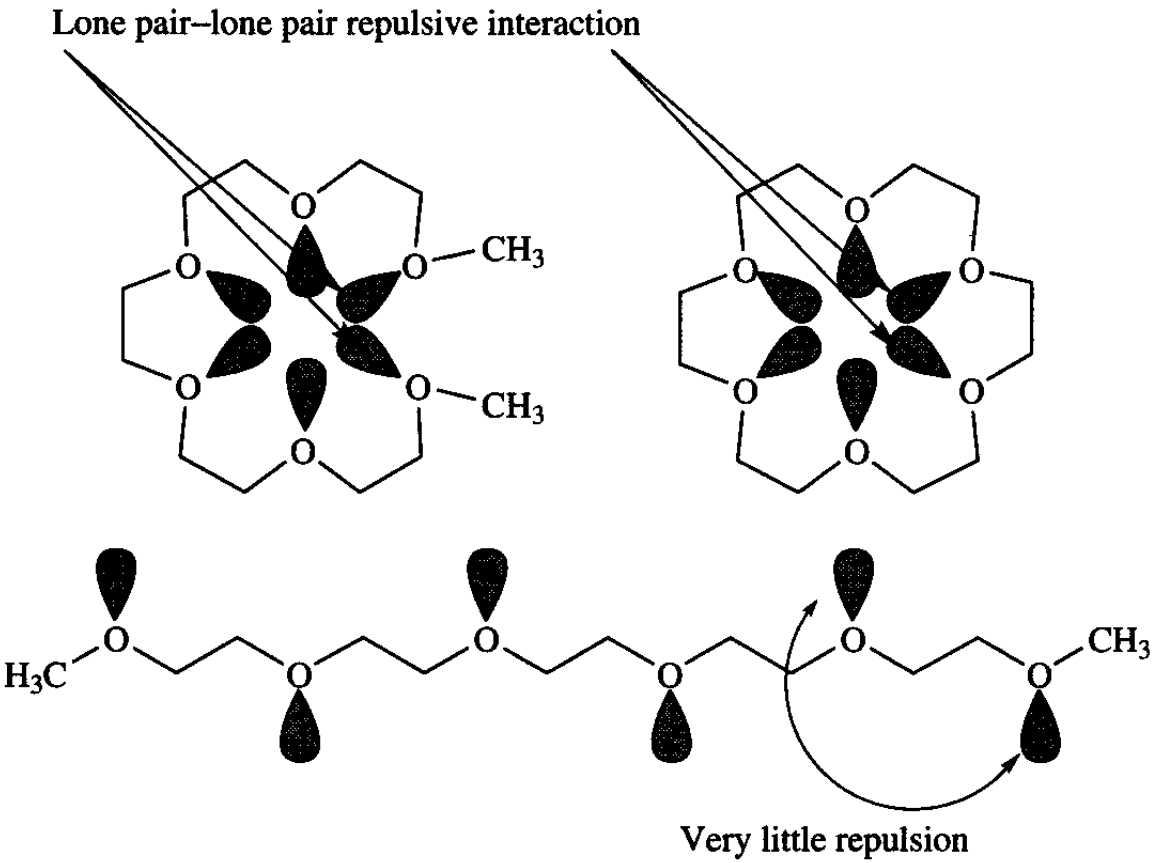

a)
flat/open
vase
barrel/cup
clas. hydro. eff. ΔS ≥ 0
water release ΔH ≤ 0
water release ΔH << 0
b)
diameter increase
void filling ΔS > 0
water release ΔH << 0
water release ΔH ≤ 0

Chelate Effect

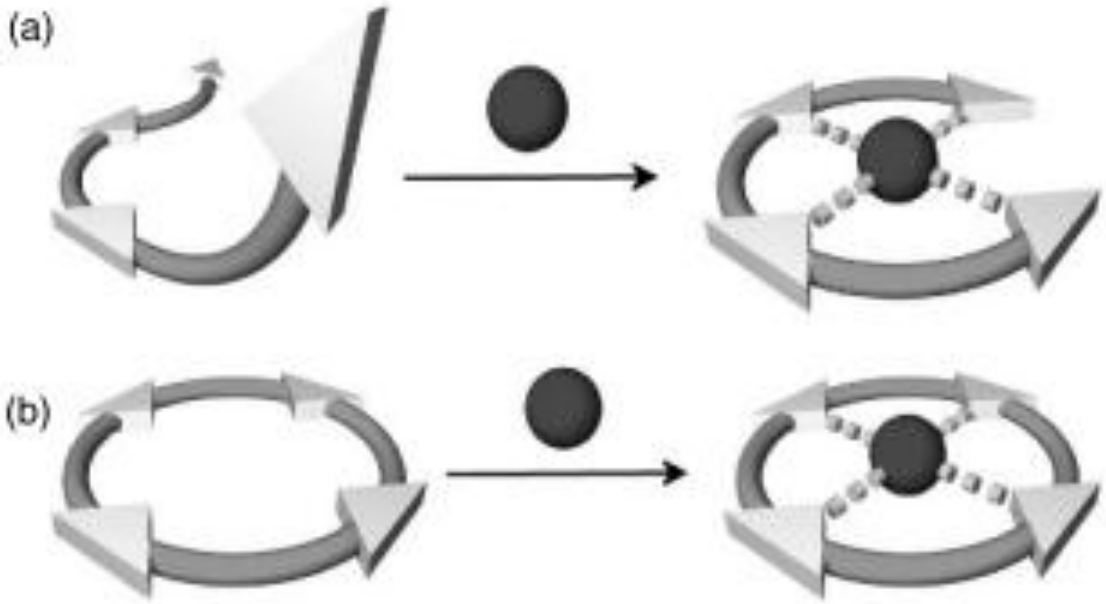


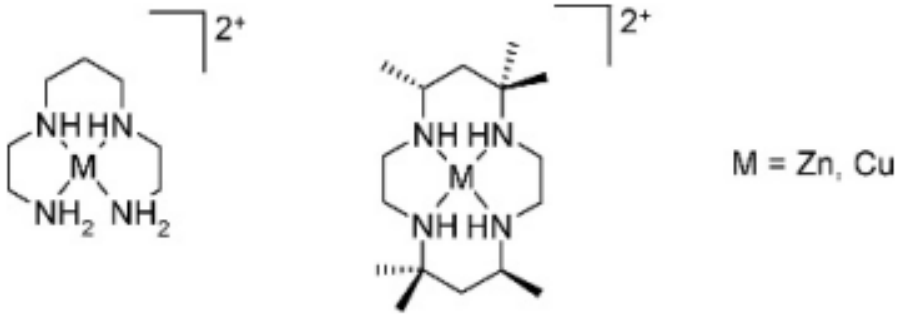


Macrocyclic Effect



Macrocyclic Effect





Stabilià: Sistema Ciclico 10^4 superiore Sistema Aciclico

Chelate and Macrocyclic Effects

$$[Ni(H_2O)_6]^{2+} + 6NH_3 = [Ni(NH_3)_6]^{2+} + 6H_2O$$

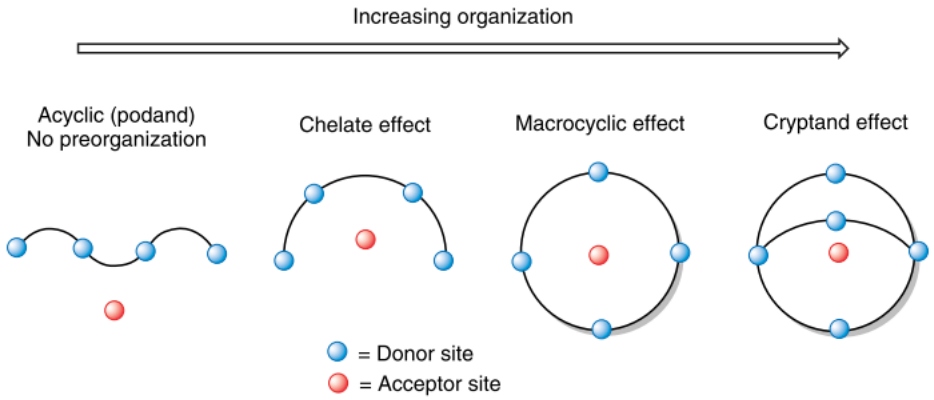
$$\beta \sim 10^9,\ \Delta G = -51.8\ \text{kJ mol}^{-1},$$

$$\Delta H = -100\ \text{kJ mol}^{-1},\ \Delta S = -163\ \text{J mol}^{-1}\text{K}^{-1}$$

$$[Ni(H_2O)_6]^{2+} + 3en = [Ni(en)_3]^{2+} + 6H_2O$$

$$\beta \sim 10^{18},\ \Delta G = -101.8\ \text{kJ mol}^{-1},$$

$$\Delta H = -117\ \text{kJ mol}^{-1},\ \Delta S = -42\ \text{J mol}^{-1}\text{K}^{-1}$$



Recettori

cationi

anioni

molecole neutre

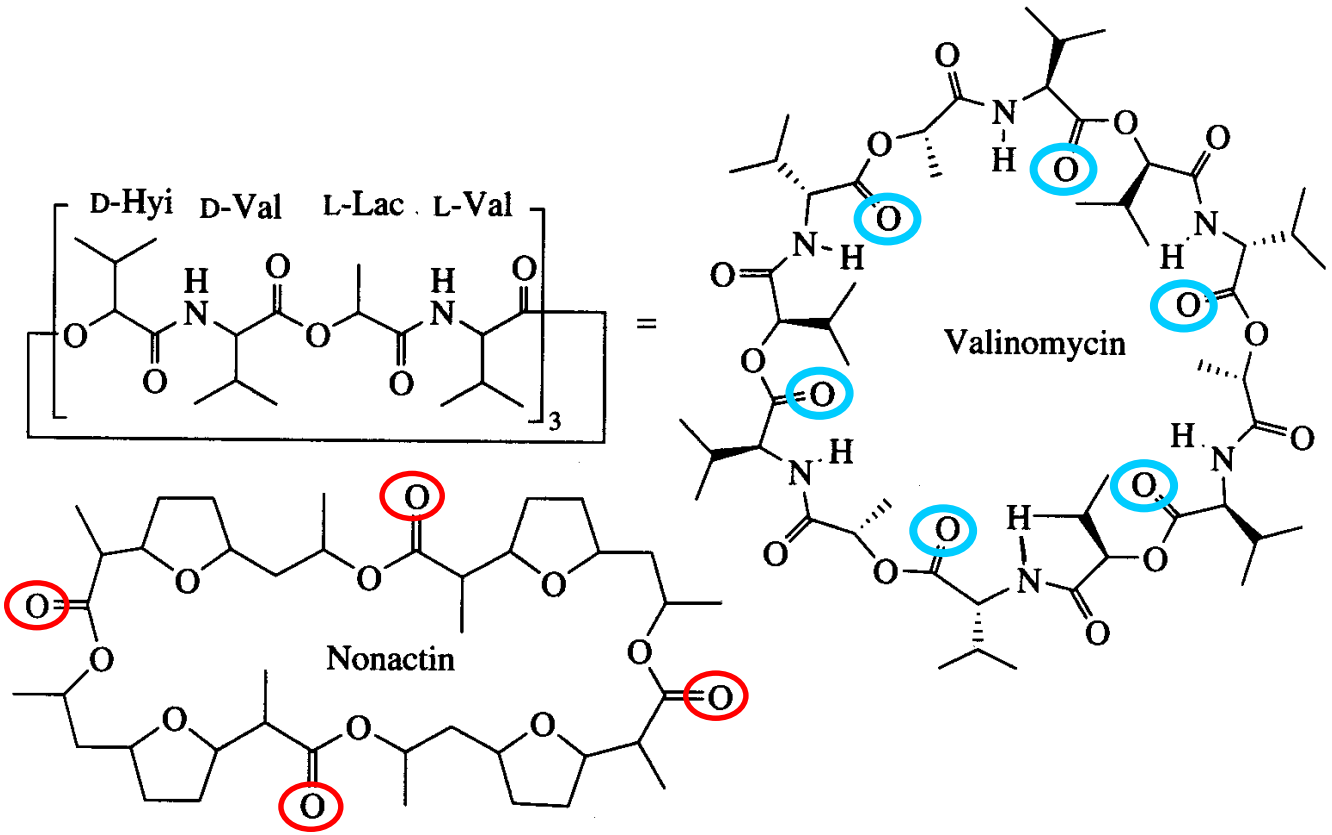
Metodi Analitici

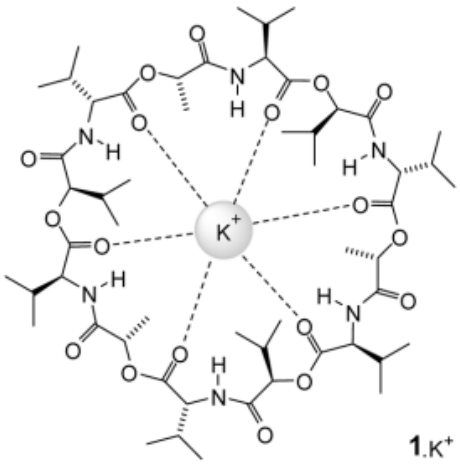
Cavitandi

Contenitori molecolari

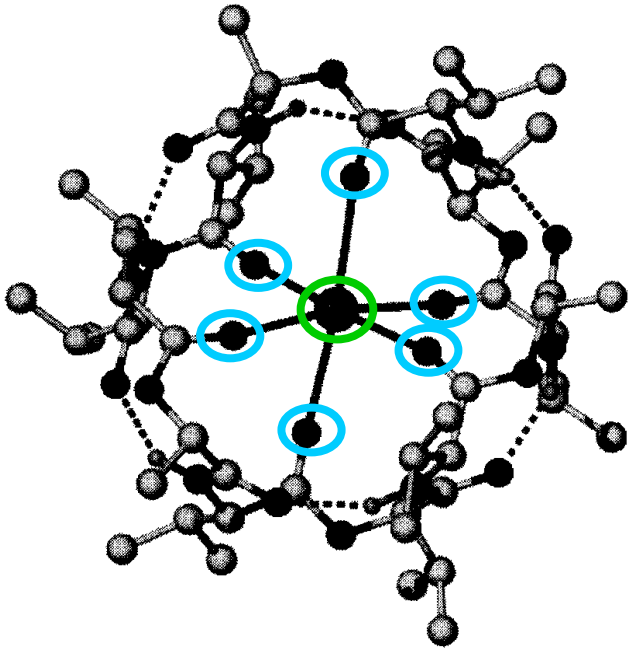
-covalenti
-auto-assemblati (legami idrogeno, legami di coordinazione, legami covalenti dinamici)

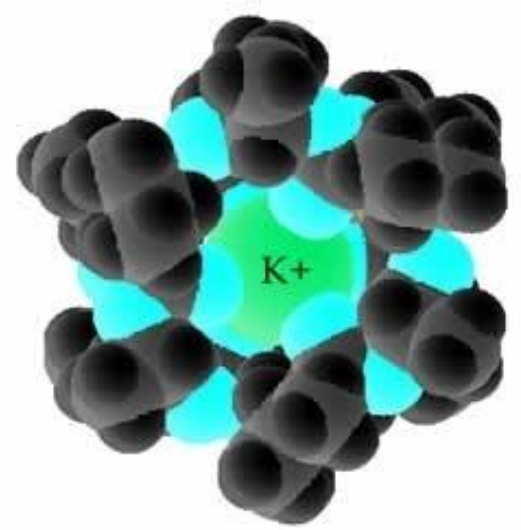
Cations and anions are ubiquitous in biological and chemical systems and their efficient and selective recognition is one of the main goals of Supramolecular Chemistry. As a matter of fact, research in this field started with Pressman's 1964 discovery[1] that valinomycin and other natural antibiotics increase the permeability of lipid bilayer membranes through the selective binding of potassium ion, and with Pedersen's finding[2] that macrocyclic polyethers (crowns) are able to complex salts of alkali metal ions and dissolve them in organic media. Since then, the topic of ion recognition by synthetic receptors has developed tremendously and is still quite fertile as testified to by the recent review articles and books concerning cation[3-7] and anion[8,9] complexation and sensing. More recently, a special role in ion

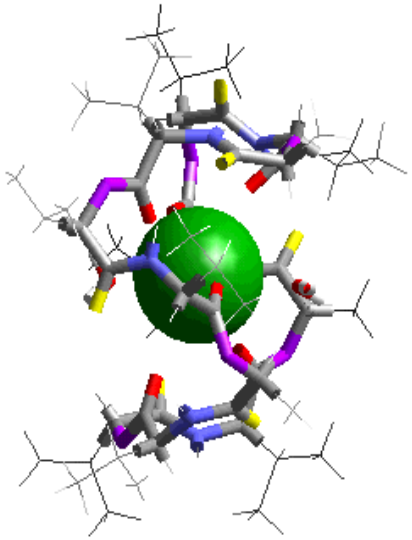

D-Hyi
D-Val
L-Lac
L-Val
3
=
Valinomycin
Nonactin



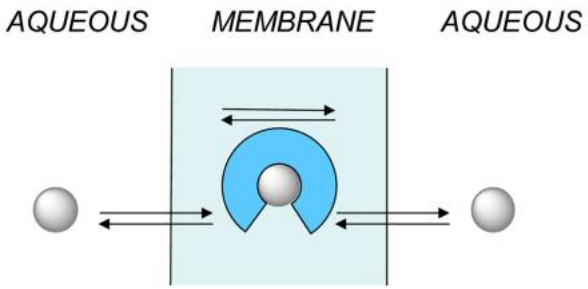
1.K⁺







$K_{K+}/K_{Na+} = 10^5$

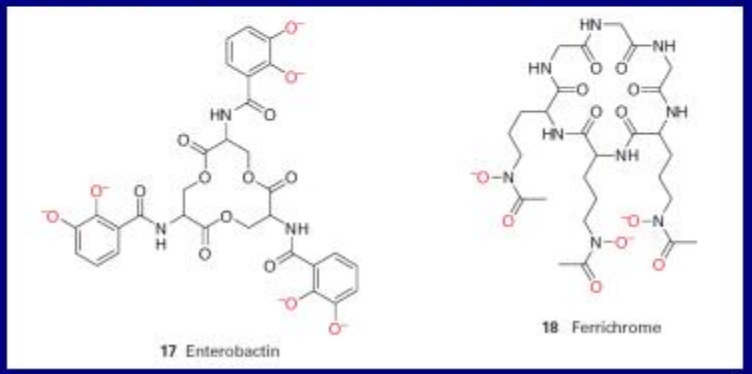


A pH fisiologico 7.4 la concentrazione di $[Fe(H_2O)_6]^{3+}$ - in equilibrio con $Fe(OH)_3$ - è circa 10^{-18}M, mentre per le condizioni ottimali di crescita i micro-organismi richiedono una concentrazione intracellulare di circa 10^{-7}M

Siderofori:

I siderofori sono piccoli leganti polidentati con O/N donatori che hanno grande affinità per lo ione hard Fe(III) (e scarsa per Fe(II)) e lo rendono solubile attraverso la formazione di complessi ottaedrici ad alto spin.

Oltre al complesso con citrato, vi sono siderofori basati su fenolati o catecolati come *l'enterobactina* (costante di associazione 10^{52}) e basati su idrossammati come l'esapeptide ciclico *ferricromo* (3 glicine + 3 N-idrossil-l-ornitine).



17 Enterobactin

18 Ferrichrome

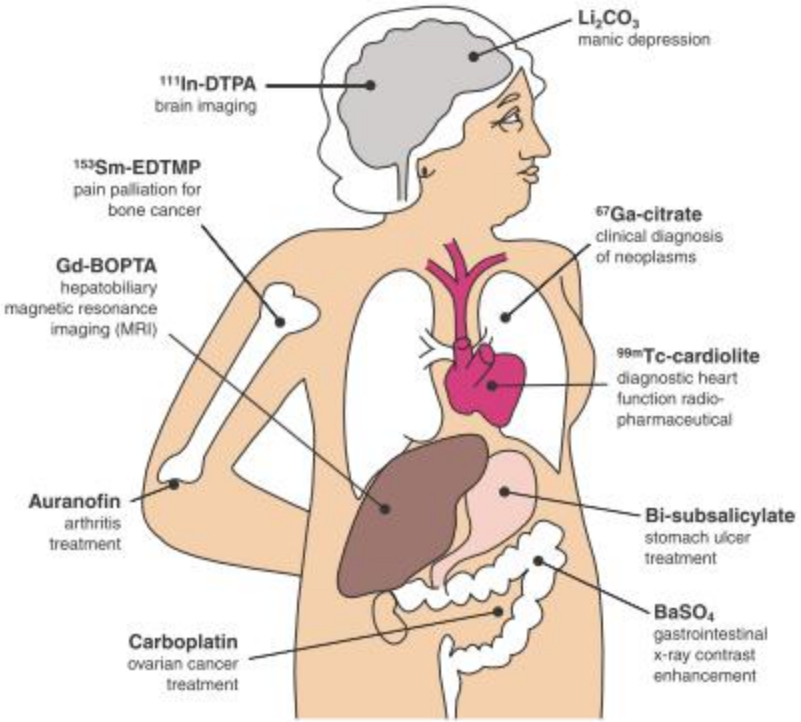
L'enterobactina-Fe^{III} complesso è anche chirale; la struttura del triestere ciclico, che è chirale in quanto ha tre carboni asimmetrici adiacenti agli azoti, impone la configurazione
Δ dei catecolati intorno al Fe(III); il suo enantiomero Λ coordina il ferro, ma non è in grado di rilasciarlo ai batteri perché non è riconosciuto da i recettori dell'enterobactina.

Science
AAAS

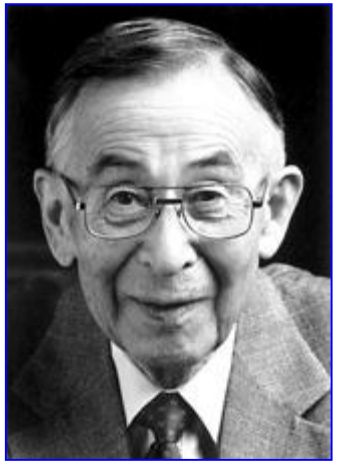
Boon and Bane of Metal Ions in Medicine

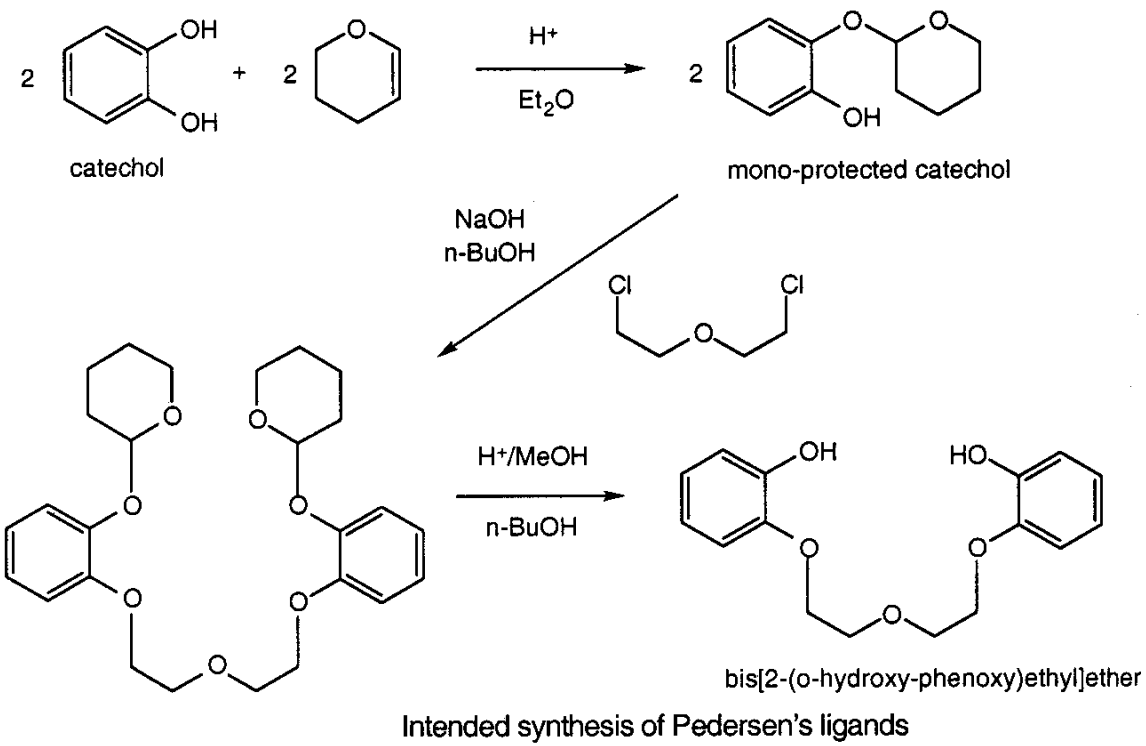
Katherine H. Thompson and Chris Orvig

Science **300**, 936 (2003);
DOI: 10.1126/science.1083004

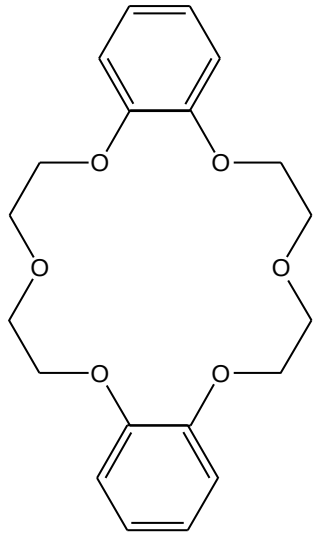


PEDERSEN (Nobel 1987), studio di leganti multi dentati per rame e vanadio (Dupont, anni ‘60)





Intended synthesis of Pedersen’s ligands

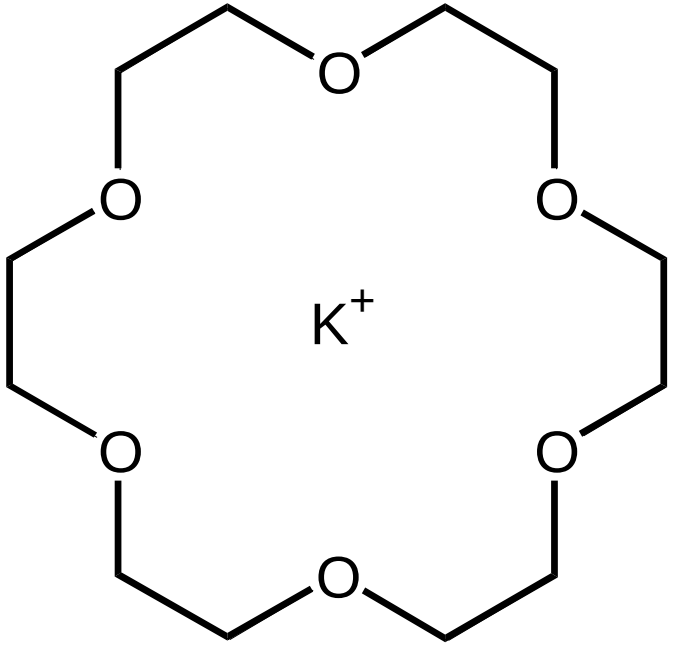


dibenzo[18]crown-6 - sottoprodotto

ETERI CORONA (Crown Ethers)

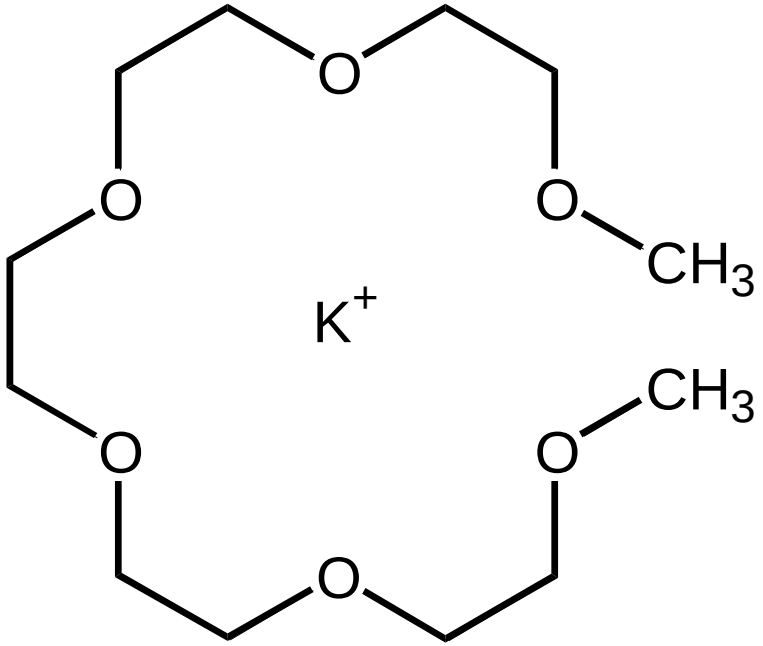
(monocilci = CORANDI)

[18]crown-6

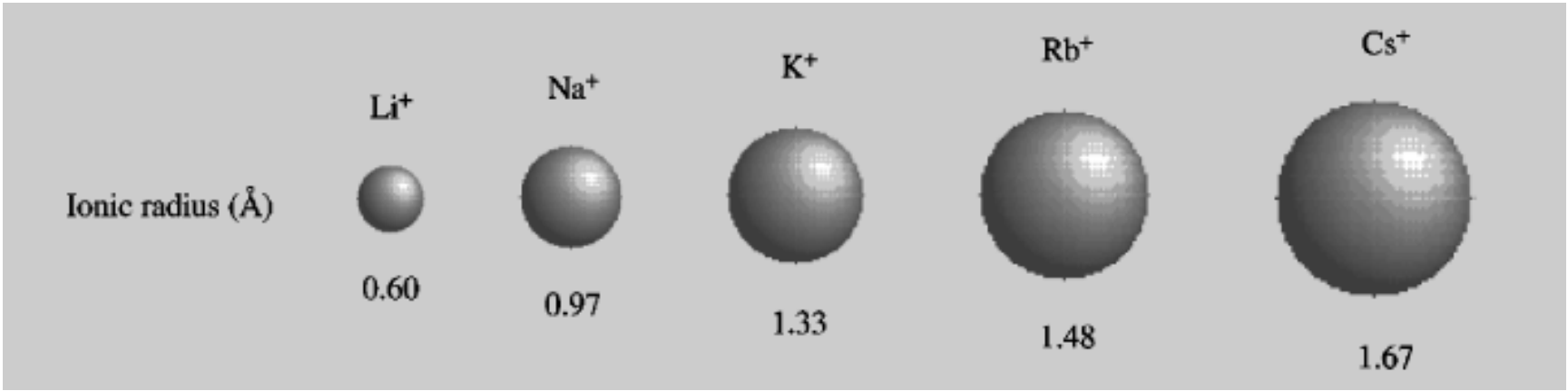


log K = 6.08

Pentametileneglicol-dietiletere

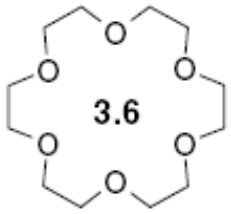


log K = 2.3

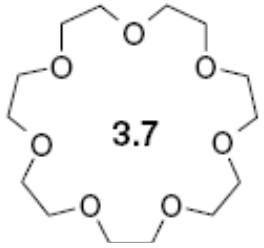


OPTIMAL SPATIAL FIT or SIZE-MATCH

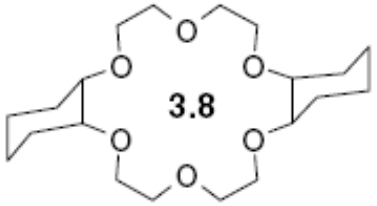
[15]crown-5
Complementary to Na^+



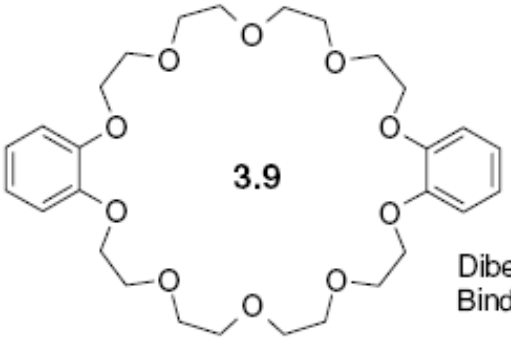
[18]crown-6
Complementary to K^+



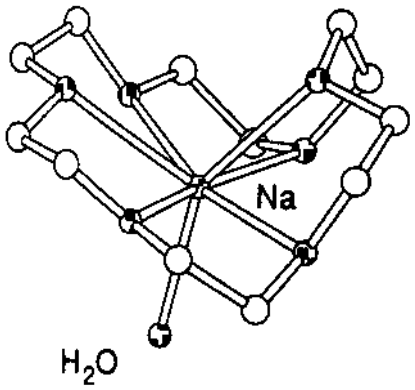
[21]crown-7
Complementary to Cs^+

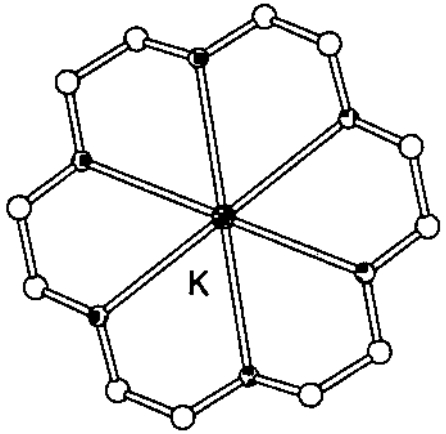


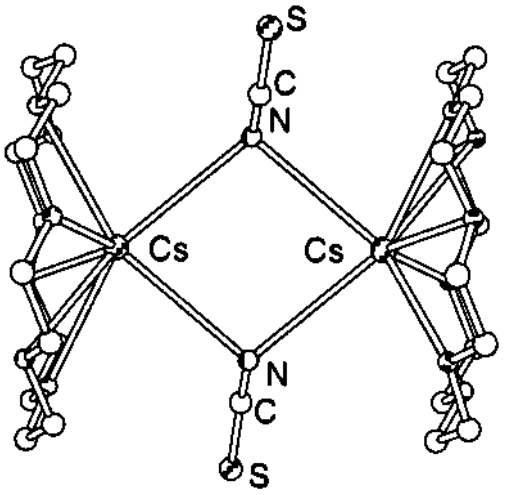
Dicyclohexyl[18]crown-6
More conformationally rigid

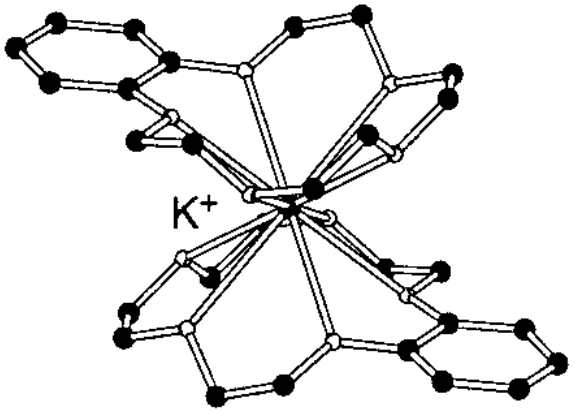


Dibenzo[30]crown-10
Binds two Na^+ ions

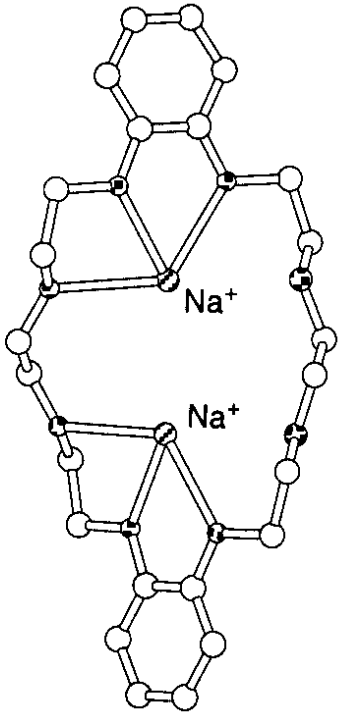








The crystal structure of two benzo-15-crown-5 molecules forming a 'sandwich complex' with a potassium cation



The crystal structure of $2Na^+$–[24]crown-8

a Cationi ***hard*** formano complessi in cui le interazioni coulombiane sono dominanti

b Cationi ***soft*** formano complessi in cui è dominante il legame covalente.

Ioni metallici di tipo ***a*** sono principalmente:

- ioni dei metalli alcalini e alcalino-terrosi
- ioni metallici leggeri e con elevata carica: Ti^{4+}, Fe^{3+}, Co^{3+}, Al^{3+}

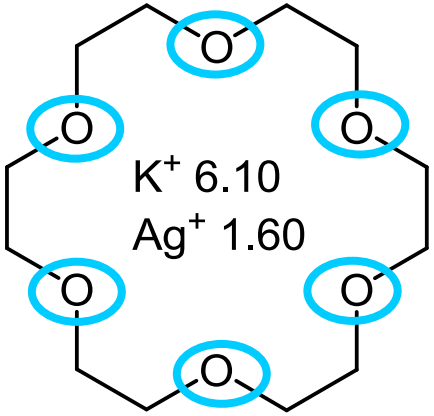
Ioni metallici di tipo ***b*** sono principalmente:

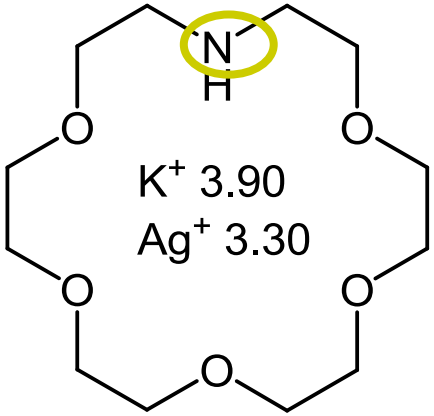
- ioni pesanti di metalli di transizione: Hg_2^{2+}, Hg^{2+}, Pt^{2+}, Pt^{4+}, Ag^{+}, Cu^{+}
- ioni di metalli in bassi stati di ossidazione, ad es. nei metallo carbonili

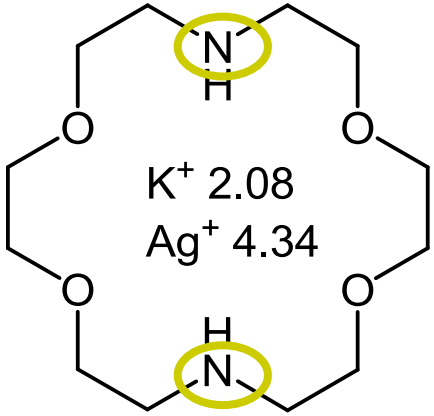
Alcuni ioni (Fe^{2+}; Co^{2+} ; Ni^{2+}; Cu^{2+} ; Zn^{2+}; Pb^{2+}) formano complessi le cui stabilità non possono essere pronosticate sulla base della classificazione hard/soft: essi formano la classe *border-line*

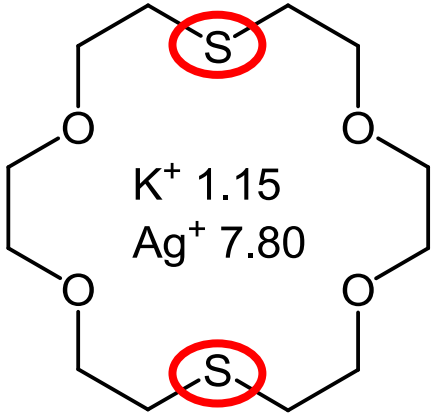
La costante di stabilità dei complessi di questi ioni con un dato legante segue l'ordine, noto come serie di **Irving-Williams**:

$$Ca^{2+} < Mg^{2+} < Mn^{2+} < Fe^{2+} < Co^{2+} < Ni^{2+} < \mathbf{Cu^{2+}} > Zn^{2+} > Pb^{2+}$$



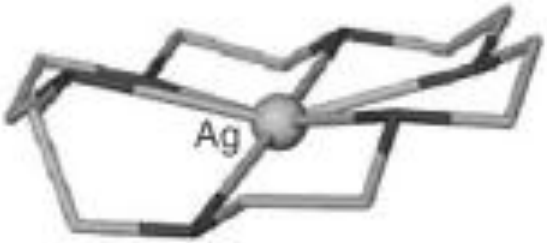


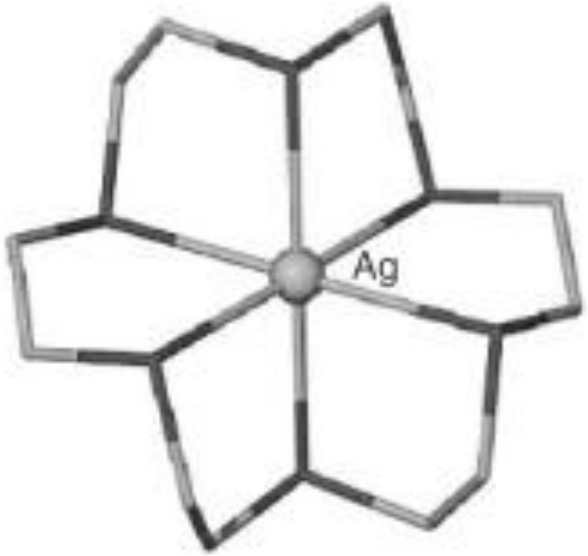


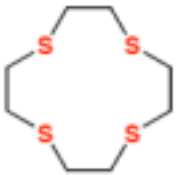


Aza-crown

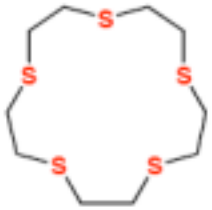
Tio-crown



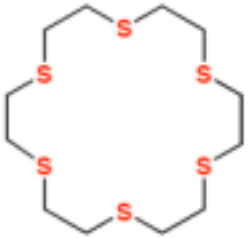




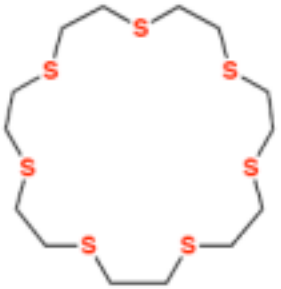
[12]S_4



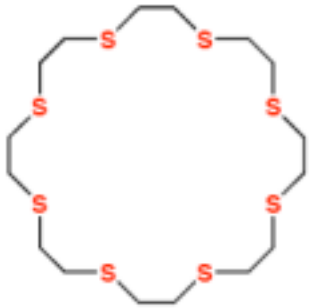
[15]S_5



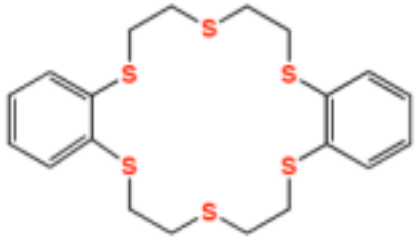
[18]S_6



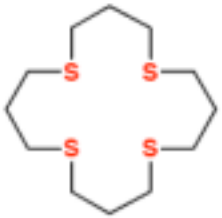
S



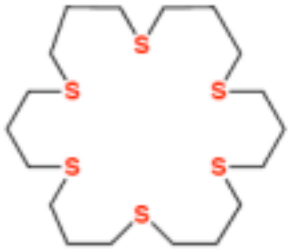
[24]S_8



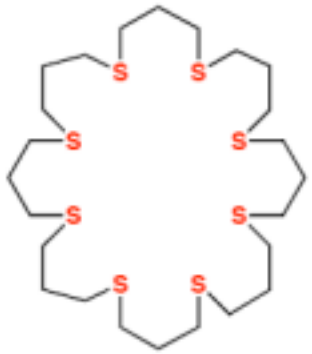
Dibenzo[18]S_6



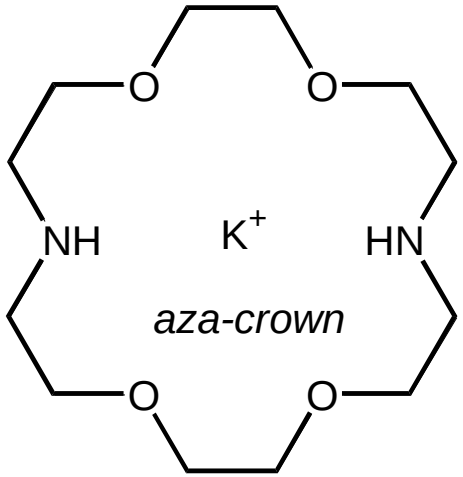
[16]S_4



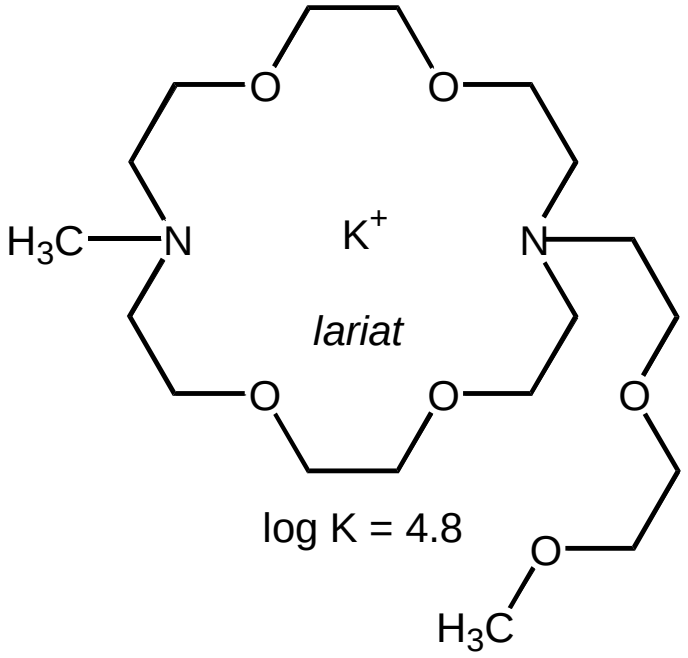
[24]S_6



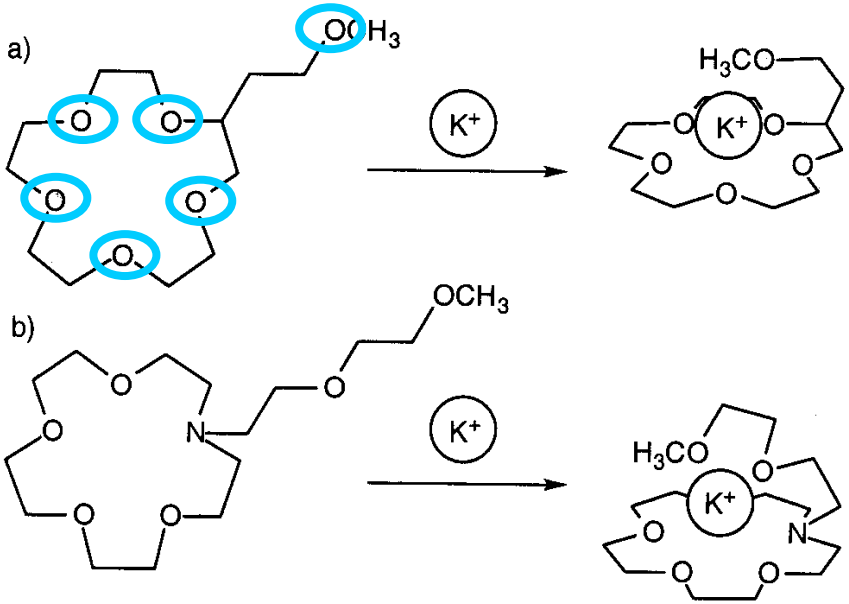
[32]S_8



log K = 2.04



log K = 4.8



(a) Carbon and (b) nitrogen pivot lariat crown ethers binding potassium cations.

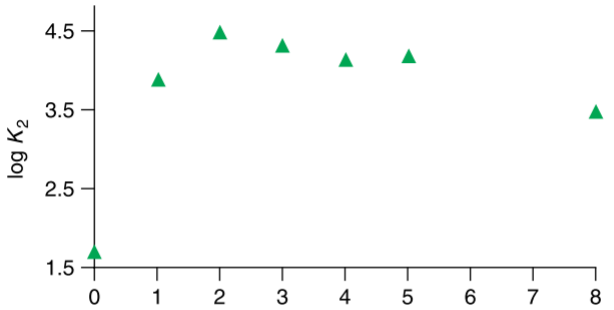
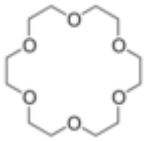
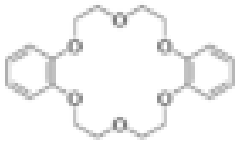


Figure 17 Na^+ complexation by aza-15-crown-5 lariat ethers with n oxygen donor atoms in the side arm ($n = 0–8$).[57]



18-crown-6

274984-1G 78.40



Dibenzo-18-crown-6

15889-25G 17.50 euro

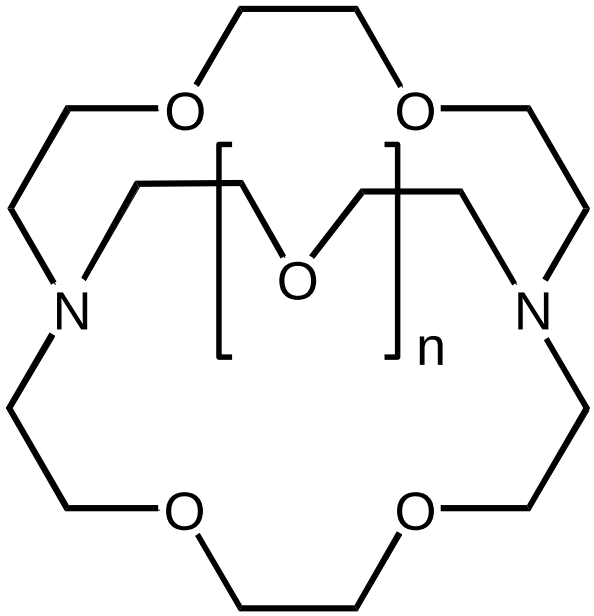
15-crown-5

188832-1G 15.30 euro

1-Aza-18-crown-6

11382-1G 212.00 euro

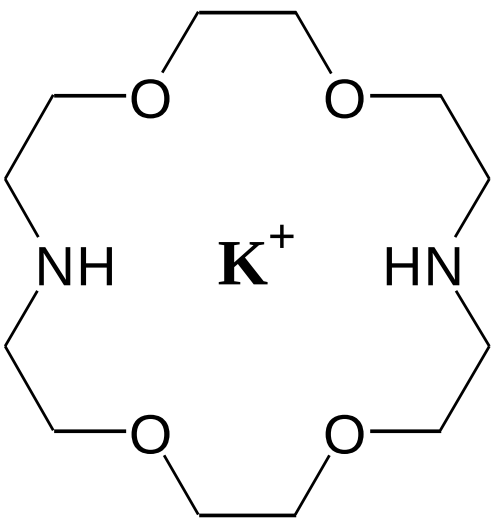
LEHN (Nobel 1987), estensione dei sistemi monociclici a sist. biciclici (CRIPTANDI,anni ‘60)



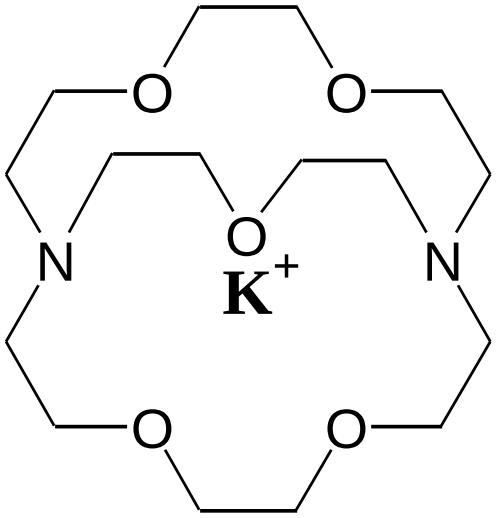
Na^+

n = 1, criptando [2,2,1]
n = 2, criptando [2,2,2]

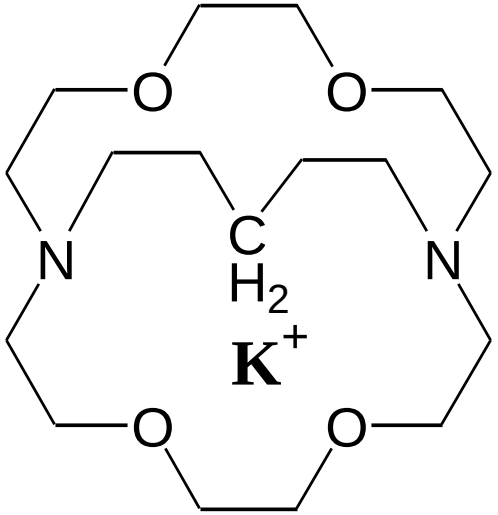
K^+



logK = 2.0

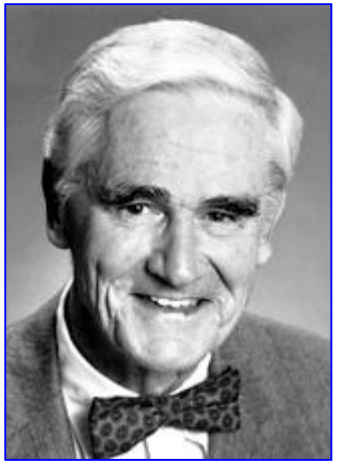


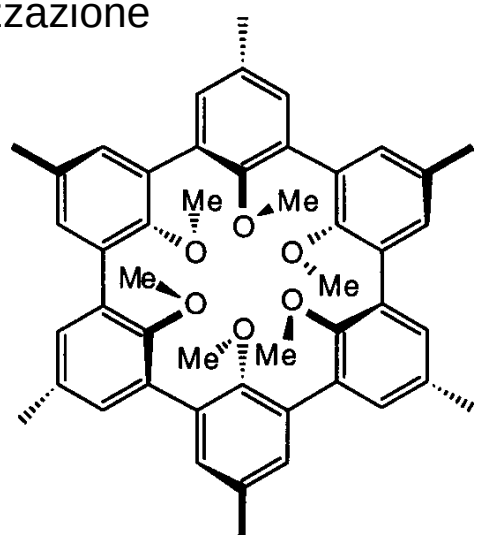
logK = 7.0



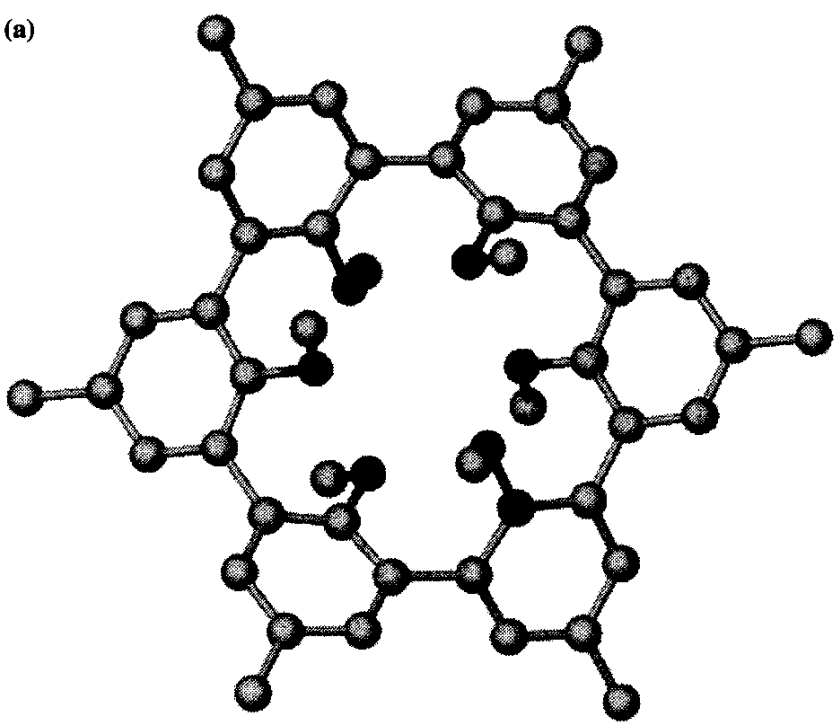
logK = 5.4

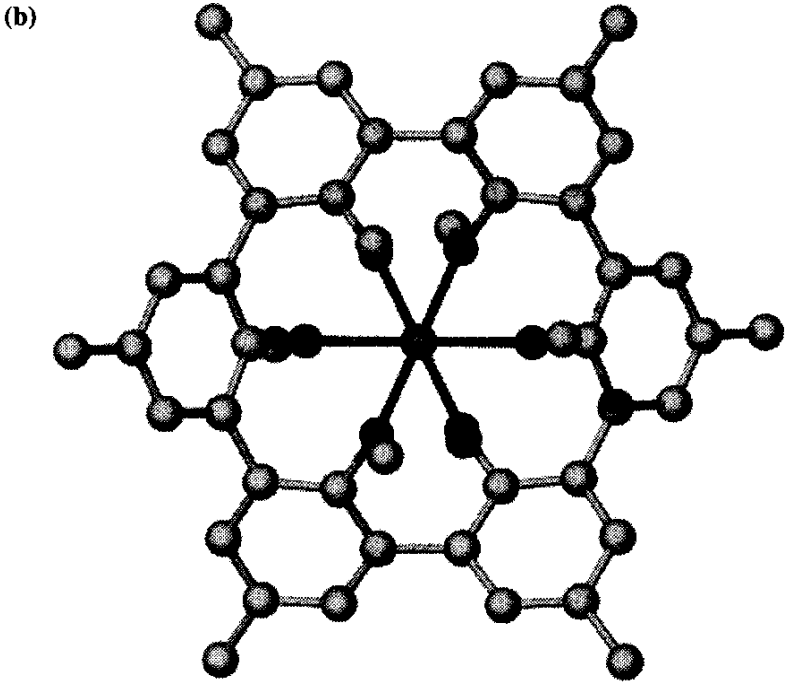
CRAM (Nobel 1987) - preorganizzazione



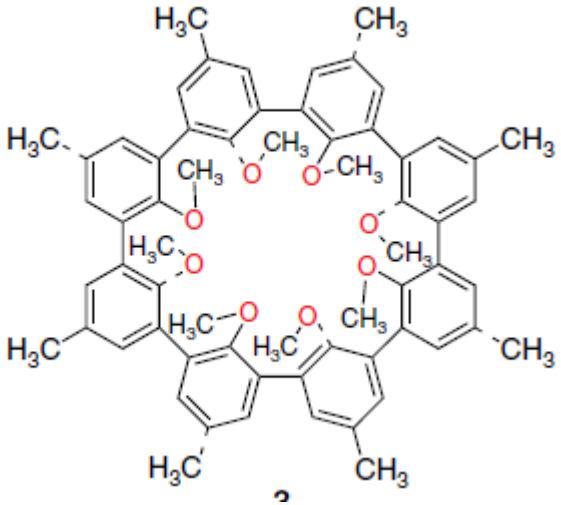


Sferandi
(*p*-metilanisolo)

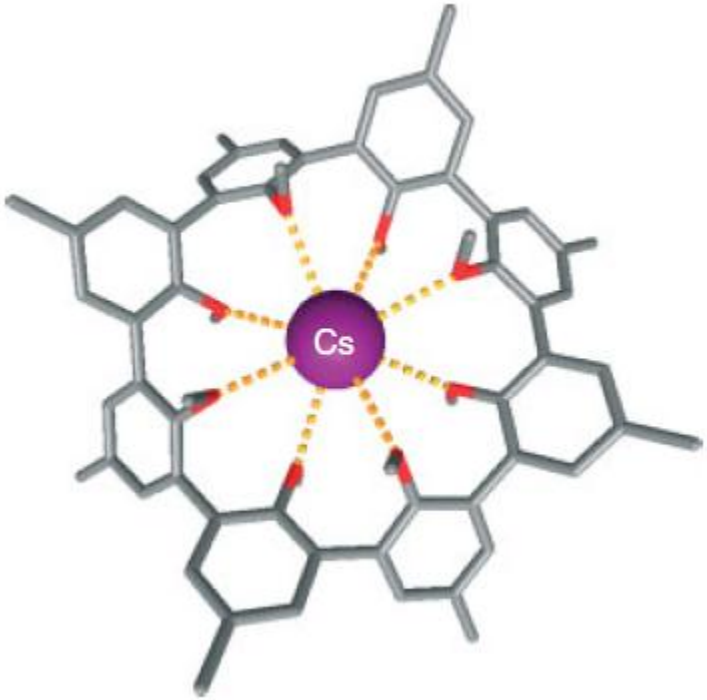


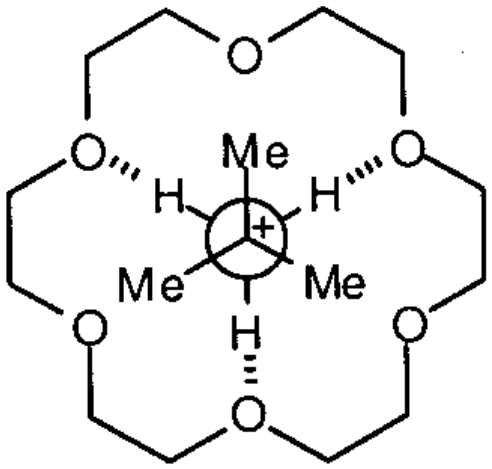


X-ray crystal structures of **(a)** free spherand **(3.30)** and **(b)** its Li^+ complex (after Trueblood *et al.* 1981).

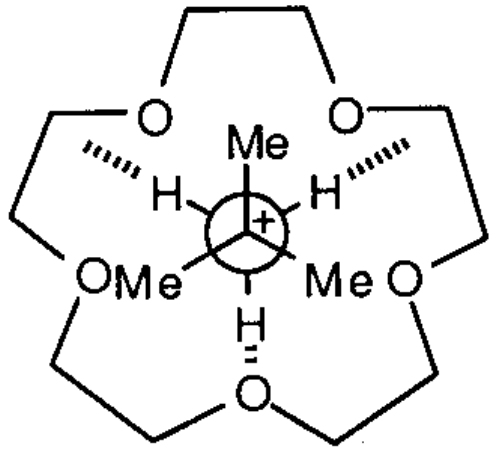

H3C
CH3
H3C
CH3
CH3
O
CH3
O
CH3
O
H3C
O
O
CH3
O
H3C
O
O
CH3
H3C
O
H3C
O
CH3
H3C
CH3
H3C
CH3

2

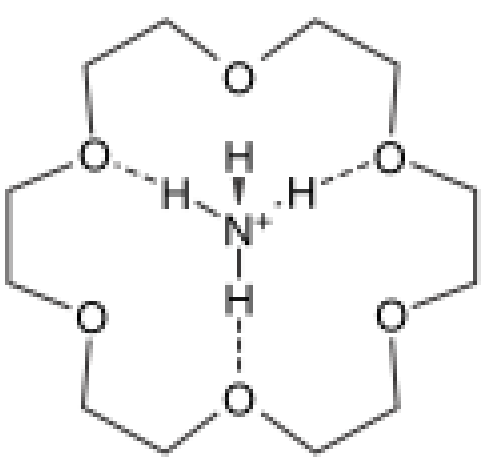

Cs



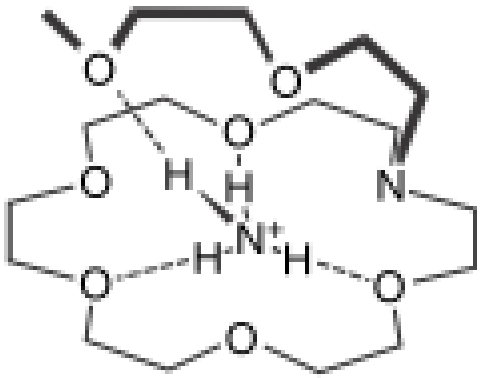
strong complex
ideal arrangement of hydrogen bond
donors and acceptors



weaker complex
mismatch in geometry of hydrogen bond
donors and acceptors

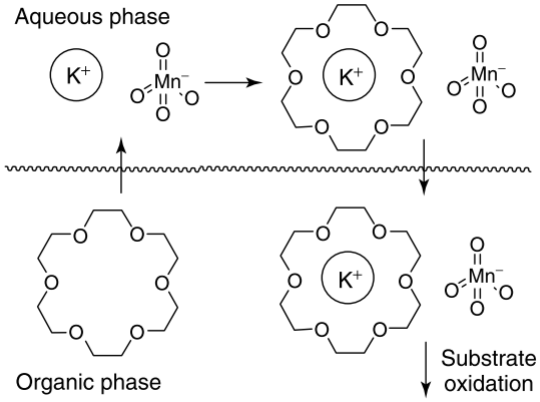


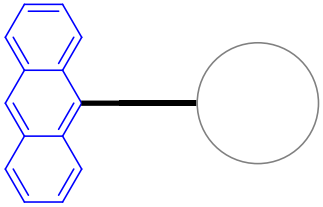
log K = 4.35

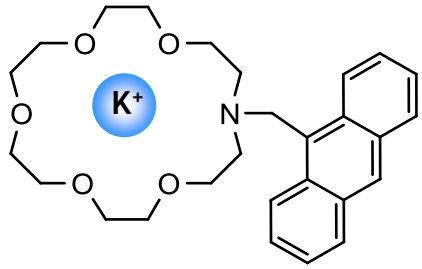


2.23·NH_4^+

log K = 4.75

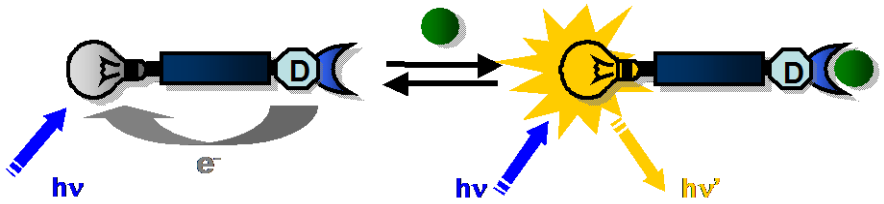

Aqueous phase
K+
Mn
K+
Mn
K+
Mn
Organic phase
Substrate
oxidation



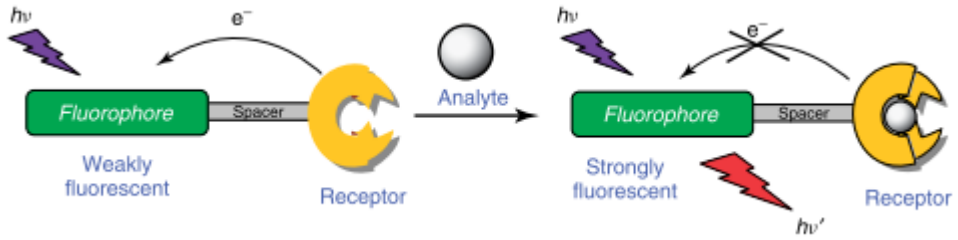


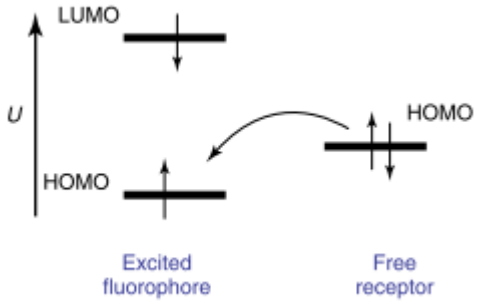
Silent substrates (analiti silenti):

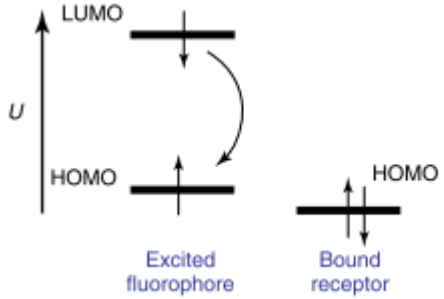
Meccanismo ON/OFF (PET) intrinseco al sensore
attivato dall'analita (ammina terziaria)
OFF in ASSENZA di analita
ON in presenza di analita



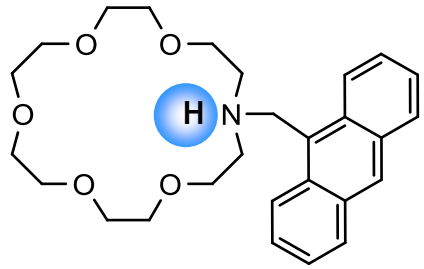
Photoinduced electron transfer (PET)



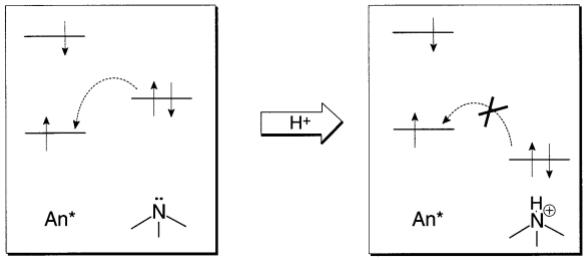




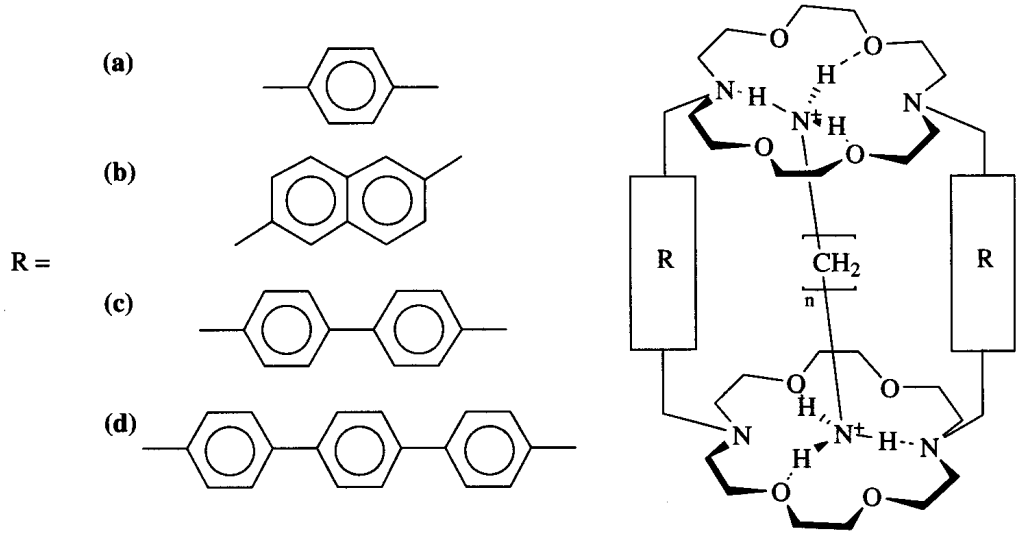
In soluzione acquosa attenzione al pH!

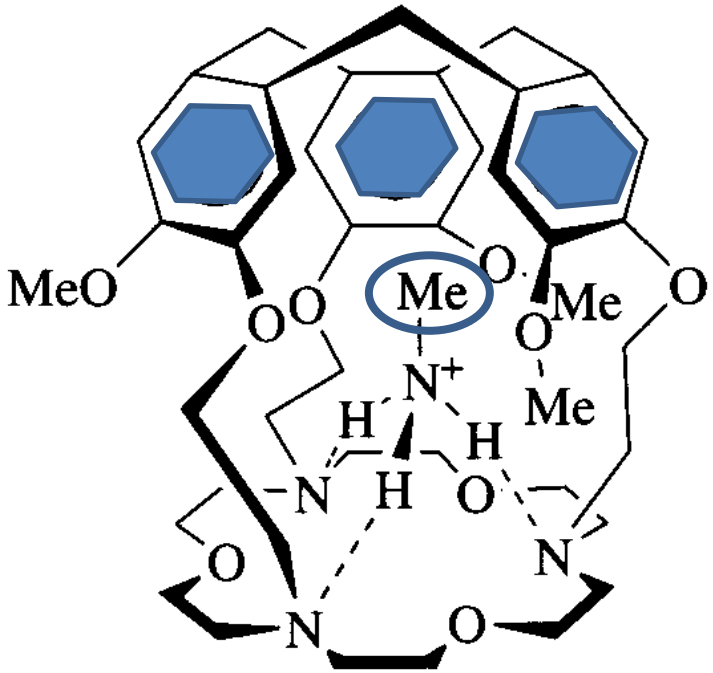


Fluorescenza accesa anche in assenza di catione se ammina protonata;
in presenza di catione l'ammina deve essere deprotonata perché il sensore si accenda!



Recettori Politopici





ciclotriveratrilene

corando

Thermodynamic selectivity : ratio of the binding constant for one guest over another:

$$H + G_1 \rightleftharpoons [HG_1] \qquad K_1$$
$$H + G_2 \rightleftharpoons [HG_2] \qquad K_2$$

$$\text{selectivity} = \frac{K_1}{K_2}$$

Selectivity is a consequence of preorganization, complementarity…
Needs to be calculated at equilibrium in the same conditions
Temperature! Solvent!

Kinetic selectivity : preference of a host for the fastest transformation of a substrate over another (Michaelis-Menten model)

-transport
-catalysis
-sensing and signaling

Selettività

Natura degli atoni donatori (O vs N VdW radius simile: hard/soft acid-base theory;

Numero e orientazione degli atomi donatori (pesa di più per cationi di M transizione, che per alcalini; alcalinoterrosi e REM).

Carica elettrostatica dello ione: a parità di raggio ionico, carica maggiore può corrispondere a maggiore energia di idratazione (*cfr* Ca^{2+} vs Na^{+});

Energie libere di solvatazione dell'host e del catione

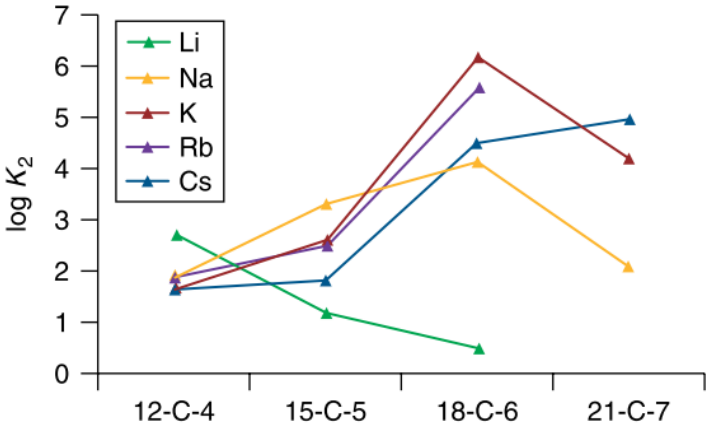
Solvente – competitivo per i dipoli/ costante dielettrica/ legami idrogeno/capacità coordinanti

Natura del contro-ione (interaz con solvente/catione/solvatazione)

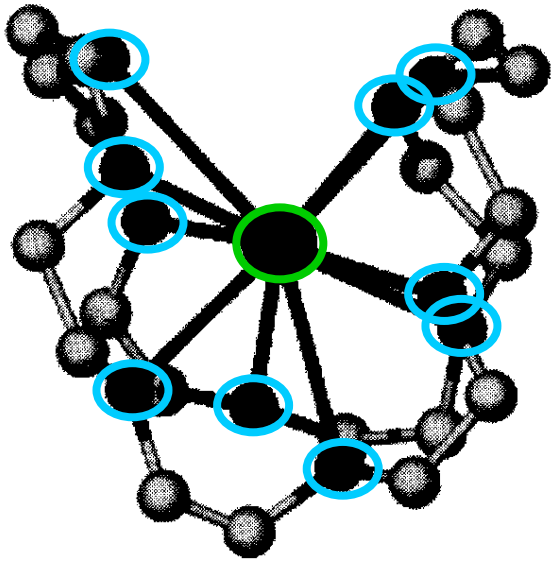
Cinetica di complessazione

Selettività

Size-match o optimal-fit (progressivamente più determinante aumentando la rigidità /preorganizzazione dell'Host) – distanza tra i dipoli del macrociclo e la carica ionica



[30]crown-10



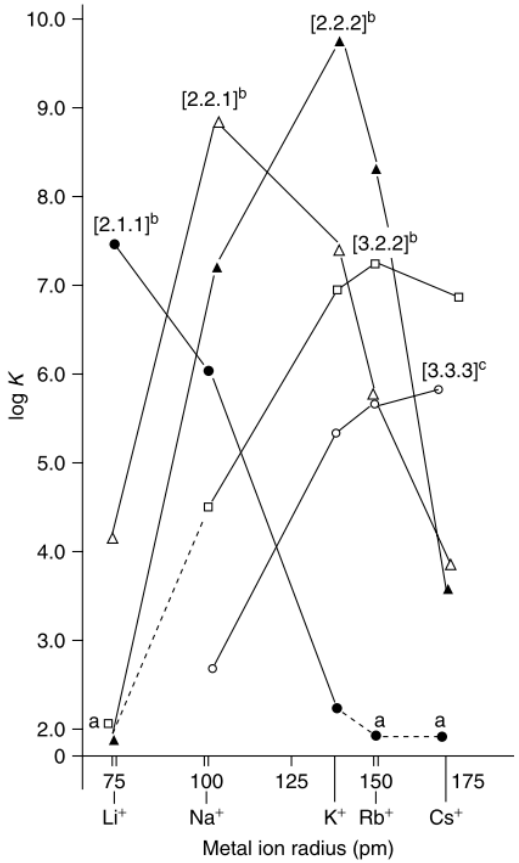


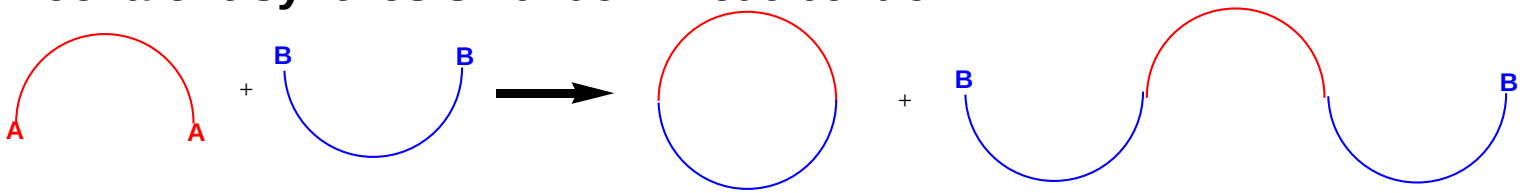
Figure 2 Selectivity of cryptands among alkali metal cations (a, value reported <2.0; b, in 95% CH_3OH; c, in methanol).

Macrocyclic Polyethers and Their Complexes[***]

By C. J. Pedersen and H. K. Frensdorff[*]

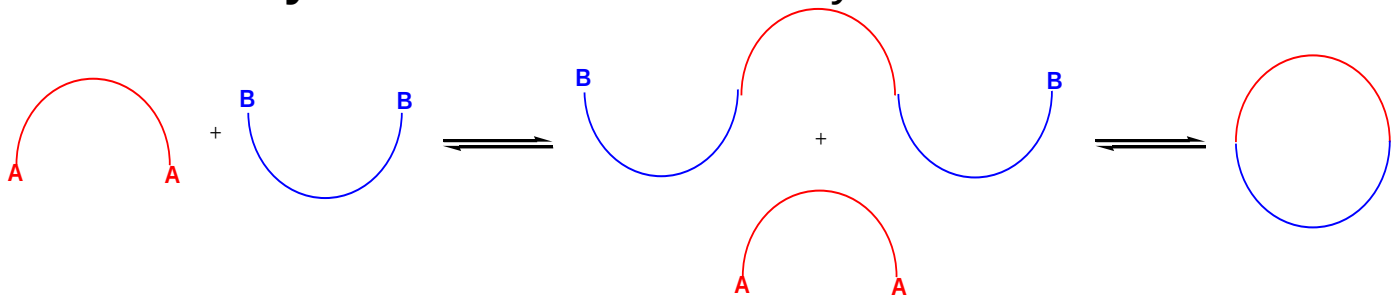
Angew. Chem. internat. Edit. / Vol. 11 (1972) / No. 1

- **covalent synthesis** : under kinetic control



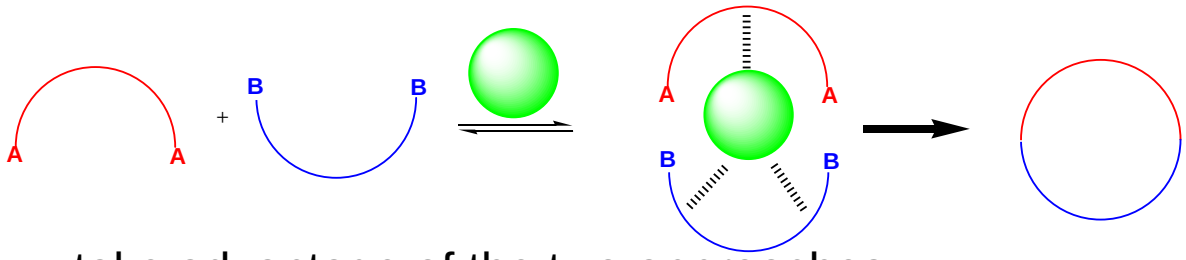
  - classical organic chemistry. Irreversible bond formation
  - highly stable molecules.
  - not adapted to big molecules. low yield

- **non covalent synthesis** : under thermodynamic control



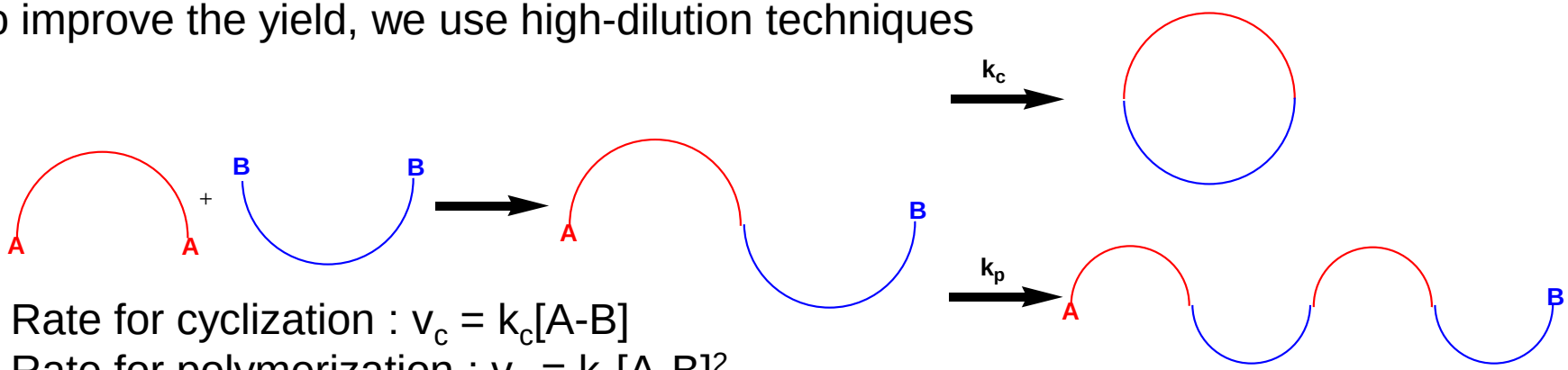
  - thermodynamic directed synthesis. Reversible bond formation
  - lower stability
  - adapted to big molecules. high yield

- a **mix**



  - take advantage of the two approaches

To improve the yield, we use high-dilution techniques



Rate for cyclization : $v_c = k_c[A\text{-}B]$

Rate for polymerization : $v_p = k_p[A\text{-}B]^2$

- the more dilute, the more cyclic product is formed
- the reaction has to be fast

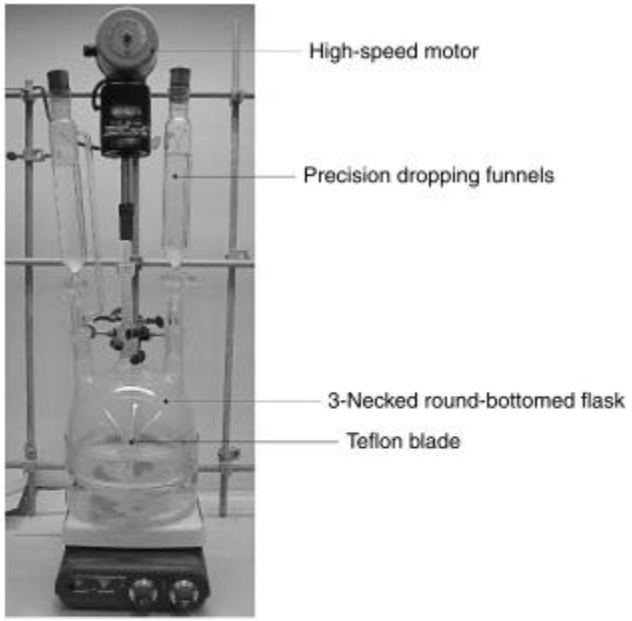
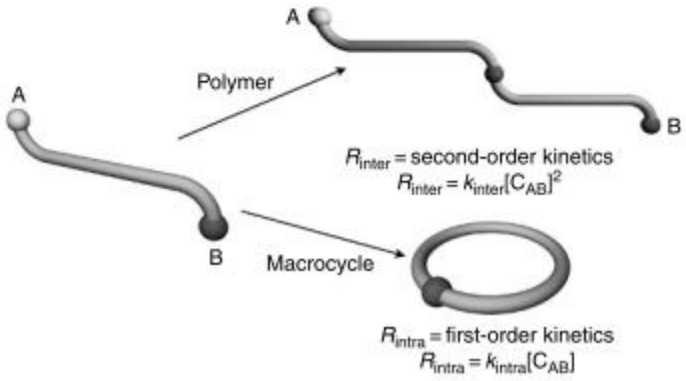
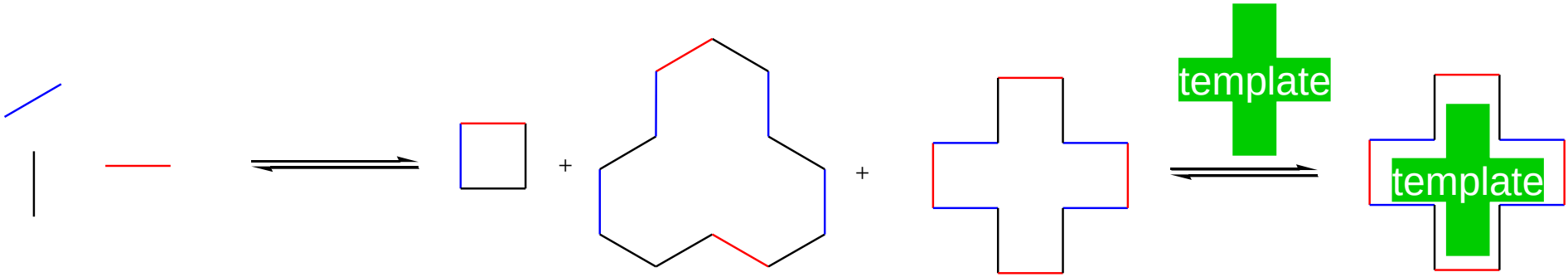
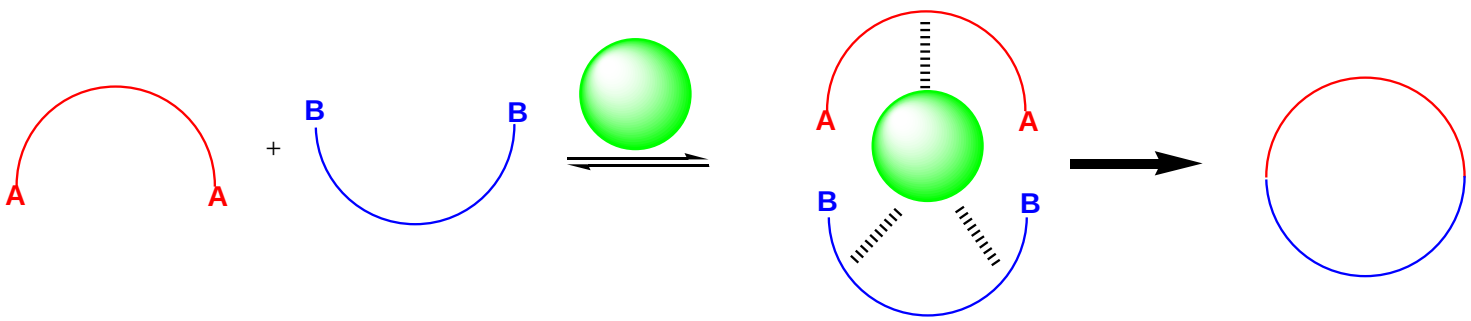


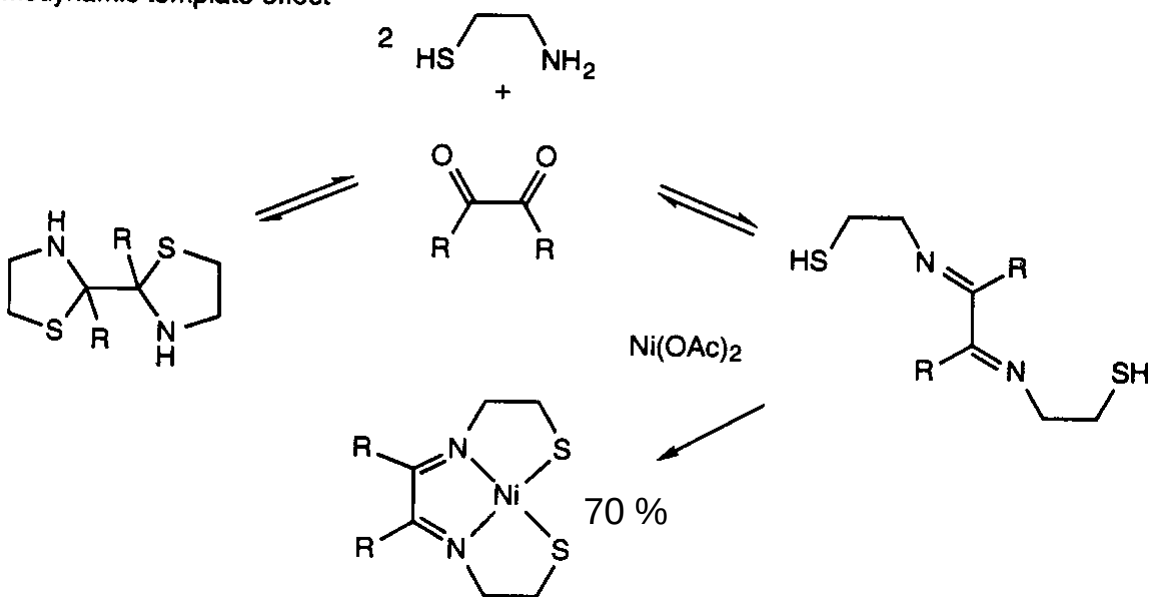
Figure 2.1 Typical apparatus used for high-dilution synthesis.



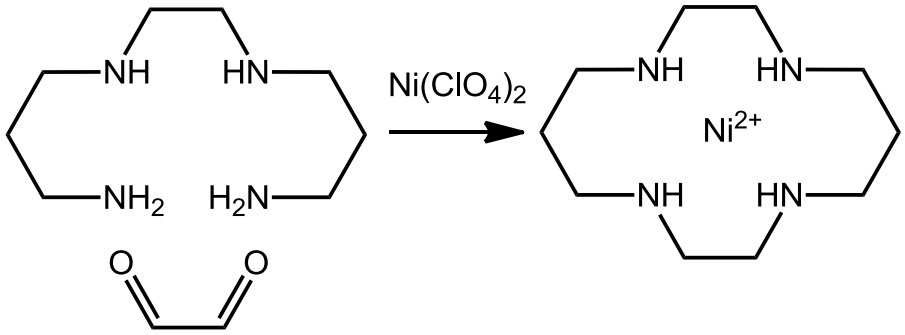

template
template

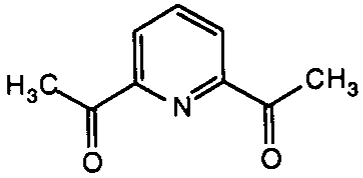

A
A
B
B
A
A
B
B

a) thermodynamic template effect



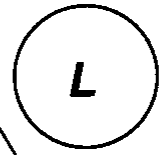
Effetto templato cinetico CYCLAM (base di Schiff)



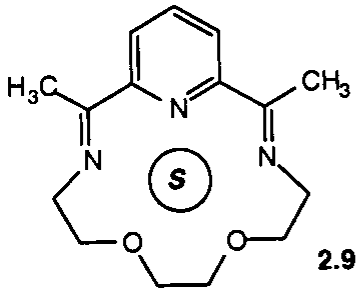


+

small metal cation templates
(e.g. Mn^{2+}, Fe^{2+}, Mg^{2+})

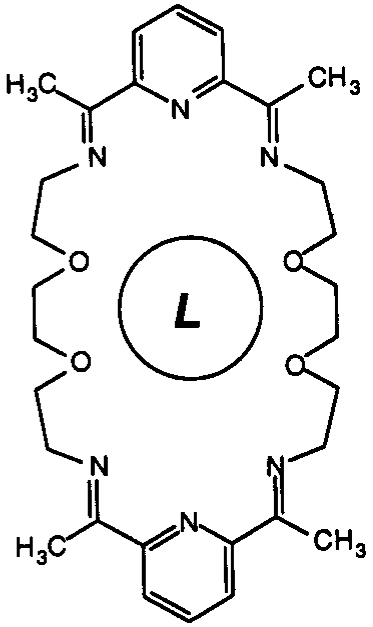


large metal cation templates
(e.g. Ba^{2+}, Pb^{2+})

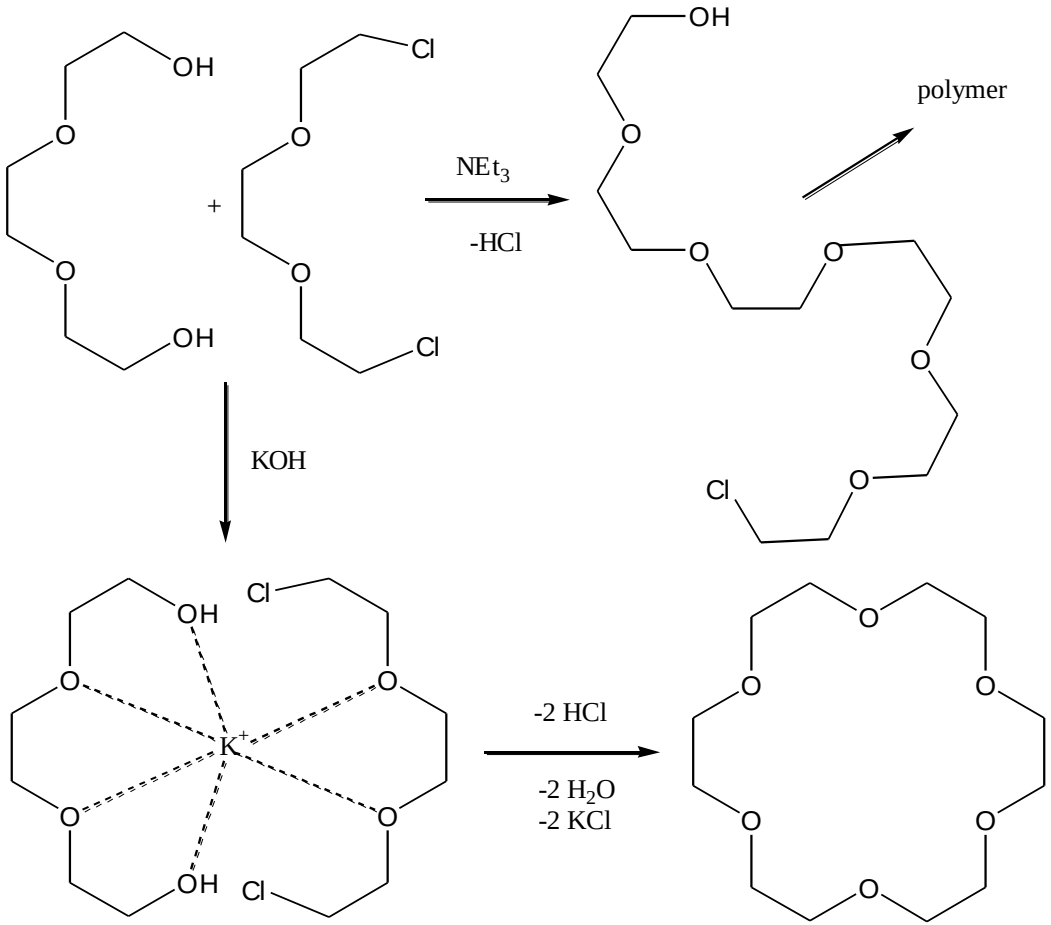


2.9

1 + 1 condensation

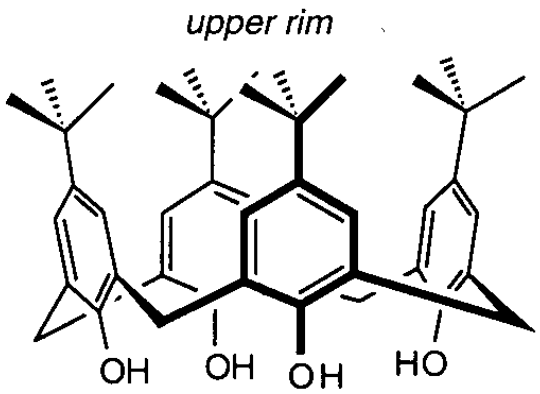


2 + 2 condensation



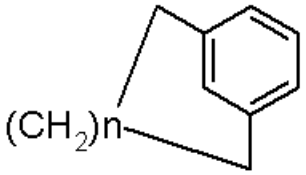
Demetallazione:
gruppi amminici – protonazione
debolm coordinat – estrazione con acqua
complessante più forte
variaz stato ox- inerzia/labilità

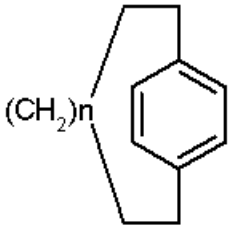
Calix[n]areni

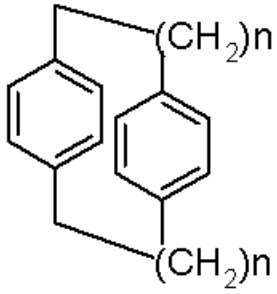


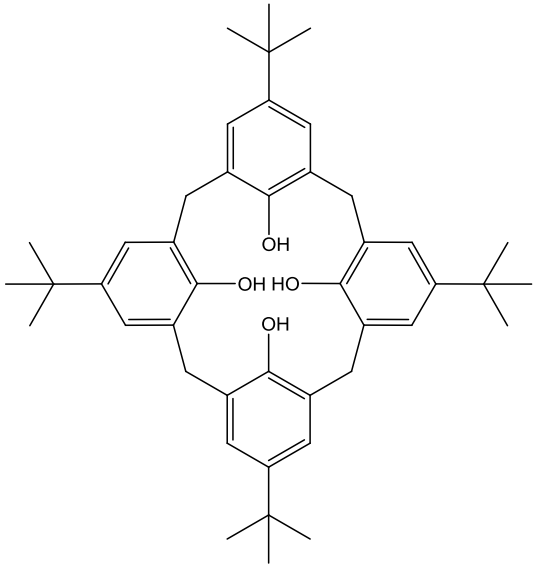
p-tert-Butylcalix[4]arene.

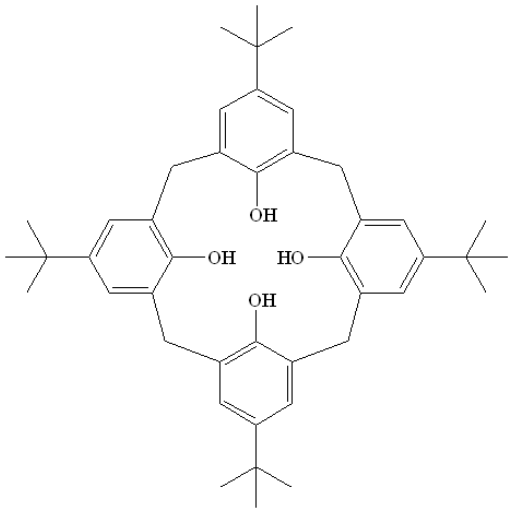
Ciclofani

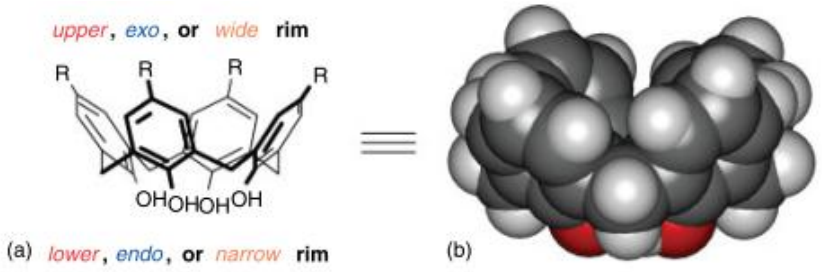


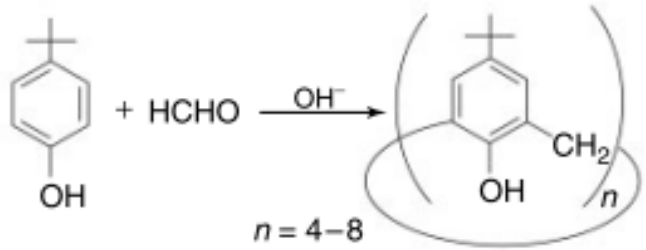




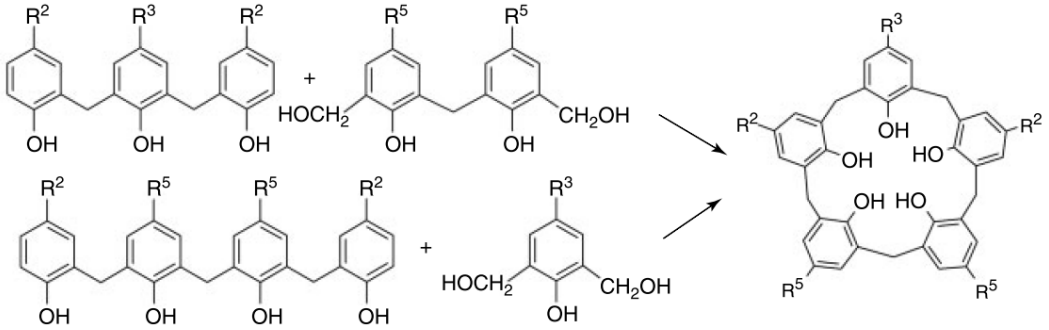



OH
OH
HO
OH

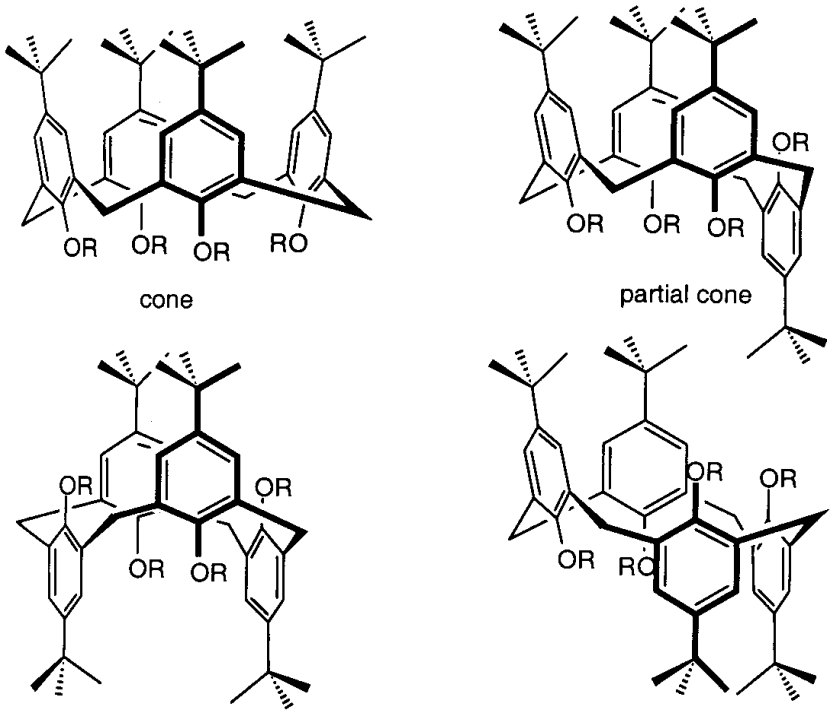

upper, exo, or wide rim
R
R
R
R
OH
OH
OH
OH
(a) lower, endo, or narrow rim
(b)



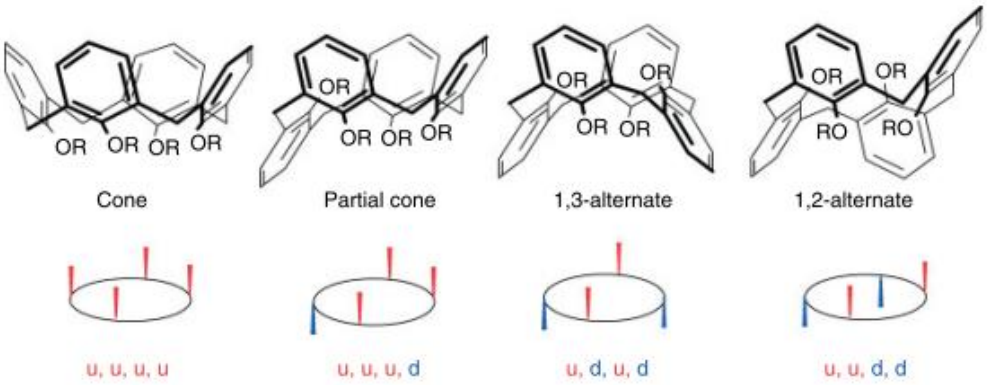
3+2 Fragment condensation

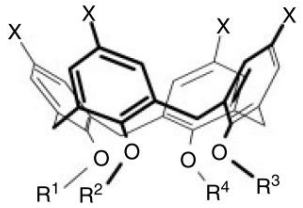


4+1 Fragment condensation

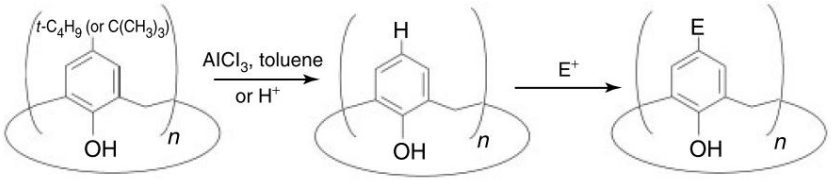


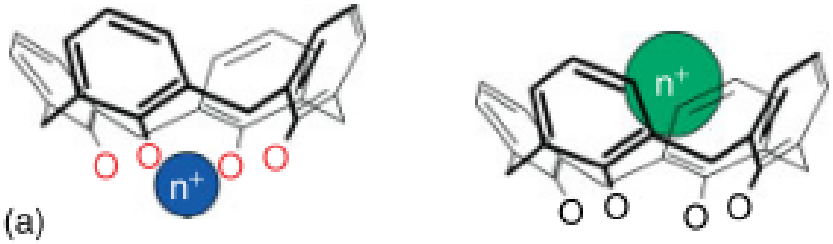
Conformations adopted by calix[4]arenes.

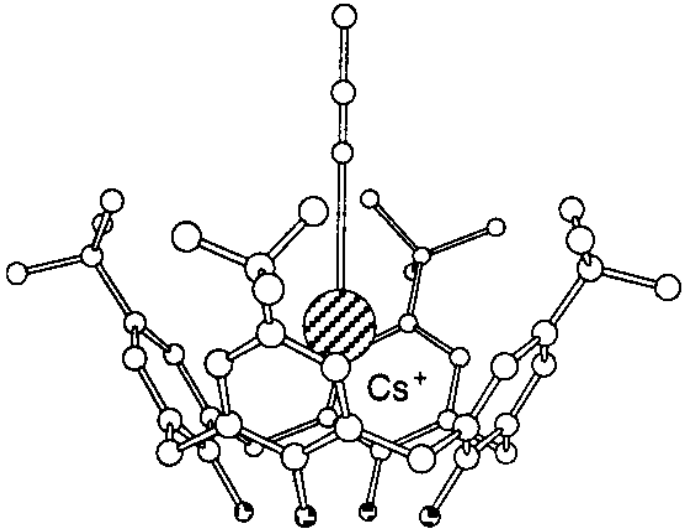


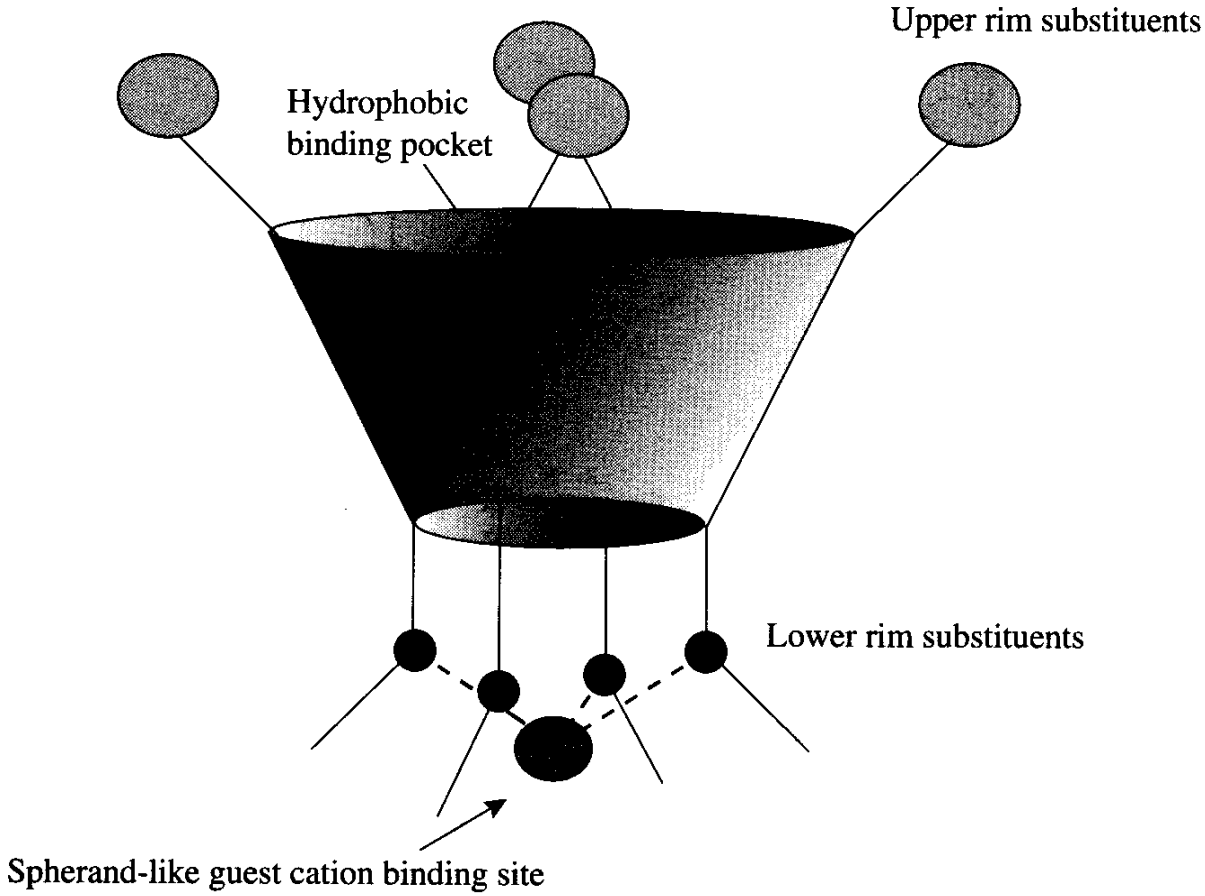


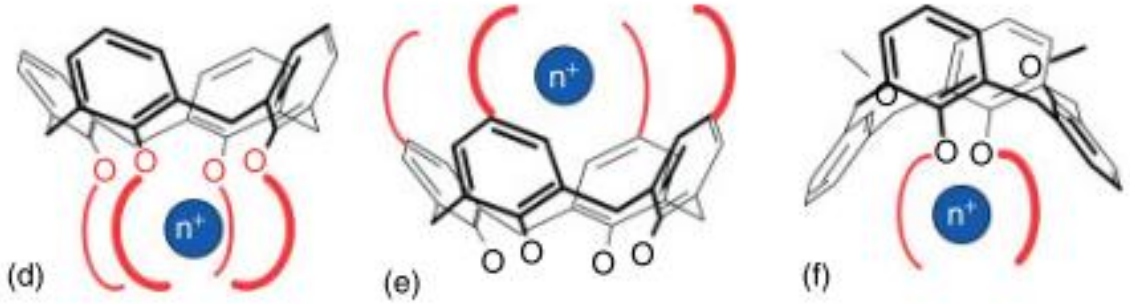
2a: R^1-R^4 = alkyl
2b: R^1, R^2 = alkyl, R^3, R^4 = OH
2c: R^1, R^3 = alkyl, R^2, R^4 = OH
2d: R^1 = alkyl, R^2–R^4 = OH
2e: R^1–R^3 = alkyl, R^4 = OH

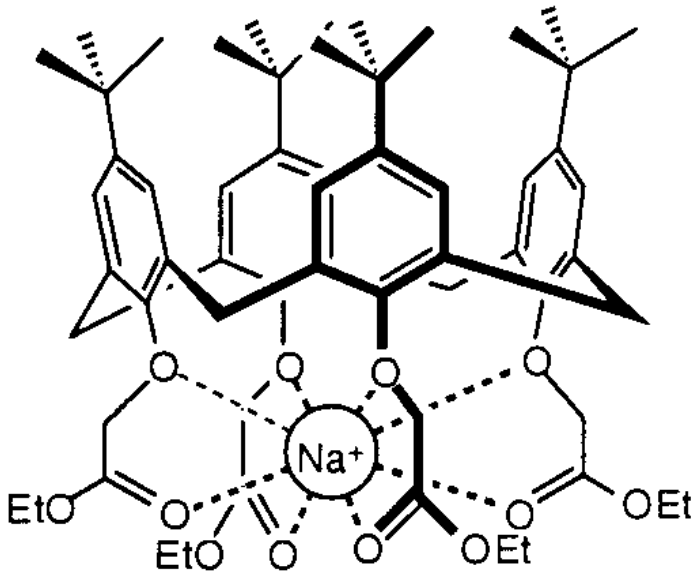


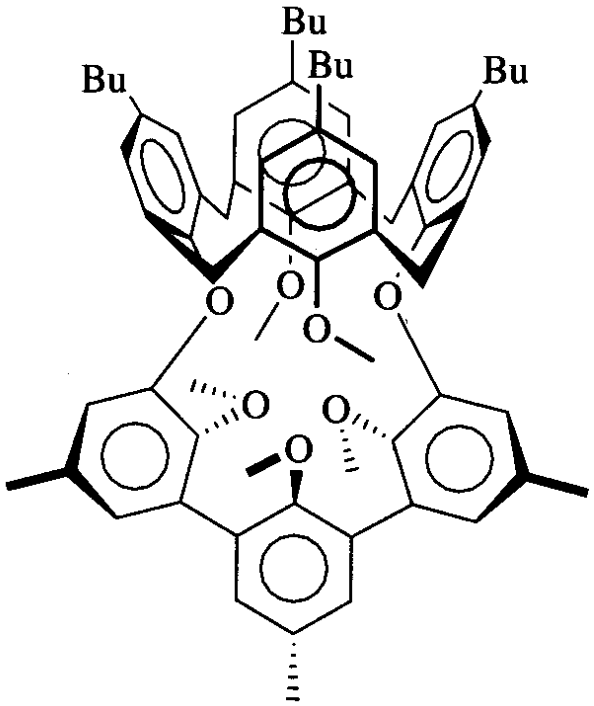

(a)
O
O
n+
O
O
n+
O
O
O
O


Cs+

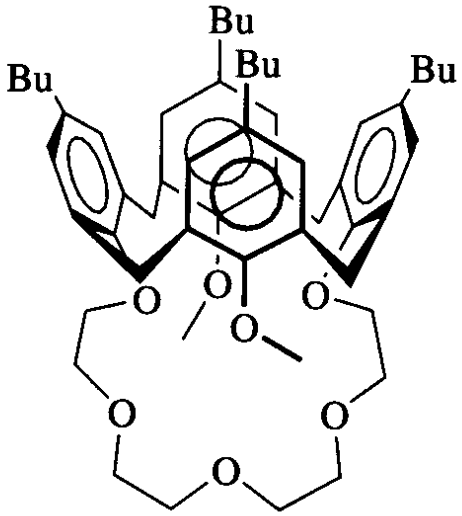

Upper rim substituents
Hydrophobic
binding pocket
Lower rim substituents
Spherand-like guest cation binding site


(d)
n+
(e)
n+
(f)
n+

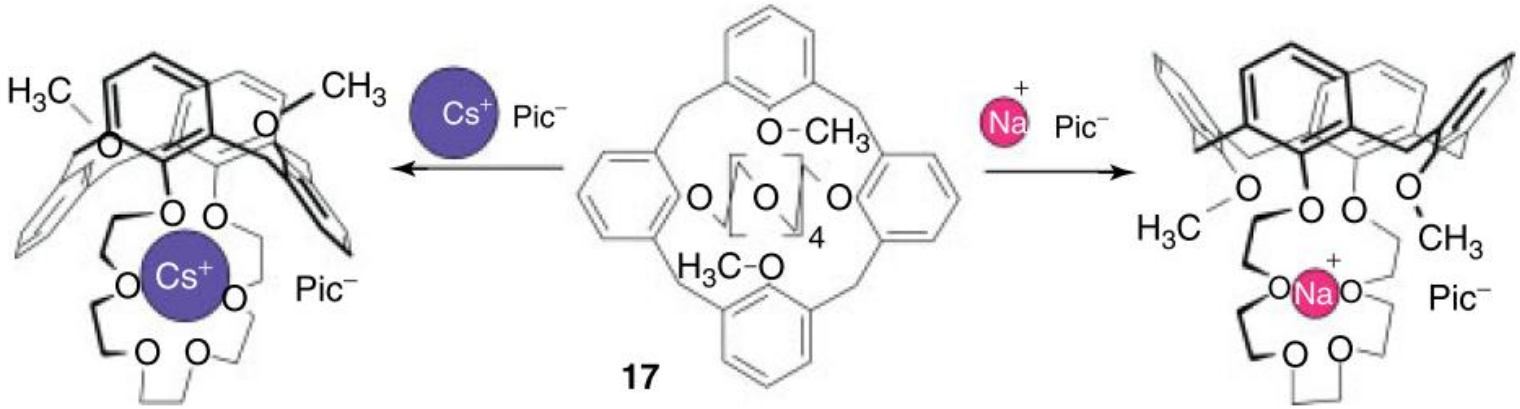

Na+
EtO
EtO
OEt
OEt



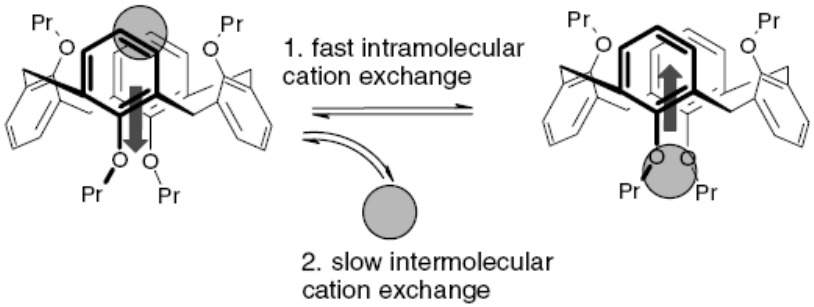
Calix-sferando

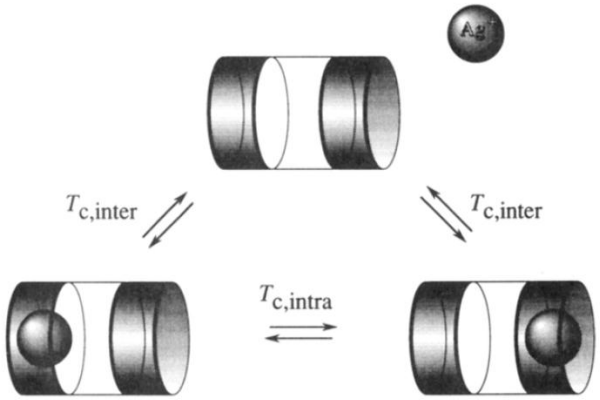


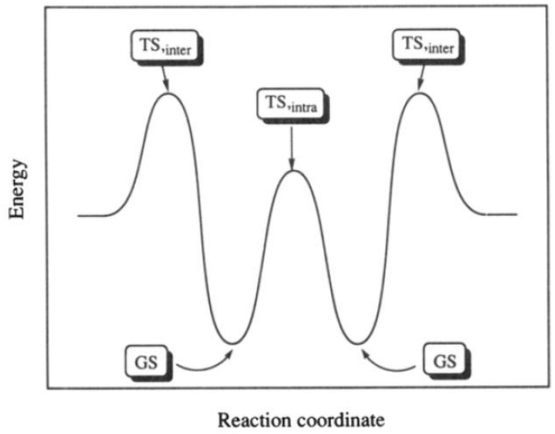
Calix-crown


H3C
CH3
O
O
O
O
O
O
O
O
Cs+
Pic−
Cs+
Pic−
O−CH3
O
O
O
4
H3C−O
17
Na+
Pic−
O
O
O
O
H3C
CH3
O
Na+
O
O
O
Pic−

Cation tunnelling



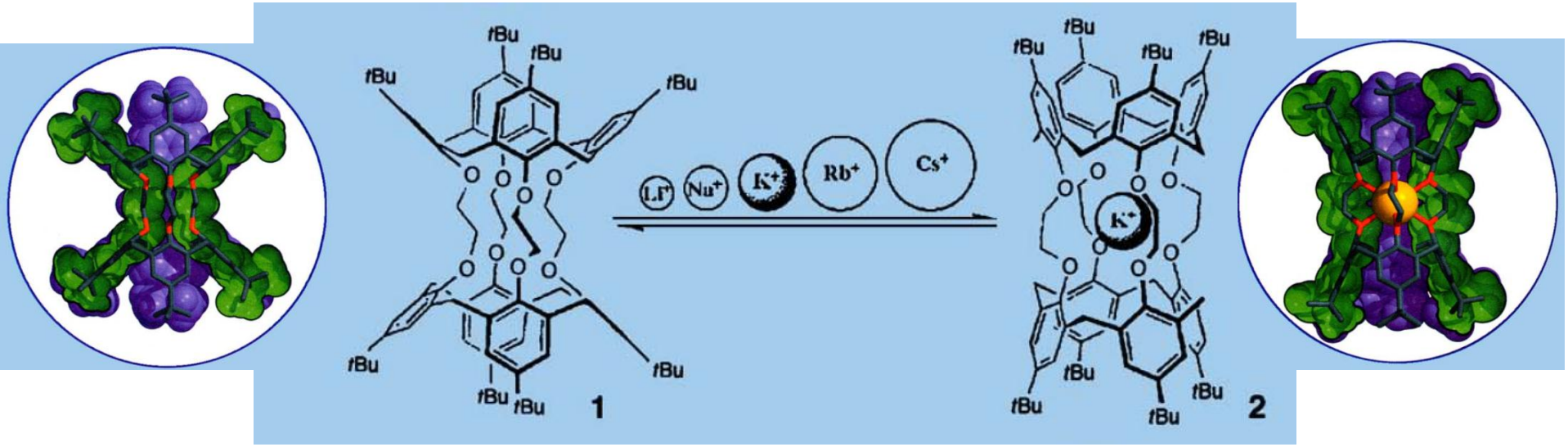


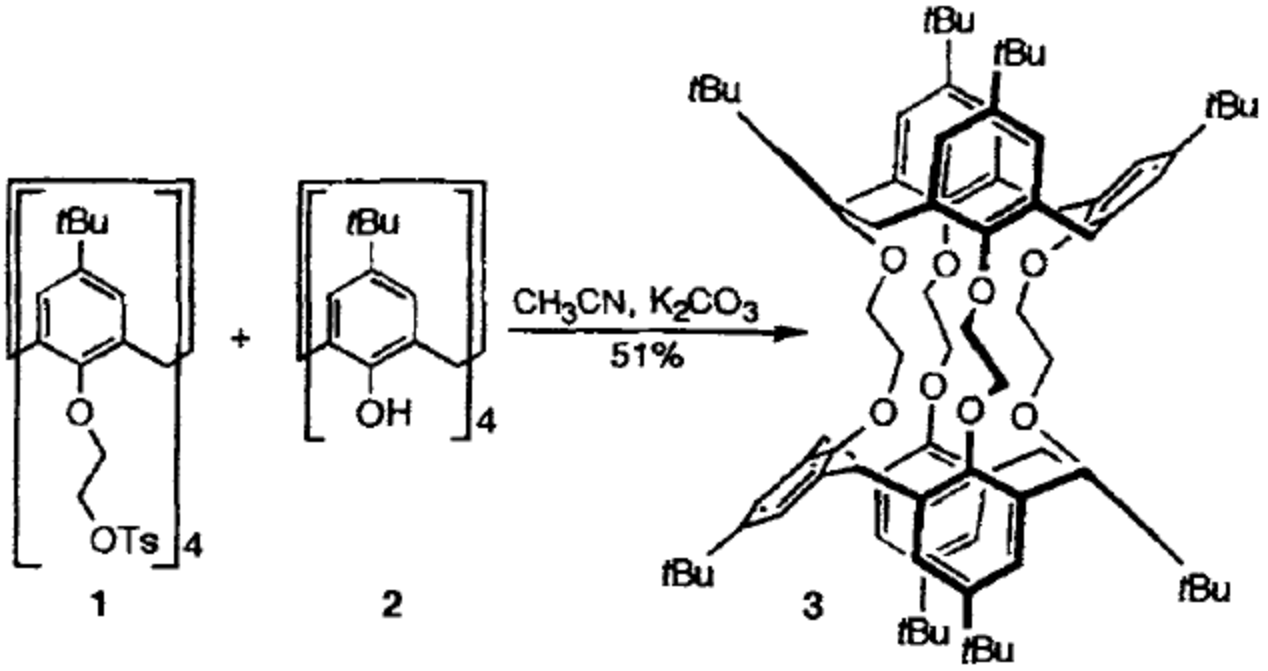


Calix[4]tube: A Tubular Receptor with Remarkable Potassium Ion Selectivity**

Philippe Schmitt, Paul D. Beer,* Michael G. B. Drew, and Paul D. Sheen

Angew. Chem. Int. Ed. Engl. **1997**, *36*, 1840





Scheme 1. Synthesis of the calix[4]tube **3**.

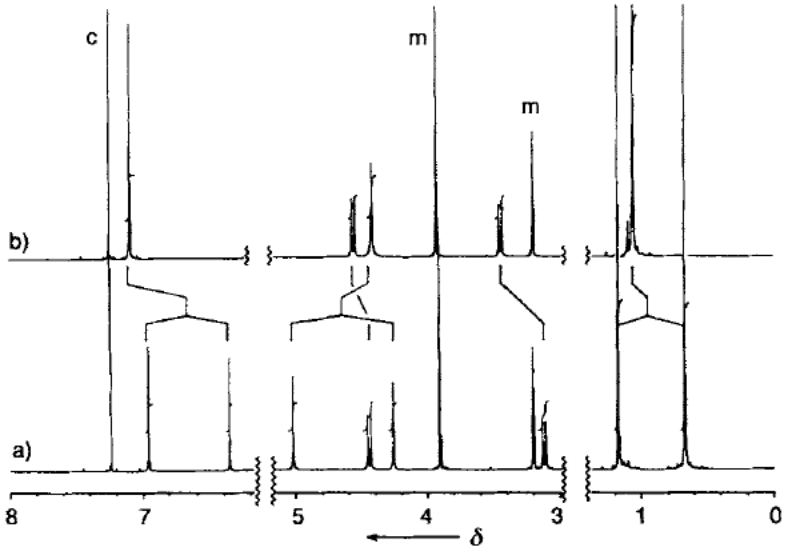


Figure 2. ^{1}H NMR spectrum of **3** [500 MHz, $CDCl_3/CD_3OD$ 4/1 (v/v)]: a) pure, b) with 10 equivalents of solid potassium iodide (c, m: solvent peaks corresponding to chloroform and methanol, respectively).

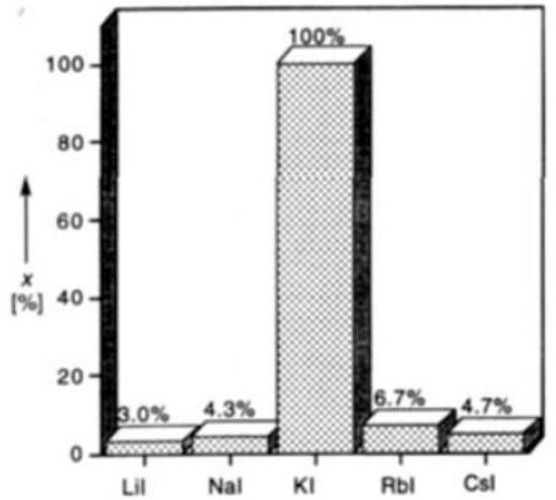


Figure 3. Uptake of alkali metal ions by **3** after treating its chloroform-methanol solution (4/1, [**3**] = 1 mM) with 10 equivalents of alkali metal iodide. The complexation ratio x was determined by integration of the ^{1}H NMR spectra after the samples had been left to stand for 90 h. In the case of KI, equilibrium was reached within an hour.

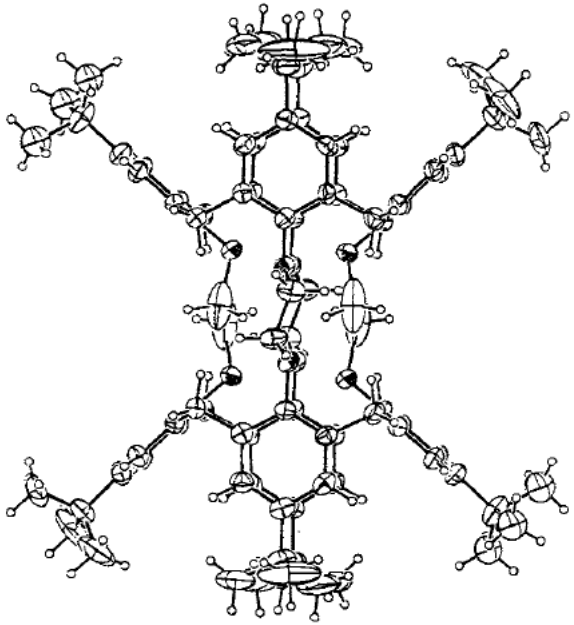


Figure 1. Crystal structure of the centrosymmetric calix[4]tube **3** in **3**·2.5 C_6H_6, with ellipsoids at 30% probability. Hydrogen atoms are included with small arbitrary radii. The benzene solvent molecules are not shown.

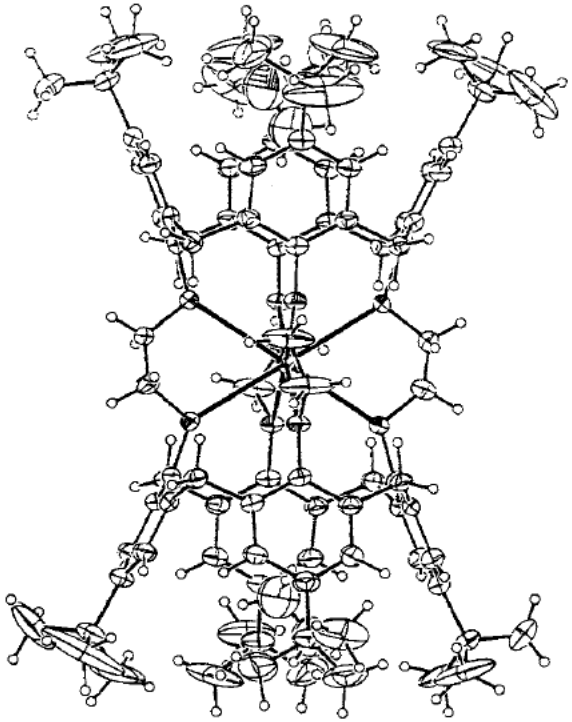
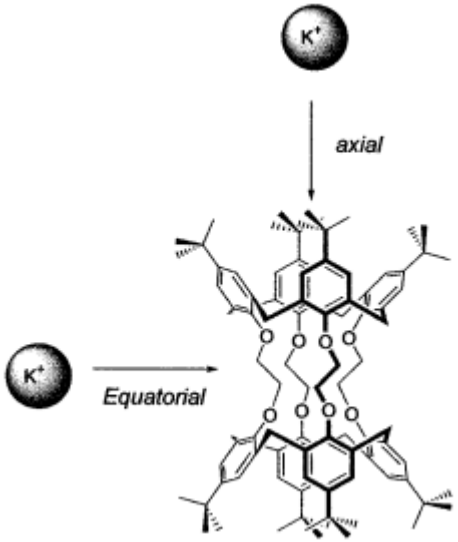
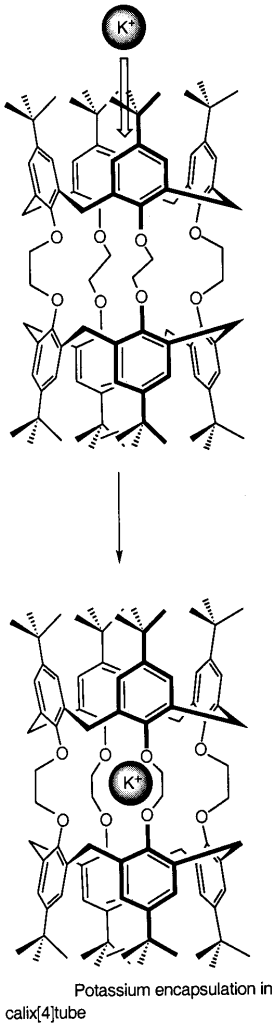


Figure 4. Structure of the K^+ complex **4** of the calix[4]tube **3** in crystals of **4**·I·3 $CHCl_3$·4 CH_3OH·H_2O. A potassium ion is located in the center of **3**, and two methanol molecules in the cone cavities. Ellipsoids are drawn at 30% probability. Hydrogen atoms are included with small arbitrary radii. The chloroform and water solvent molecules are not shown.

Calix-tubes





Potassium encapsulation in calix[4]tube

http://www.nobelprize.org/nobel_prizes/chemistry/laureates/2003/

Peter Agre **Roderick MacKinnon**

The Nobel Prize in Chemistry 2003 was awarded *"for discoveries concerning channels in cell membranes"* jointly with one half to Peter Agre *"for the discovery of water channels"* and with one half to Roderick MacKinnon *"for structural and mechanistic studies of ion channels"*.

Science
AAAS

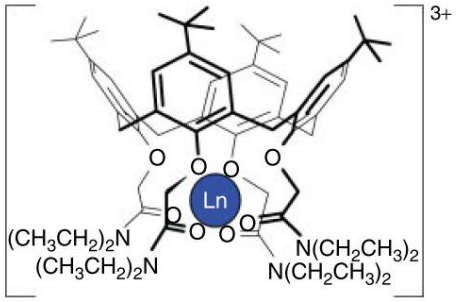
The Structure of the Potassium Channel: Molecular Basis of K^+ Conduction and Selectivity

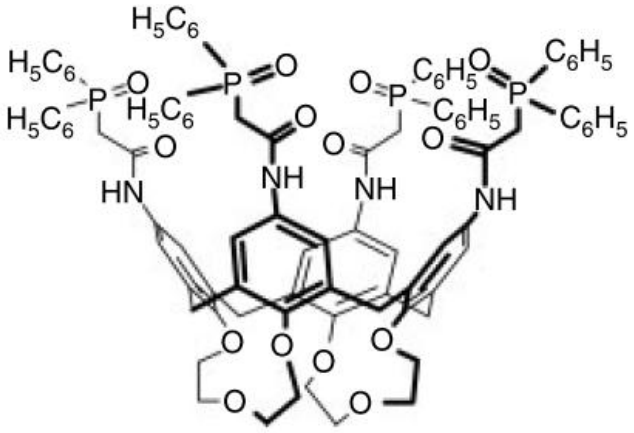
Declan A. Doyle, João Morais Cabral, Richard A. Pfuetzner, Anling Kuo, Jacqueline M. Gulbis, Steven L. Cohen, Brian T. Chait, Roderick MacKinnon*

Science **280**, 69 (1998);
DOI: 10.1126/science.280.5360.69

Ln^{3+} recognition

(treatment of radiactive waste/extraction- high distribution coefficiet even from very acidic water solutions)

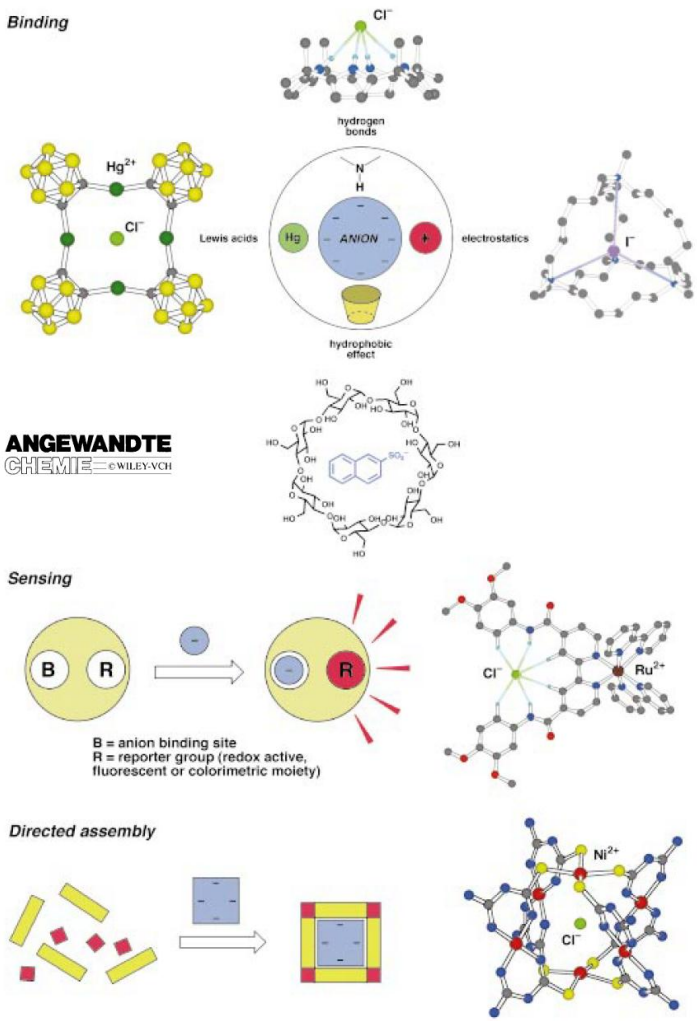




Anion Recognition and Sensing: The State of the Art and Future Perspectives

Paul D. Beer* and Philip A. Gale*

Angew. Chem. Int. Ed. **2011**, *50*, 1845–1848



N. H. Evans and P. D. Beer

DOI: 10.1002/anie.201309937

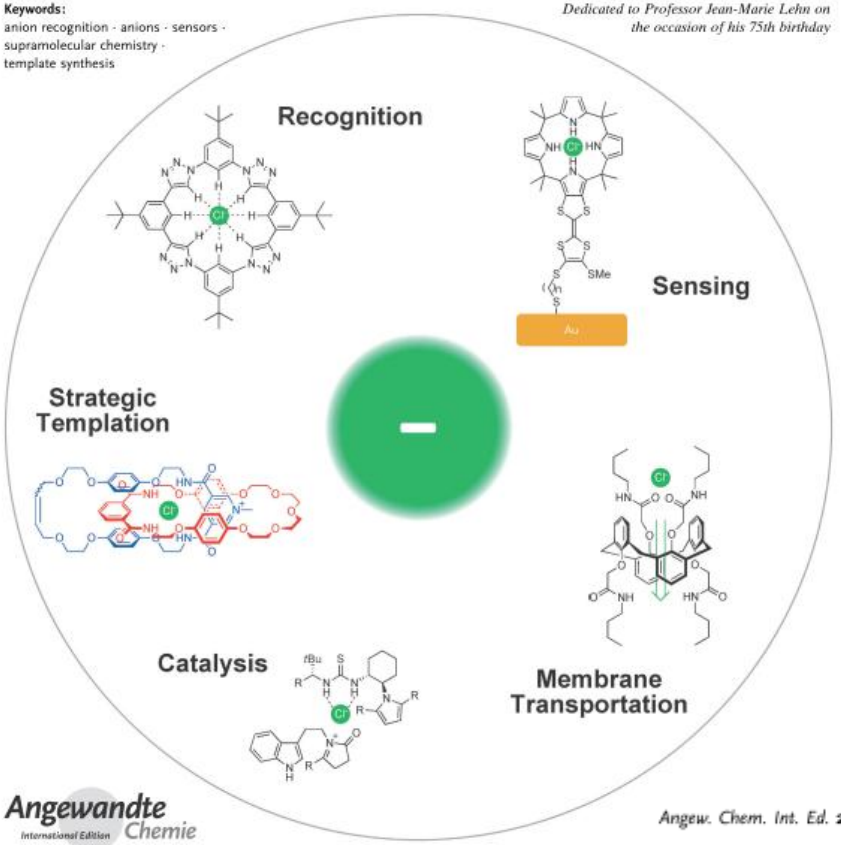
Supramolecular Chemistry of Anions

Advances in Anion Supramolecular Chemistry: From Recognition to Chemical Applications

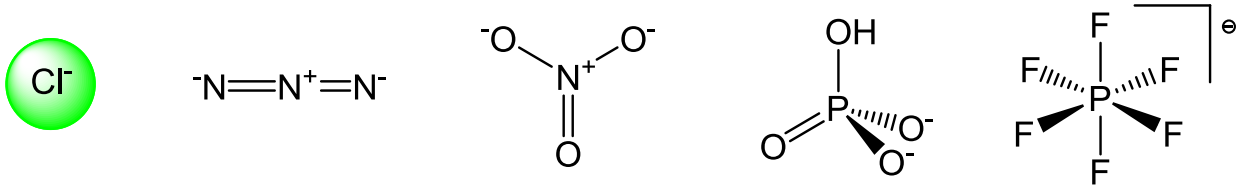
Nicholas H. Evans and Paul D. Beer**

Keywords:
anion recognition · anions · sensors · supramolecular chemistry · template synthesis

Dedicated to Professor Jean-Marie Lehn on the occasion of his 75th birthday



- anions are large and require receptors of bigger size than cations - $r(F^-) \approx rK^+$
- large diversity of shapes and geometries (spherical, linear, trigonal, tetrahedral…)



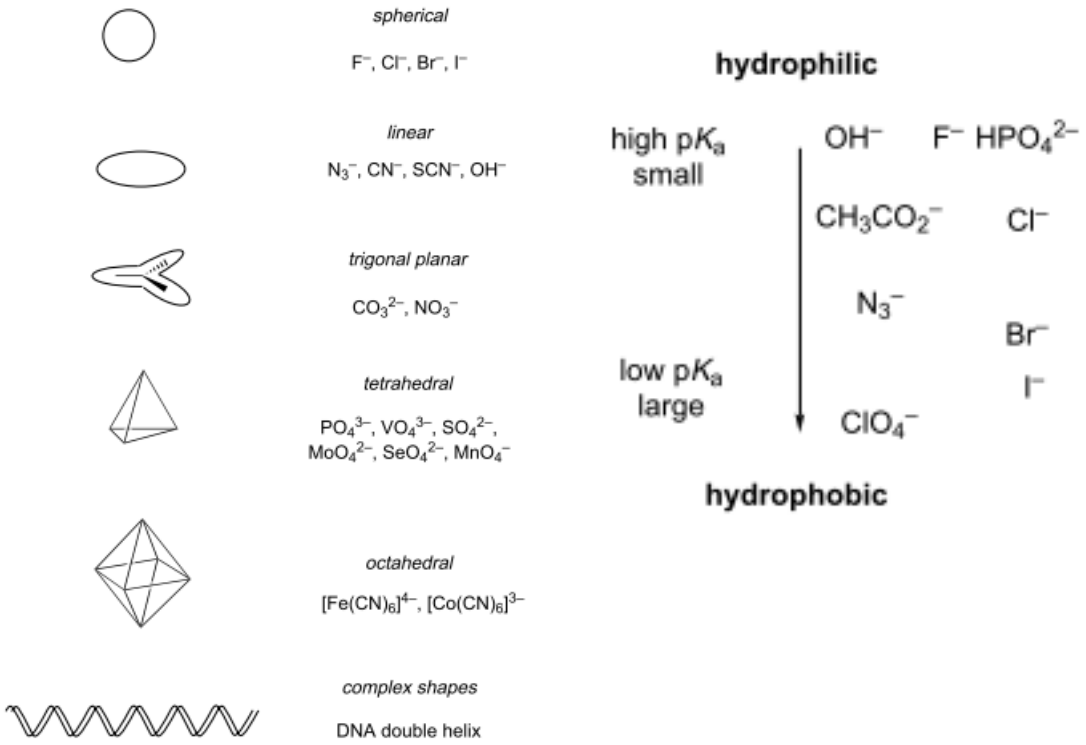
- high free energies of hydration

$\Delta_r G°_{hydr}(F^-) = -465$ kJ.mol^{-1} $\Delta_r G°_{hydr}(K^+) = -295$ kJ.mol^{-1}

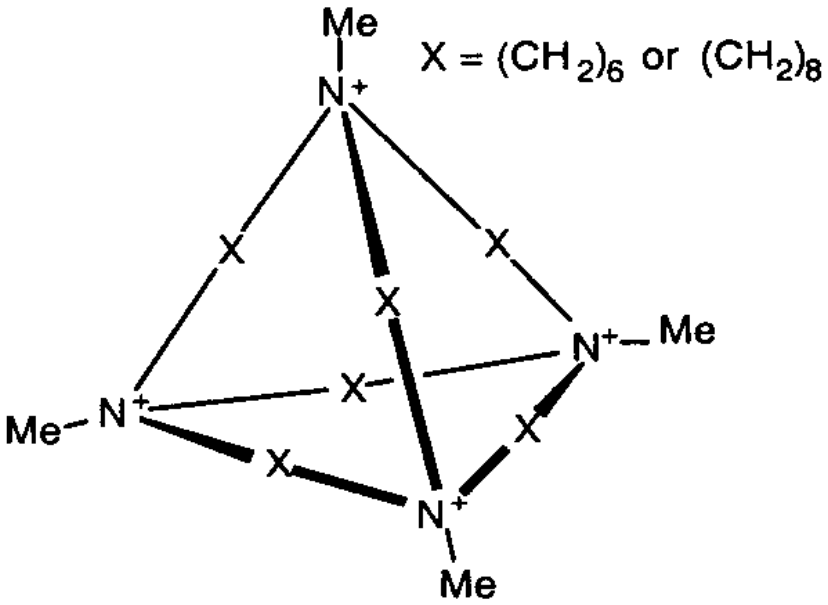
- anions are sensitive to pH (crucial for recognition on water)
- anions are coordinatively saturated : only weak interactions (H bond, electrostatic, Van der Waals), no strict coordination number
- Lewis bases

Table 1. A comparison of the radii r of isoelectronic cations and anions in octahedral environments.[7]

Cation	r [Å]	Anion	r [Å]
Na^+	1.16	F^-	1.19
K^+	1.52	Cl^-	1.67
Rb^+	1.66	Br^-	1.82
Cs^+	1.81	I^-	2.06



Host cationici



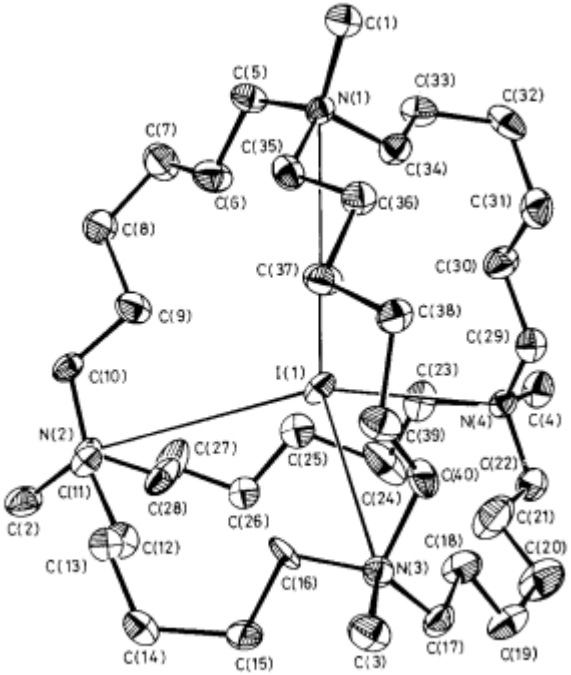
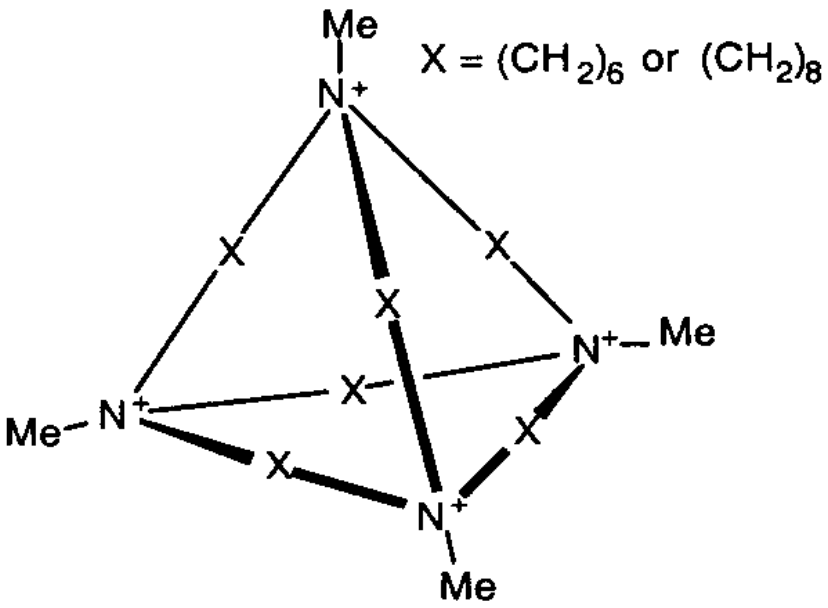


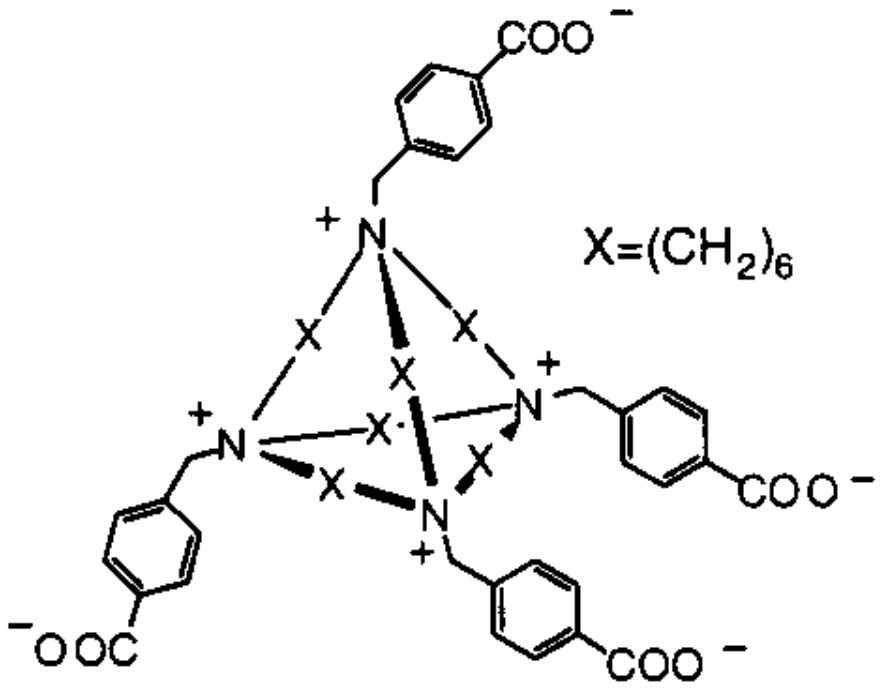
Figure 2. The X-ray crystal structure of the iodide complex of receptor **1**

Schmidtchen

Host cationici



Host zwitter-ionici

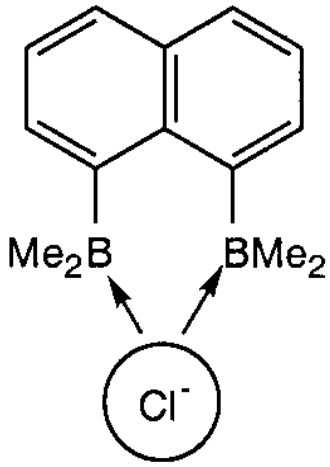


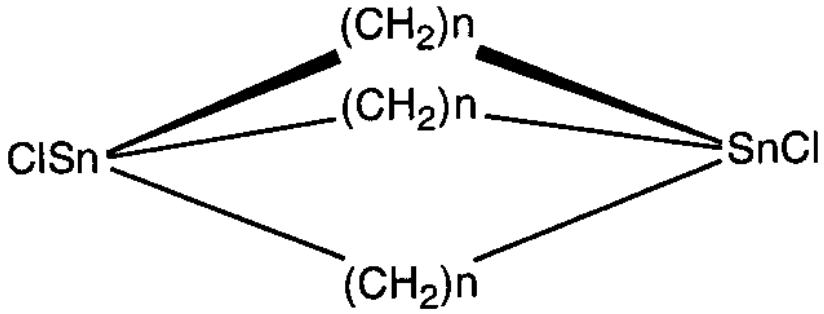
K(Br^-) = 1020 (H_2O)

K (Br^-) = 2150 (H_2O)

Selettività <<

K(Br^-) = 1020 K(I^-) = 500 K(Cl^-) = 50

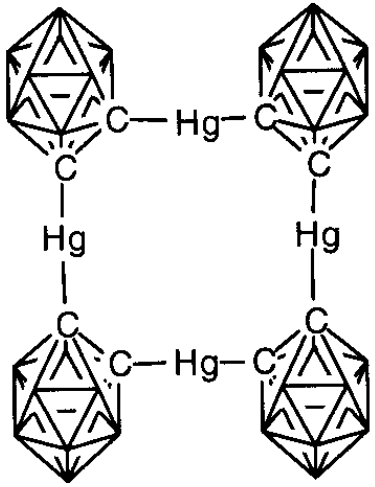




n= 6 , 8

Organotin cryptand encapsulates fluoride anions.

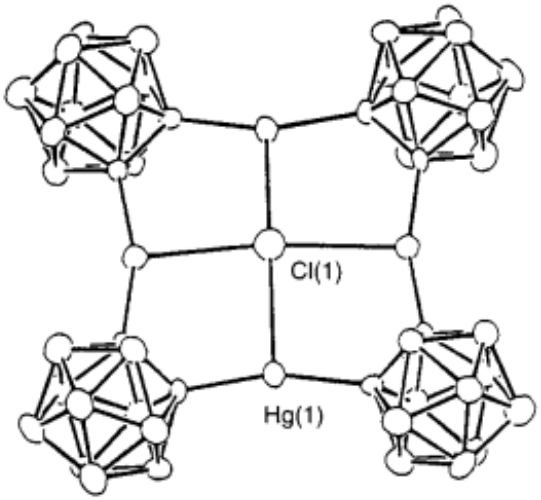
Organo-Boro



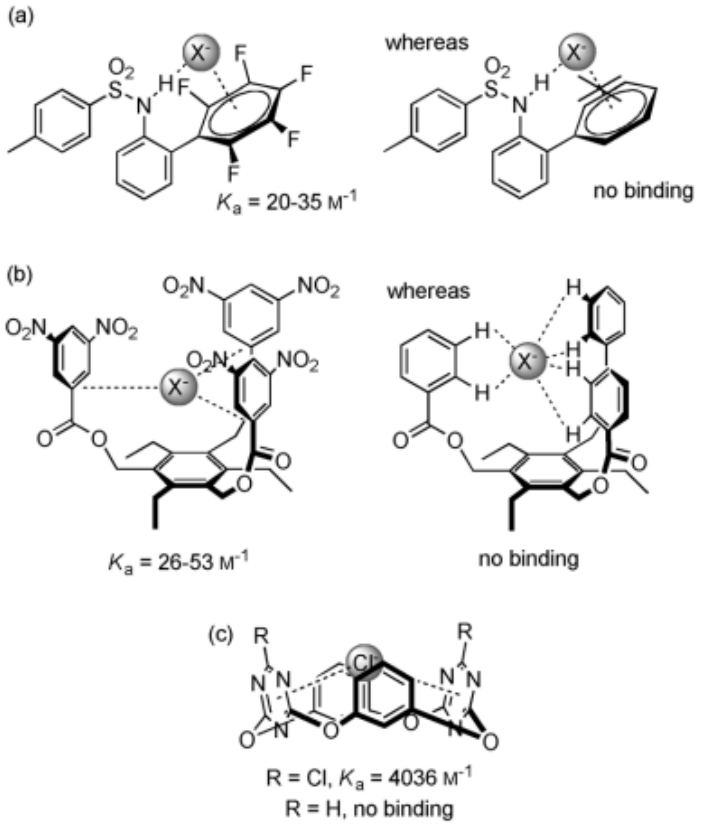
= $B_{10}C_2$

Organo-Sn(IV)

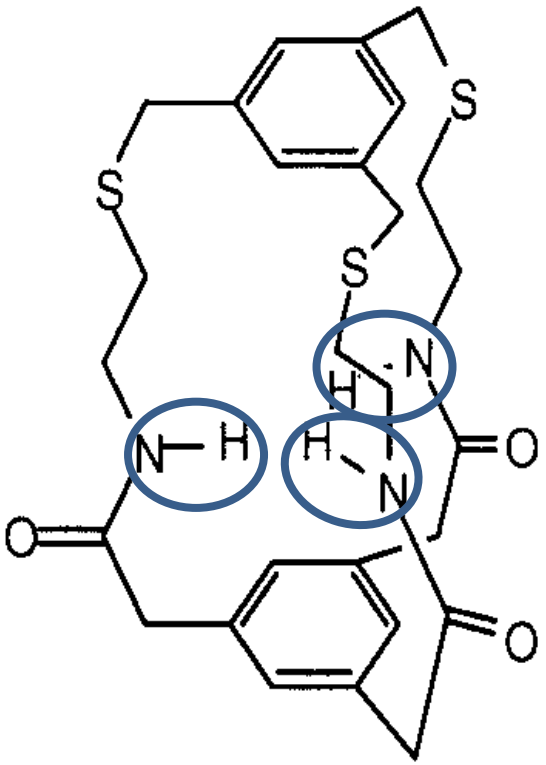
Organo-Hg(II)



Hawthorne

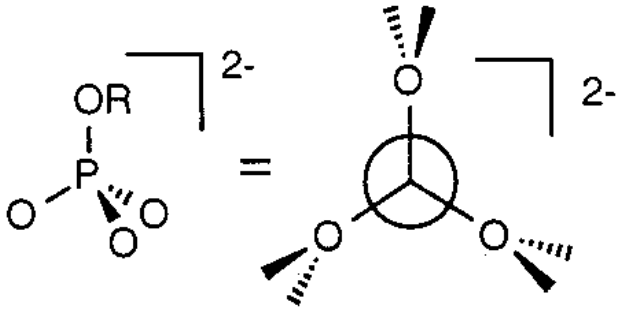

(a)
whereas
K_a = 20-35 M^{-1}
no binding
(b)
whereas
K_a = 26-53 M^{-1}
no binding
(c)
R = Cl, K_a = 4036 M^{-1}
R = H, no binding

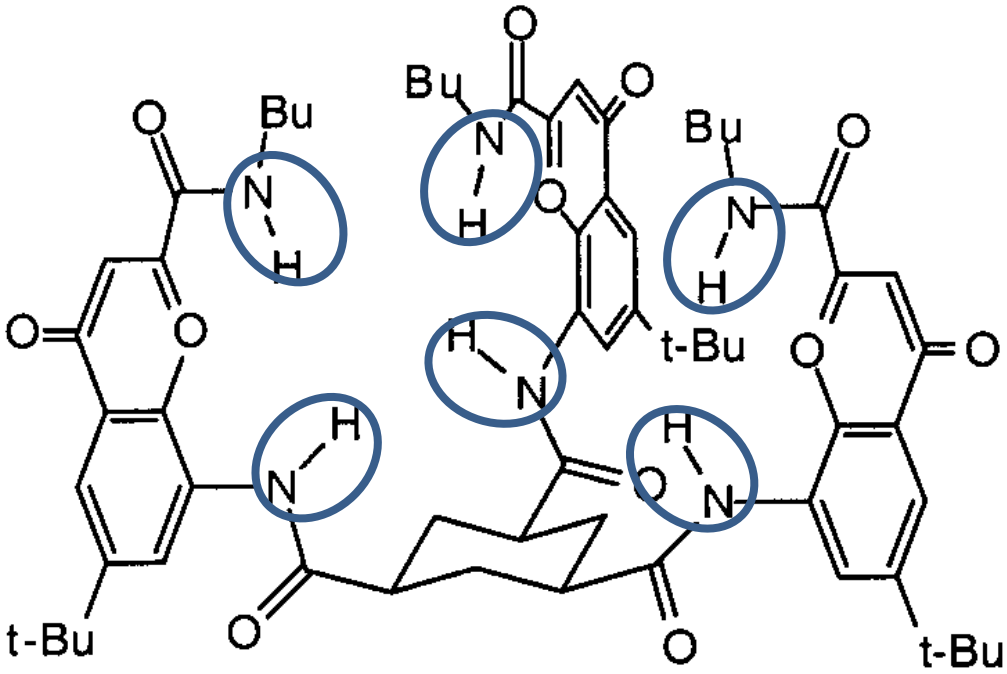
Berryman



Hydrogen bonding receptor for fluoride anions.

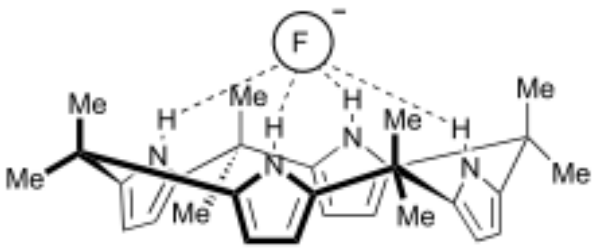
Pascal

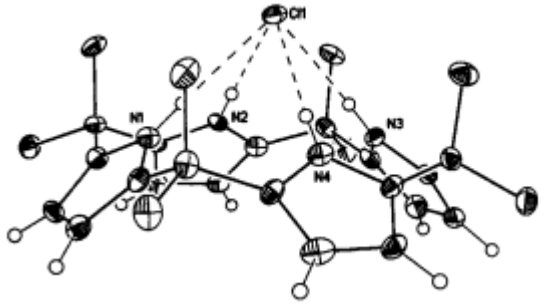


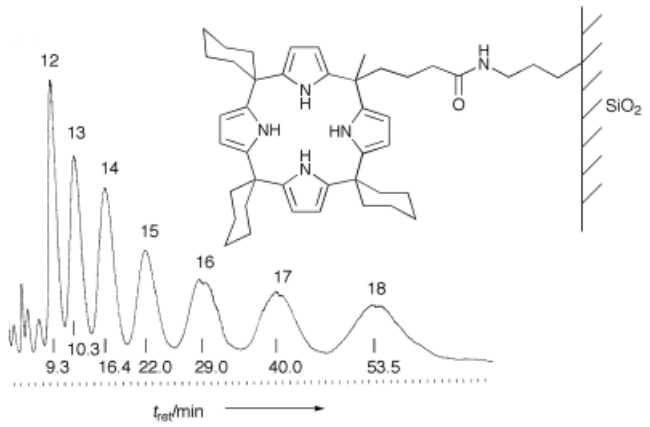


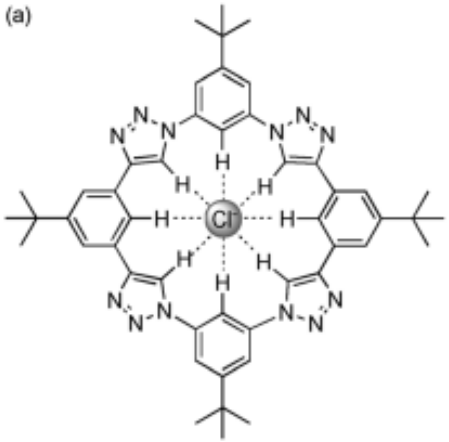
Trigonal receptors can bind phosphate anions strongly in competitive solvents.

Raposo



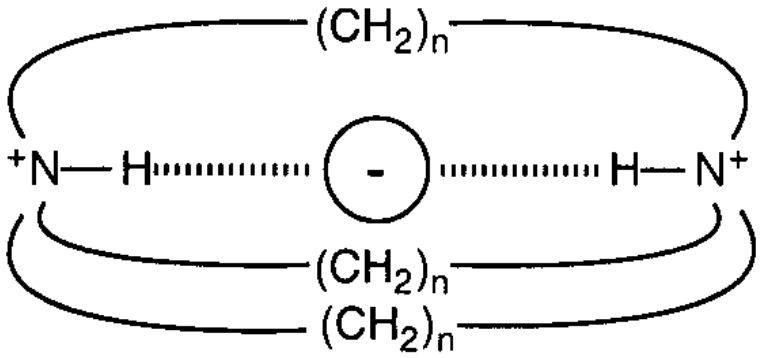




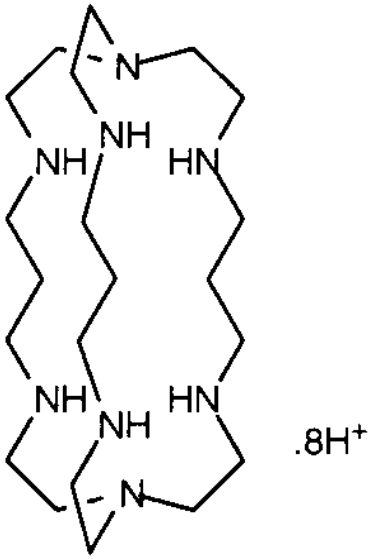


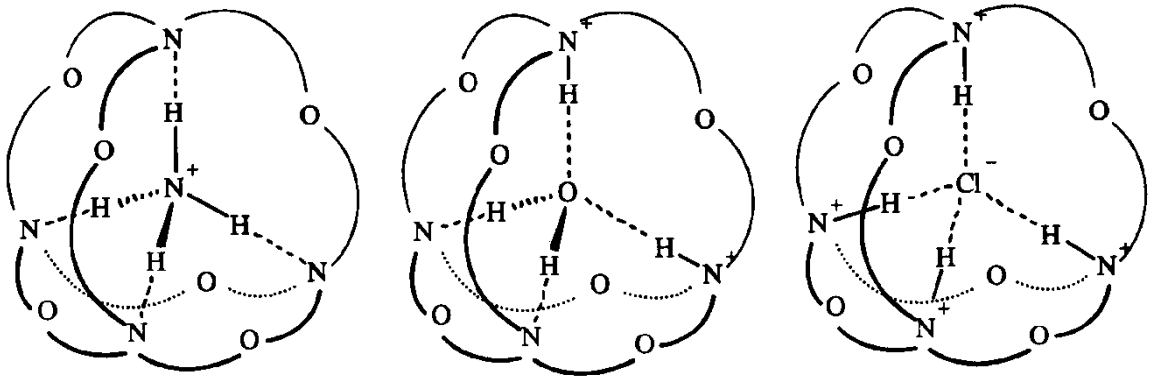
HPLC Separation of oligonuclotides of different lenght

Sessler



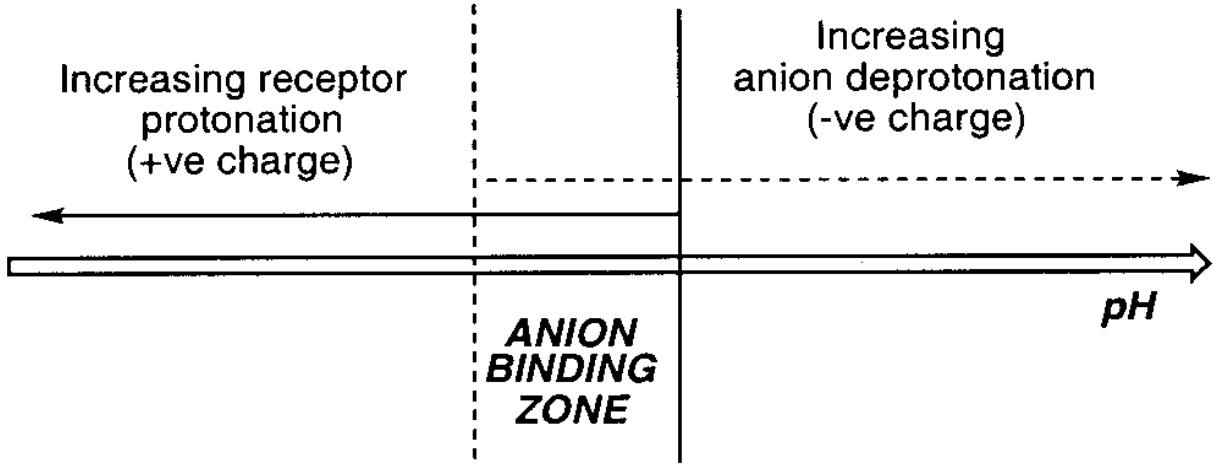
poliazamacrocicli



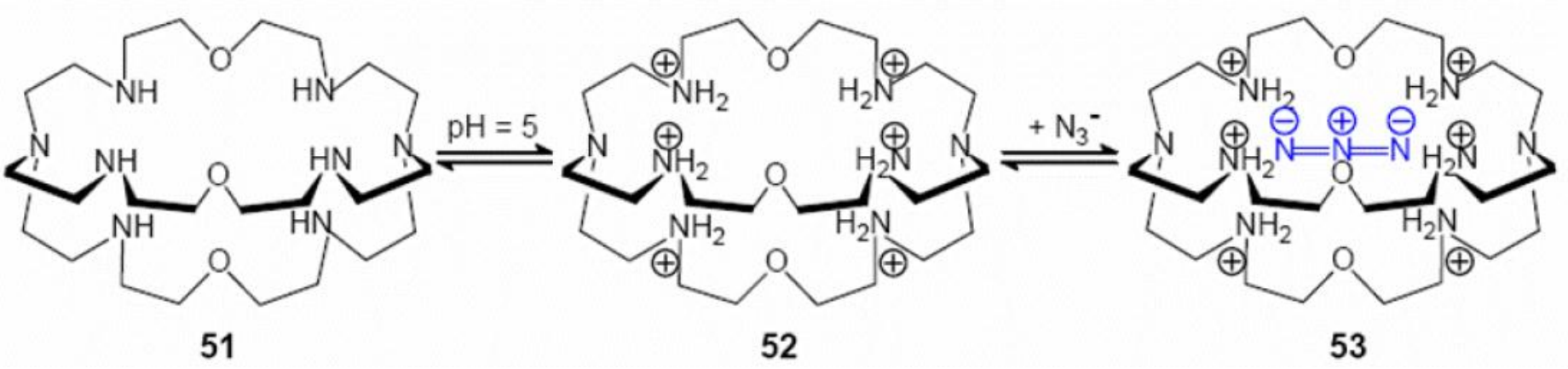


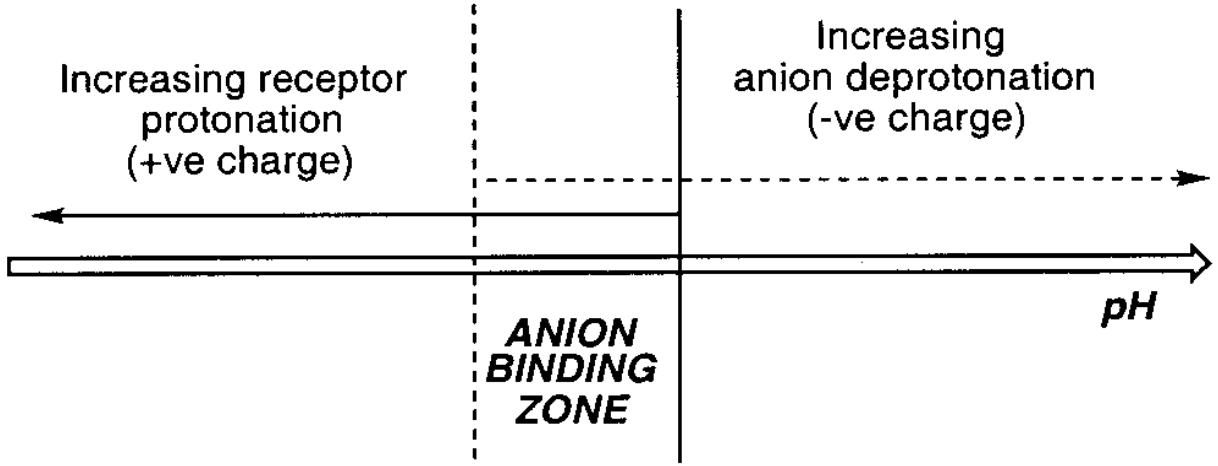
Receptors for anions.

Lehn

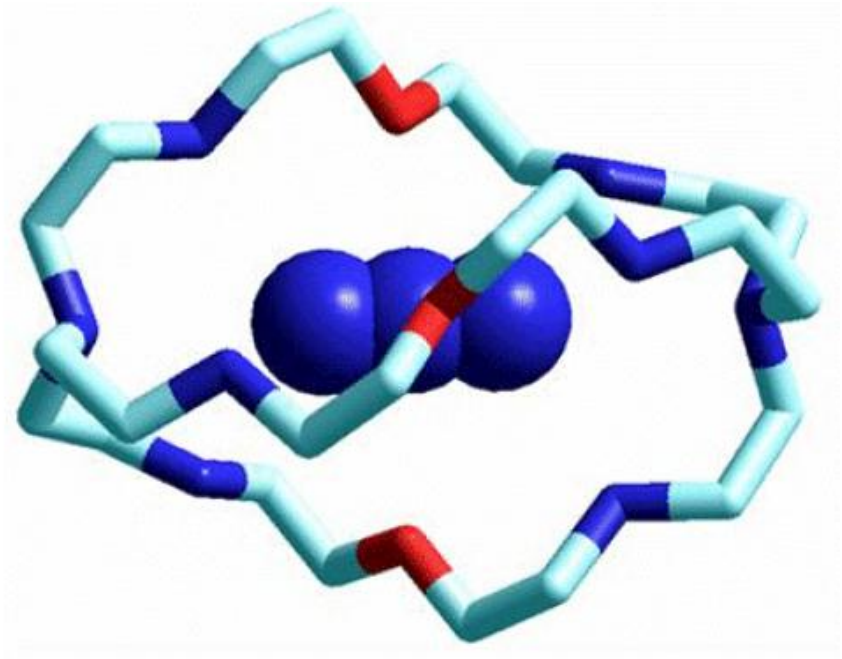


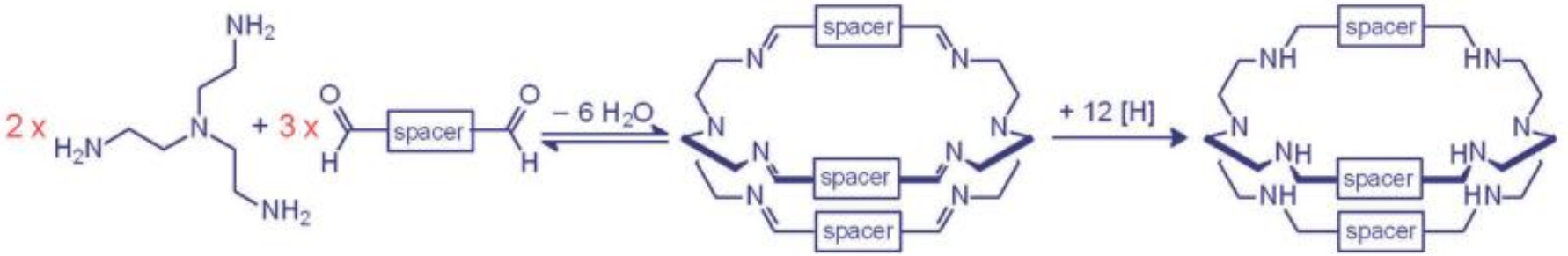
Balance between host protonation and guest deprotonation.

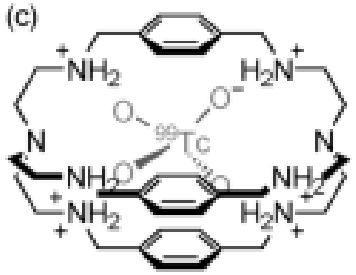




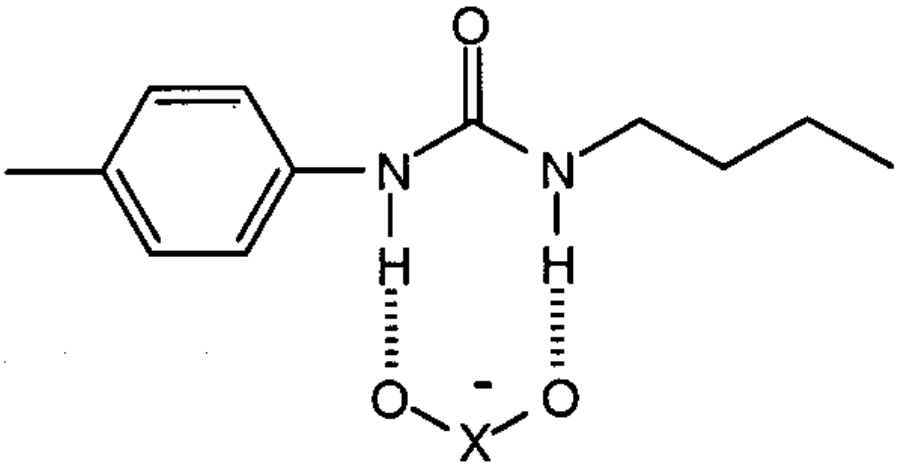
Balance between host protonation and guest deprotonation.



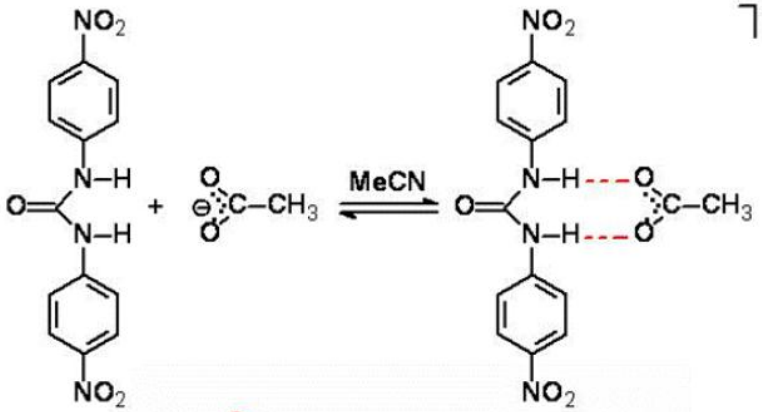

2 x
NH2
H2N
N
NH2
+ 3 x
O
H
spacer
O
H
– 6 H2O
spacer
N
N
N
N
N
N
spacer
spacer
+ 12 [H]
spacer
NH
HN
N
N
NH
HN
NH
HN
spacer
spacer


(c)
NH2
H2N
O
O
99Tc
N
N
NH2
NH2
NH2
H2N

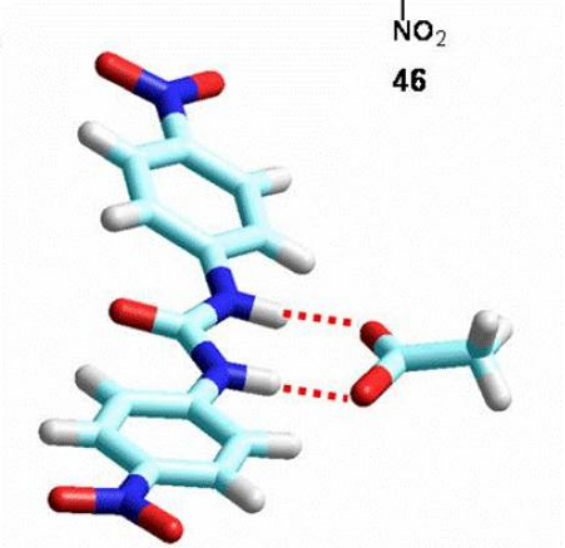
Fabrizzi



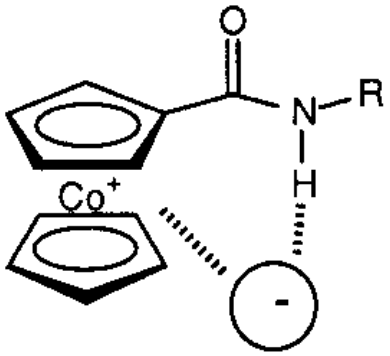
a



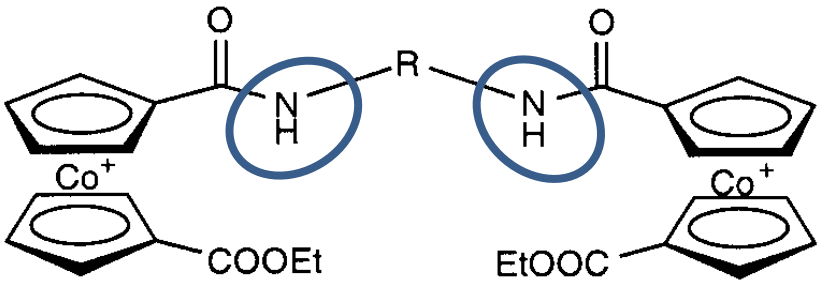
b

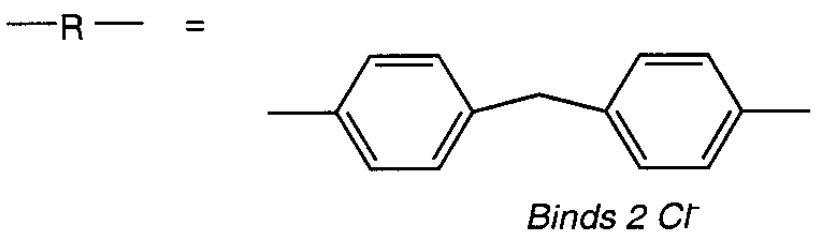


Fabrizzi



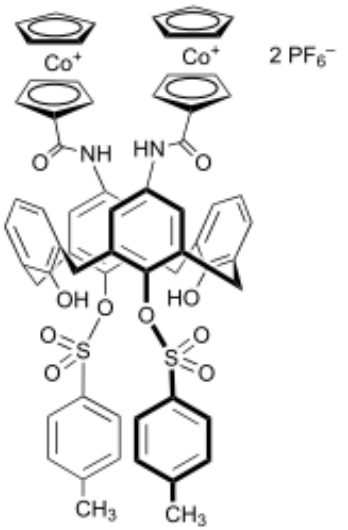
Amide functionalized cobaltocenium binds anions.



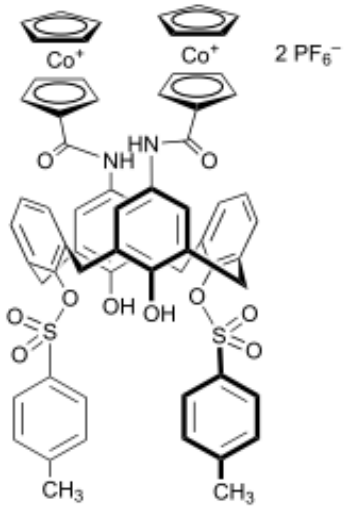


Cobaltocenium based anion receptors have easily tunable binding sites.

Beer



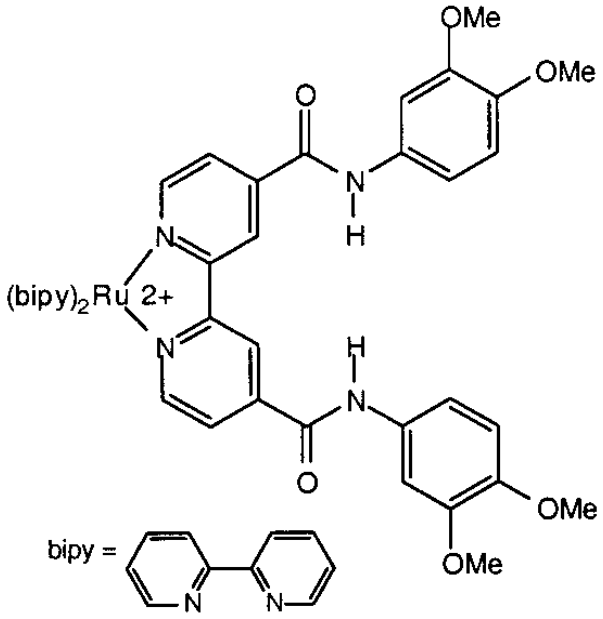
50

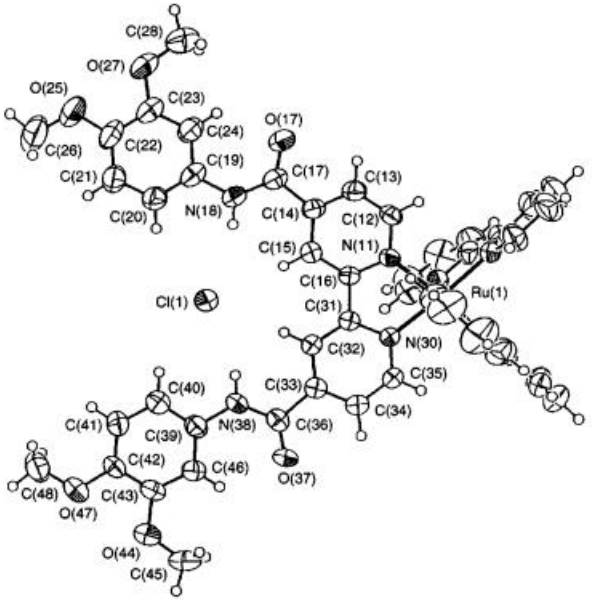


51

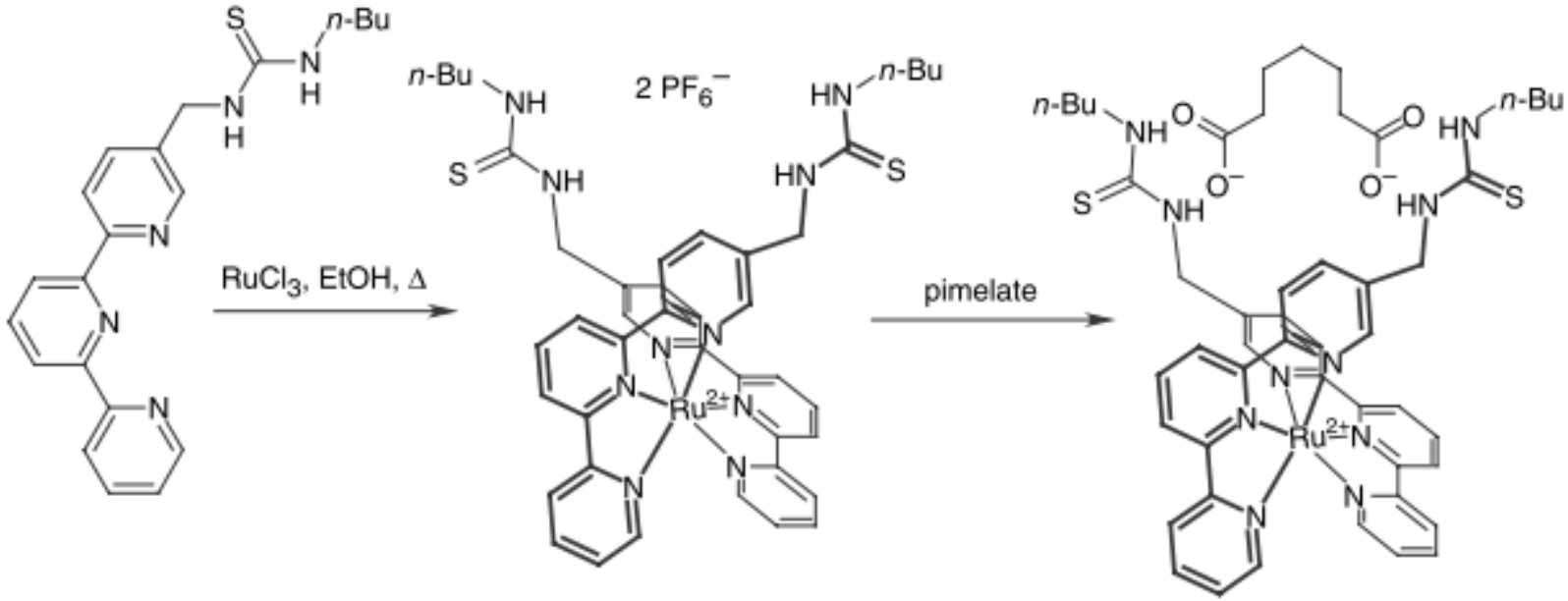
50: $CH_3CO_2^-$ >> $H_2PO_4^-$

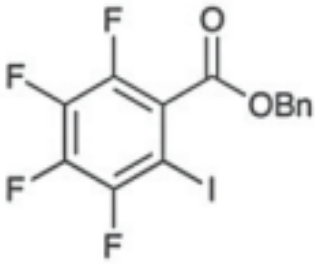
51: $CH_3CO_2^-$ >> HPO_4^-

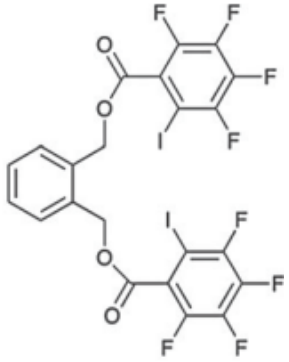

OMe
OMe
O
N
H
N
(bipy)2Ru 2+
N
H
N
O
OMe
OMe
bipy =
N
N

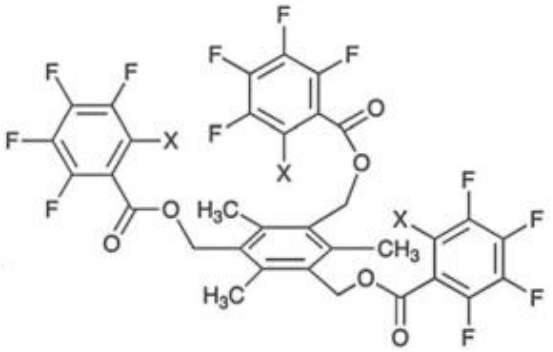

C(28)
O(27)
O(25)
C(23)
C(24)
O(17)
C(26)
C(22)
C(19)
C(17)
C(13)
C(21)
C(20)
N(18)
C(14)
C(12)
C(15)
N(11)
C(16)
Cl(1)
C(31)
Ru(1)
C(32)
N(30)
C(35)
C(40)
C(33)
C(41)
C(39)
N(38)
C(36)
C(34)
C(42)
C(46)
O(37)
C(48)
C(43)
O(47)
O(44)
C(45)

Beer


S
n-Bu
N
H
N
H
N
N
N
RuCl3, EtOH, Δ
n-Bu
NH
S
NH
2 PF6−
HN
n-Bu
HN
S
Ru2+
pimelate
O
O
O−
O−

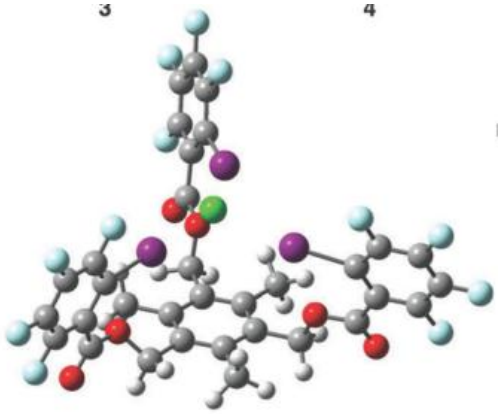




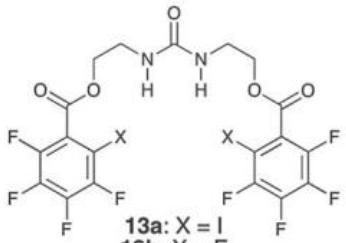


ortho-substituted iodotetrafluroroarenes on to trimethylbenzene scaffold

In acetone: $Cl^- > Br^- > I^-$



Taylor



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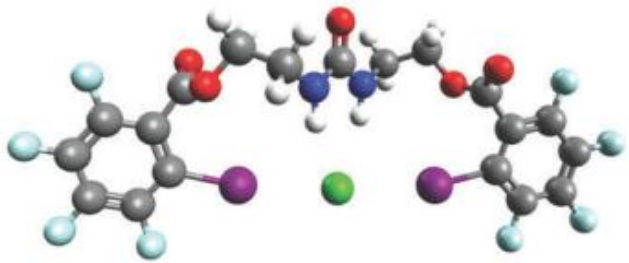
13b: X = F



(a)

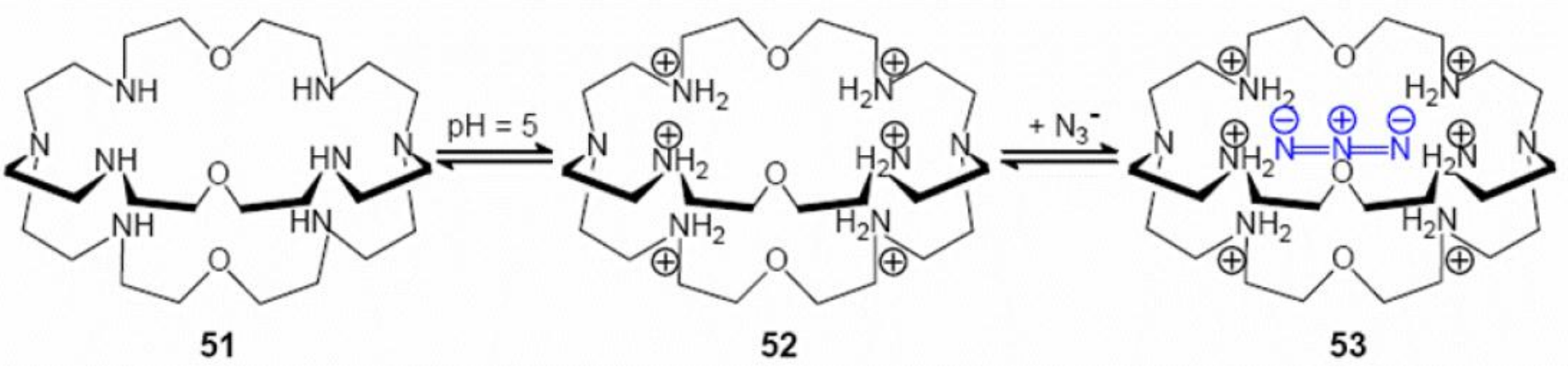
A cascade complex.

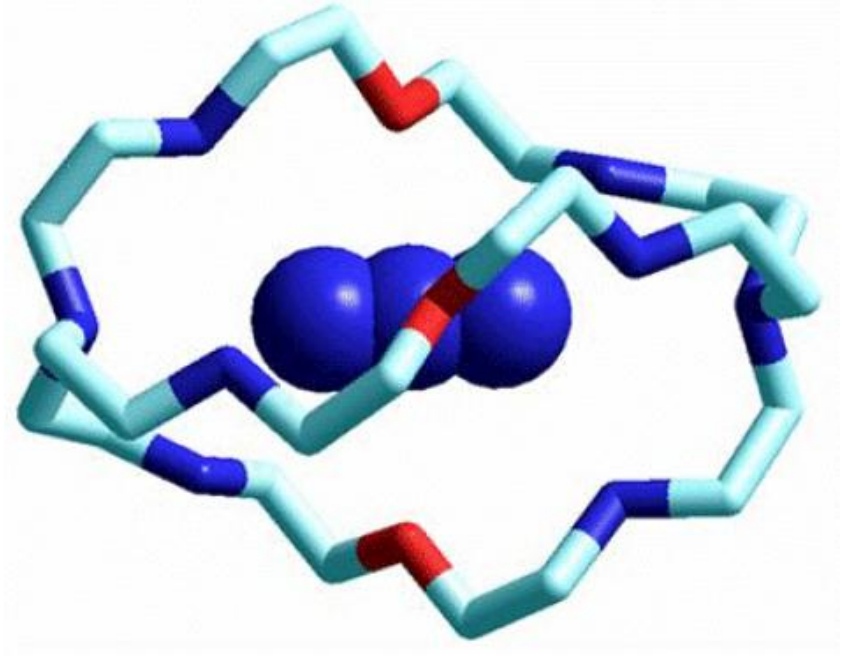
(b)

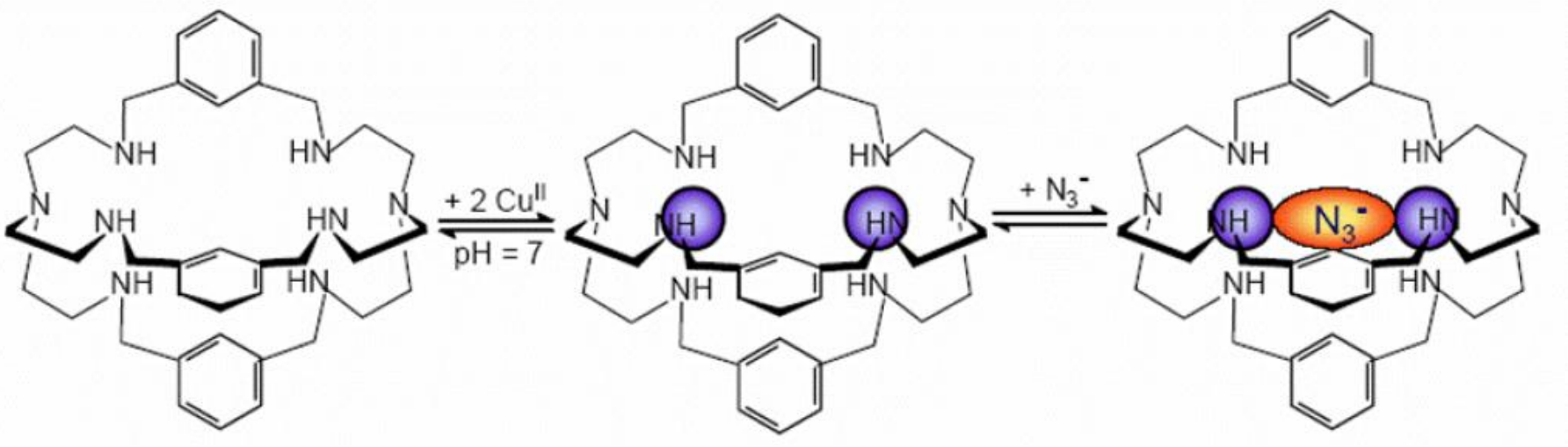
Receptor with individual cation and anion recognition sites.

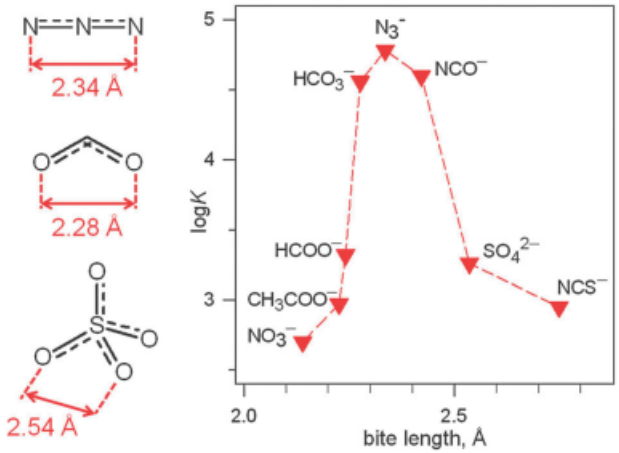
(c)

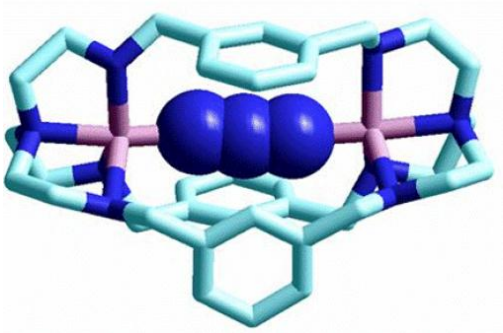
Receptor for zwitterionic guests.

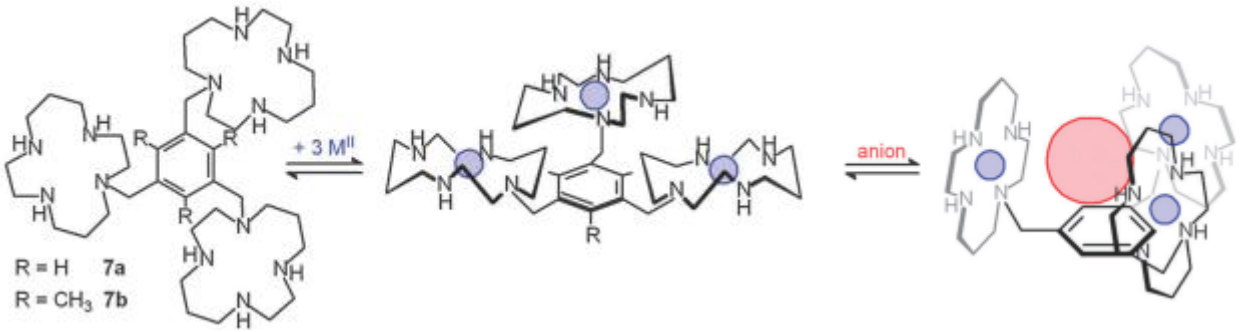

pH = 5
+ N_3^-
51
52
53




NH
HN
N
+ 2 Cu^II
pH = 7
+ N3-
N3-


2.34 Å
2.28 Å
2.54 Å
log K
bite length, Å
N3-
HCO3-
NCO-
HCOO-
CH3COO-
NO3-
SO4 2-
NCS-





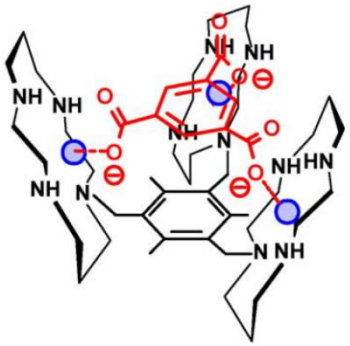
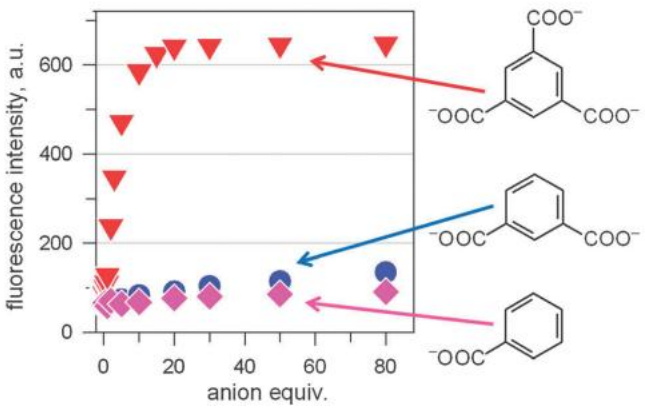
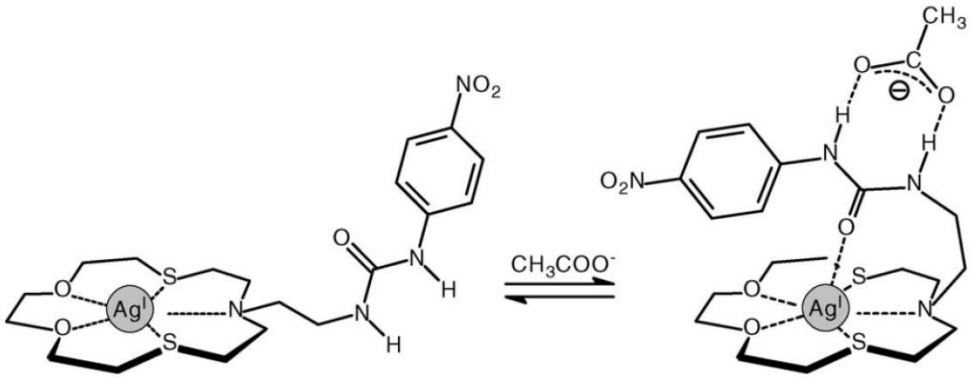
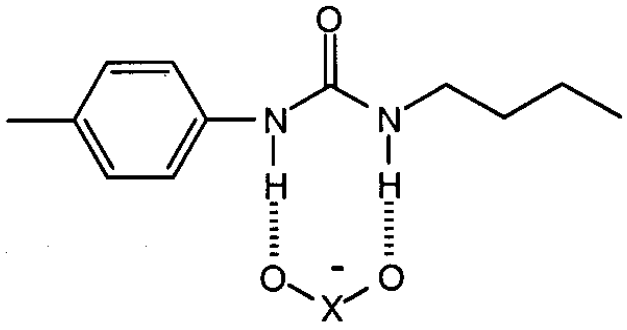


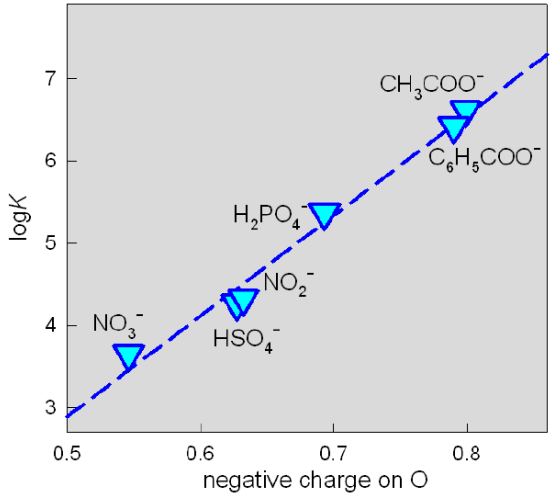
Fig. 25 The crystal structure of the complex salt $[Ni^{II}_3(\mathbf{7a})](ClO_4)_6 \cdot H_2O$.[58] Non-coordinating ClO_4^- ions and water molecule have been omitted for clarity, as well as hydrogen atoms. Each low-spin Ni^{II} centre shows a square coordination geometry.

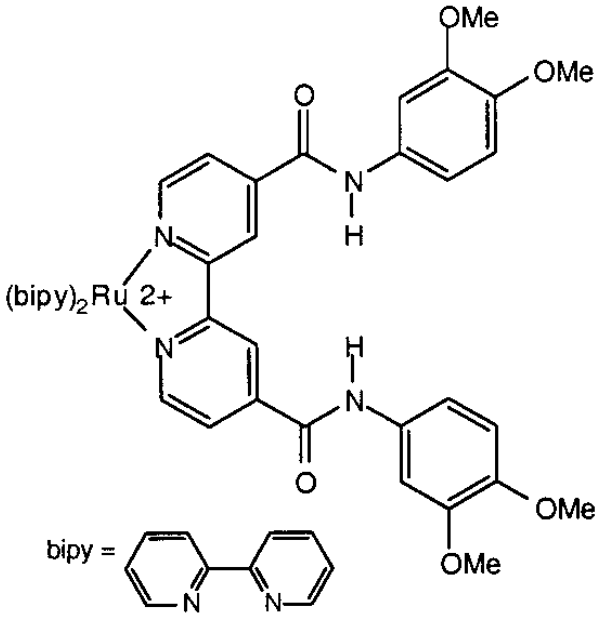

fluorescence intensity, a.u.
0
200
400
600
0
20
40
60
80
anion equiv.
COO⁻
⁻OOC
COO⁻
⁻OOC
COO⁻
⁻OOC

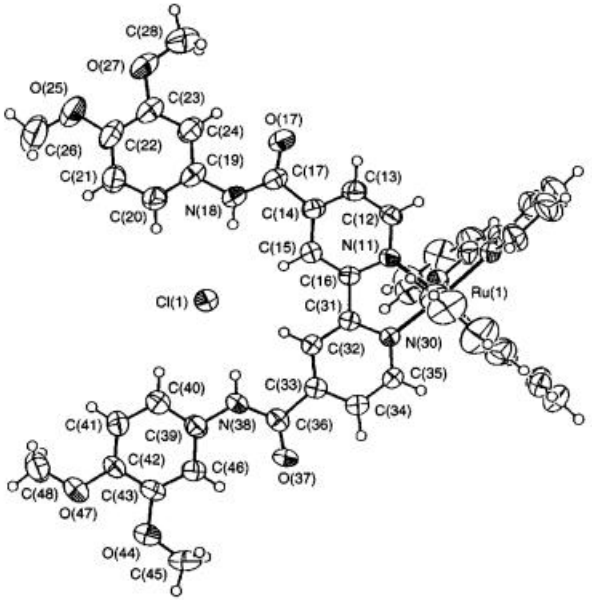


Scheme 4. Enhanced affinity of the urea subunit toward acetate, through coordination of the carbonyl oxygen atom to the proximate Ag^{I} centre.






OMe
OMe
O
N
H
N
(bipy)2Ru 2+
N
H
N
O
OMe
OMe
bipy =
N
N


C(28)
O(27)
O(25)
C(23)
C(24)
O(17)
C(26)
C(22)
C(19)
C(17)
C(13)
C(21)
C(20)
N(18)
C(14)
C(12)
C(15)
N(11)
C(16)
Ru(1)
Cl(1)
C(31)
C(32)
N(30)
C(35)
C(33)
C(34)
C(40)
C(41)
C(39)
N(38)
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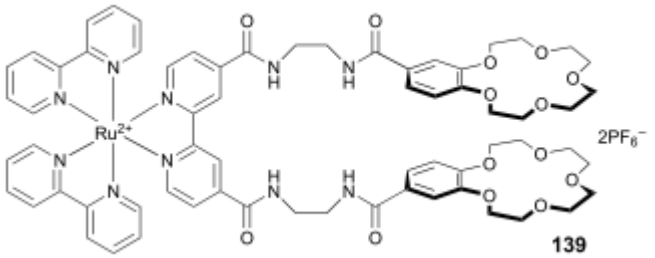
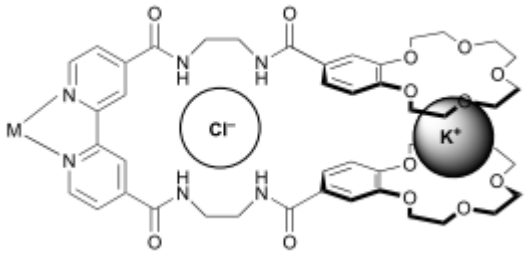
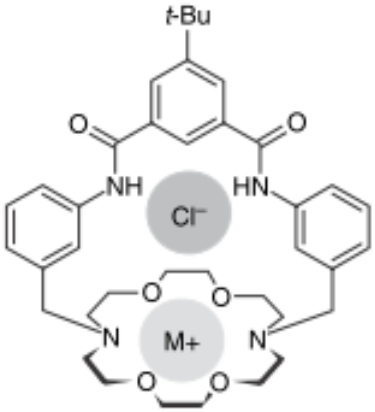
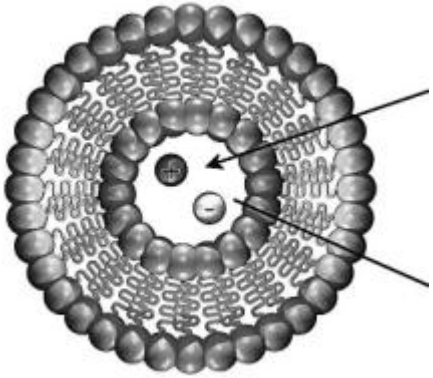
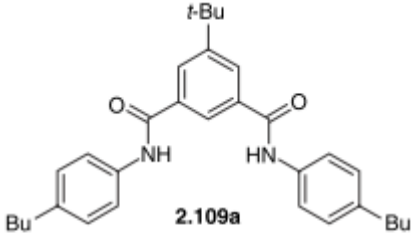
C(42)
C(46)
O(37)
C(48)
C(43)
O(47)
O(44)
C(45)


Ru2+
2PF6−
139

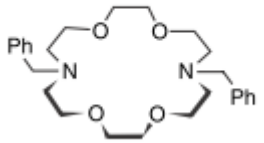

M
Cl−
K+

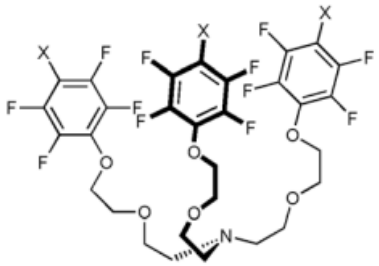




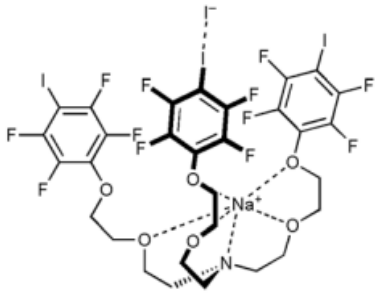


2.109a



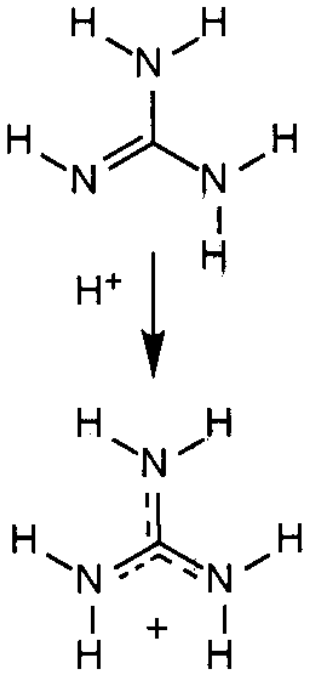


2a: X = I
2b: X = F

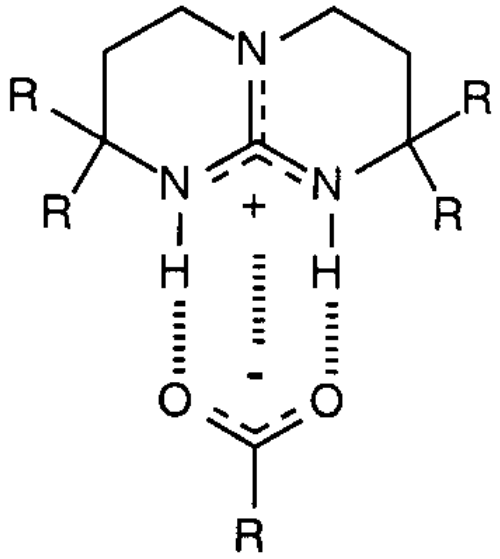


2a---NaI

K_a (**2a**---NaI) = 2.6 x 10^5 M^{-1}
K_a (**2b**---NaI) = 1.3 x 10^4 M^{-1}
$\Delta\Delta G_{XB}$ = 7 kJ/mol

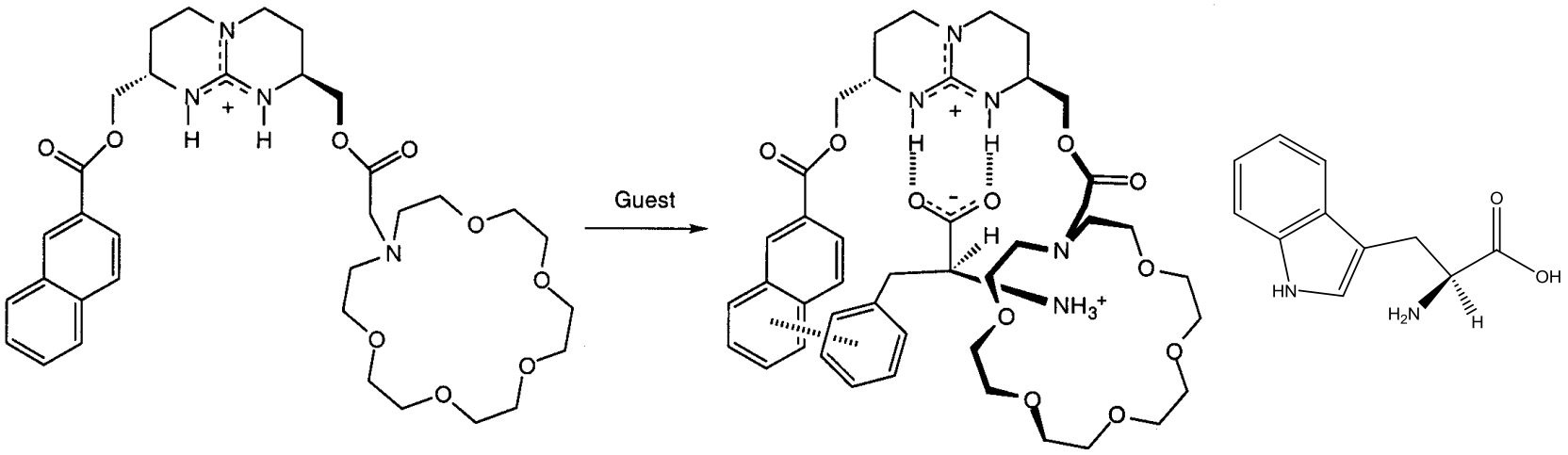


pKa = 13.6



Bicyclic guanidinium is preorganized and complementary for binding bidentate anions.

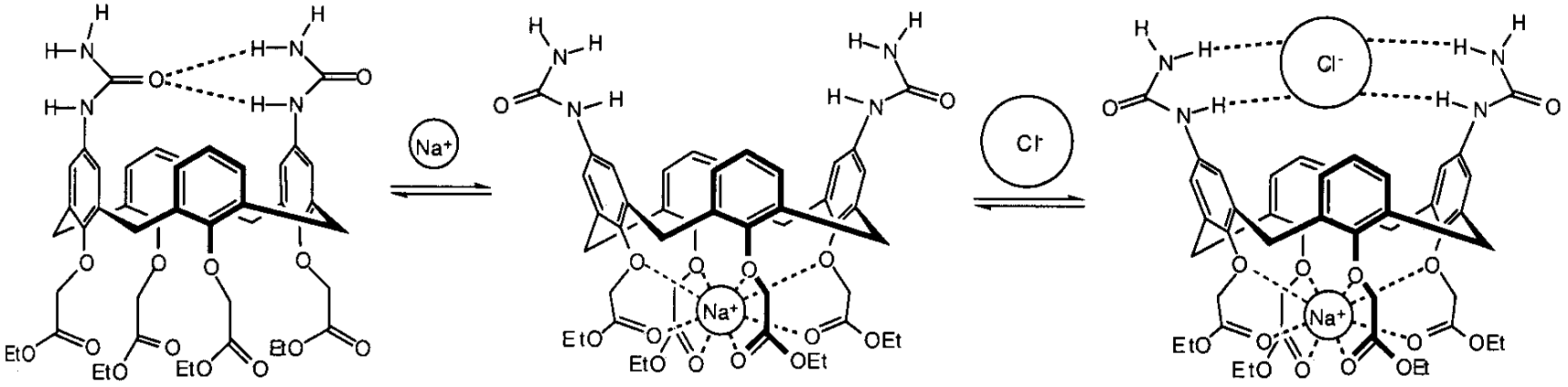
Estrazione di aa con catene laterali aromatiche (Phe, Trp) in CH_2Cl_2

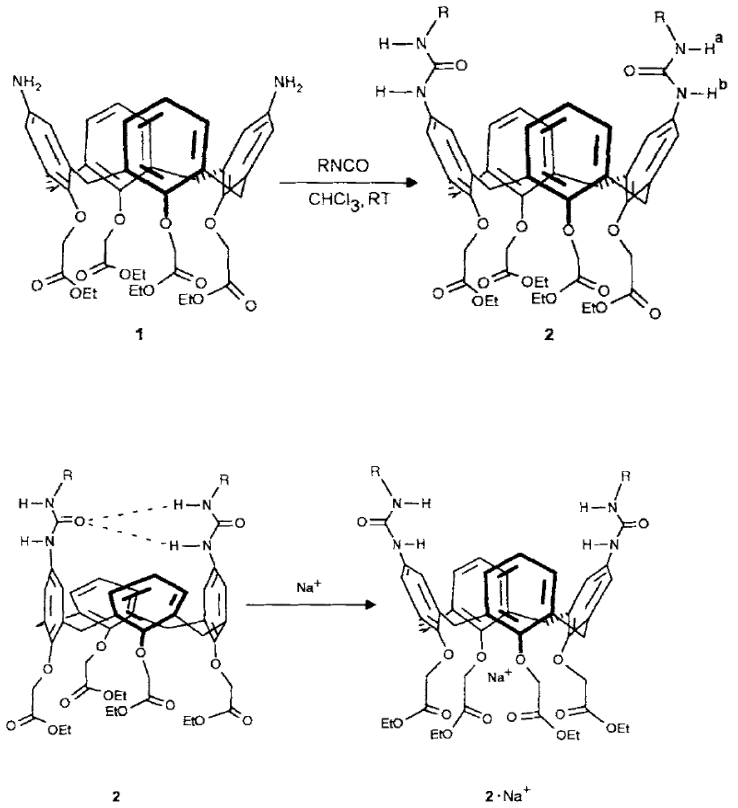


Three point receptor for the selective recognition and extraction of zwitterionic amino acids.

Solubilization of NaX Salts in Chloroform by Bifunctional Receptors**

Jurgen Scheerder, John P. M. van Duynhoven, Johan F. J. Engbersen, and David N. Reinhoudt*





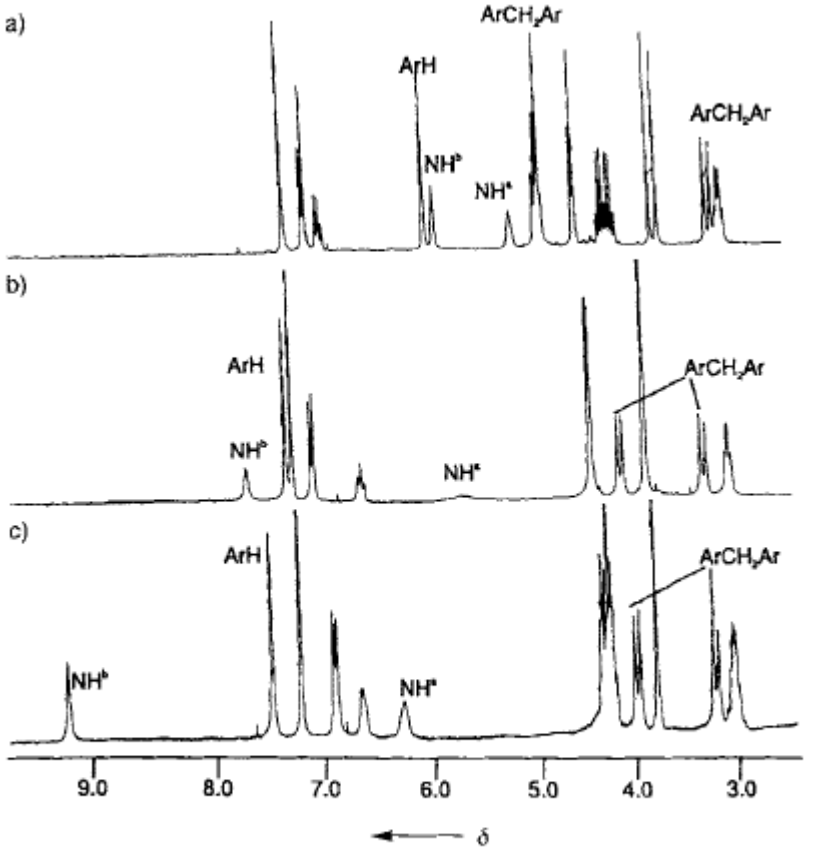
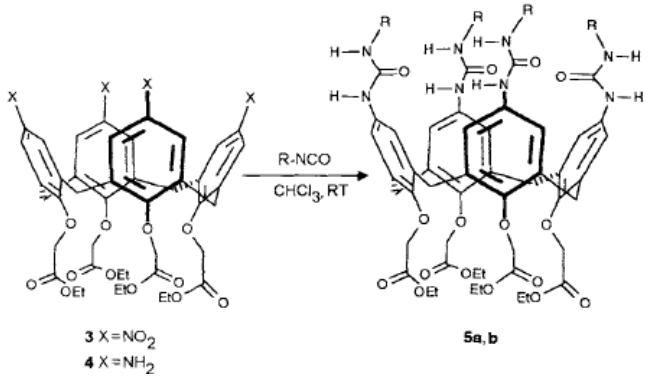


Fig. 1. ^{1}H NMR spectra of **2** ($CDCl_3$, 5 mM). a) Uncomplexed, b) [**2**·Na]ClO_4, c) [**2**·NaCl]. For NH^a and NH^b see Scheme 1; for ArH and $ArCH_2Ar$ see the text or ref. [14].



3 X = NO_2
4 X = NH_2

5a,b

[14] NOESY experiments with **5a,b** reveal through-space connectivities between the aromatic hydrogens of the calix[4]arene skeleton and the $NH^a CH_2 CH_2$ and $NH^a CH_2 CH_2$ hydrogens of **5a** and the *tert*-butyl hydrogens of **5b**. These connectivities cannot result from through-space interactions within a single molecule since in the same molecule these hydrogens are not close enough [14a]. Consequently, these NOE connectivities must result from intermolecular interactions. Furthermore, the sign of the NOE connectivities is positive, suggesting that slow-tumbling entities with increased molecular mass (≥ 2000) are present [14a]. Using the initial rate approximation [14b] and the distance between the equatorial and axial calix[4]arene bridging methylene hydrogens as a reference (1.79 Å) the cross relaxation constants (σ_{12}) for a two-spin system involving two atoms (1 and 2) were determined [14c]. The σ_{12} values are an indication of the degree of aggregation of the two atoms involved [14a]. The σ_{12} values for **5a** and **5b** are -0.7 and -0.2, respectively. The negative σ_{12} values suggest the presence of species with a higher molecular mass. These results support the dimeric structure for **5a,b** proposed by Rebek [13]. a) D. Neuhaus, W. P. Wil-

[15] According to Shimizu and Rebek, Jr. the presence of two signals for the aromatic hydrogens of tetra(ureido)calix[4]arenes **5a,b** results from hindered rotation of the urea moieties around the aryl–urea bond due to hydrogen bonding in the dimer [13]. The fact that upon the complexation of Na^+ by **5a,b** one signal for these hydrogens is present in the ^1H NMR spectra indicates that this hindered rotation is absent and that the dimer is no longer present.

Table 1. Percentage of MX complex formed with **2** and **5a,b** after L–S extraction [a].

	2			**5a**			**5b**		
	Na^+	K^+	Cs^+	Na^+	K^+	Cs^+	Na^+	K^+	Cs^+
Cl^-	100	–	–	100	29	–	100	30	–
Br^-	100	16	–	100	62	–	100	75	–
I^-	100	100	–	100	100	–	100	100	–

[a] The concentration of **2** and **5a,b** is 5 mM in $CDCl_3$. See also ref. [18].

[18] A 5 mM solution (0.5 mL) of **2** or **5a,b** in $CDCl_3$ was stirred with an excess of MX for 24 h. The organic layer was separated and the relative amount of complex formed was determined on basis of the intensities of the ^1H NMR signals for the bridging calix[4]arene methylene hydrogens of the complex and the free ligand.

J. Org. Chem. **1997,** *62,* 3568−3574

Molecular Design of a "Molecular Syringe" Mimic for Metal Cations Using a 1,3-Alternate Calix[4]arene Cavity

Atsushi Ikeda, Takanobu Tsudera, and Seiji Shinkai*

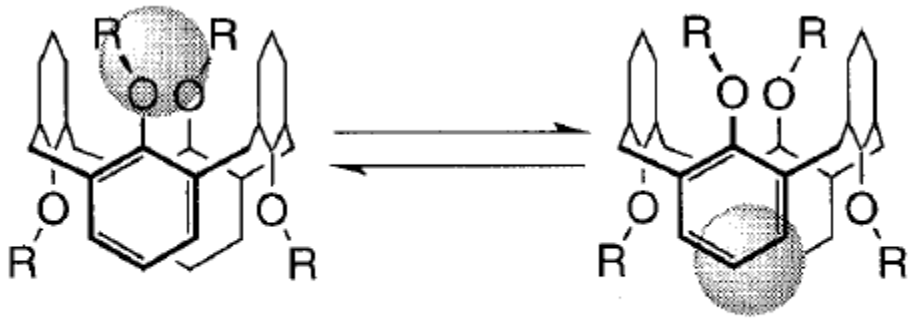
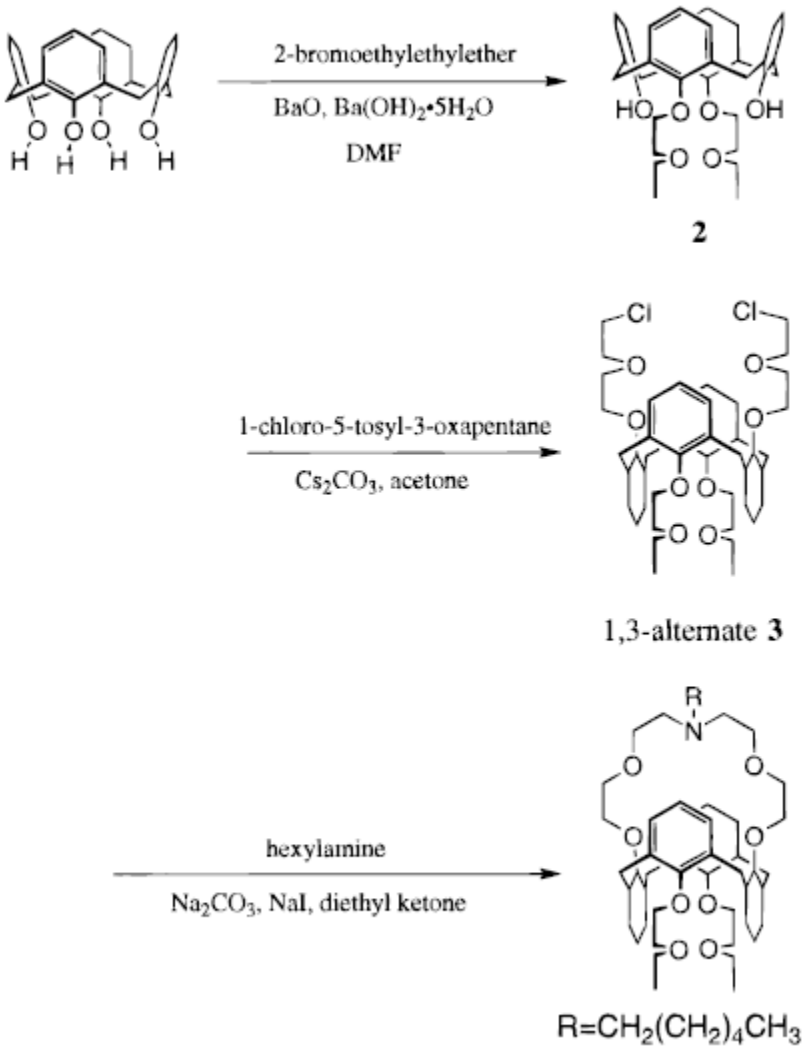


Figure 1. Schematic representation of the metal-tunneling through a π-basic tube of 1,3-alternate calix[4]arene.

Scheme 1


2-bromoethylethylether
BaO, Ba(OH)2•5H2O
DMF
2
1-chloro-5-tosyl-3-oxapentane
Cs2CO3, acetone
1,3-alternate 3
hexylamine
Na2CO3, NaI, diethyl ketone
R=CH2(CH2)4CH3
1

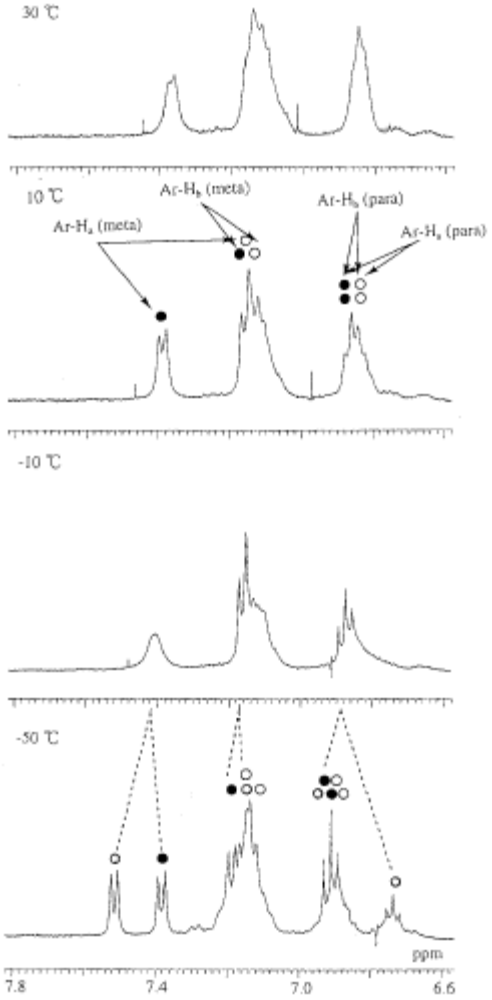


Figure 2. Partial ^{1}H NMR spectra of a **1**-Ag^+ system: 400 MHz, CD_2Cl_2:CD_3OD = 4:1 v/v, [**1**] = 5.00 mM, [CF_3SO_3Ag] = 2.50 mM. Ar-H_a and Ar-H_b denote the aromatic protons at crown-capped side and those at bis(ethoxyethoxy) side, respectively. Open and solid (or shaded) circles denote the signals for free **1** and those for the **1**·Ag^+ complex, respectively.

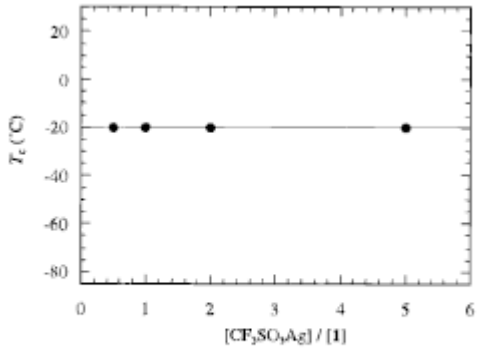


Figure 3. Concentration dependence of $T_{c,intra}$: [**1**] = 5.00 mM, CD_2Cl_2:CD_3OD = 4:1 v/v. The concentration of **1** was maintained constant while the concentration of CF_3SO_3Ag was varied.

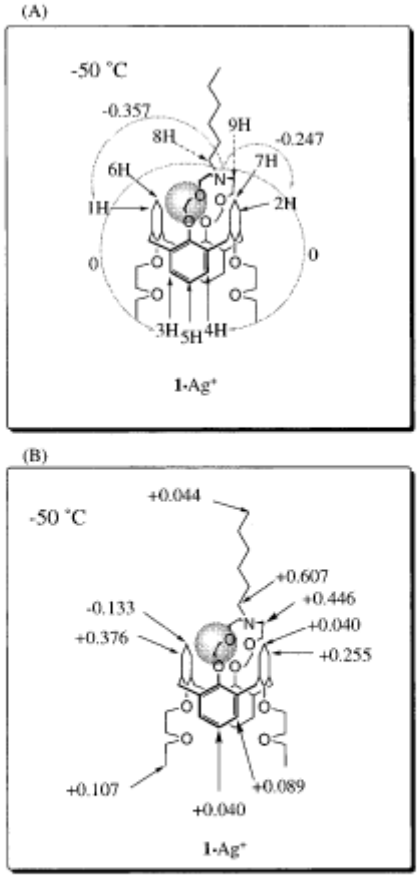


Figure 4. (A) Assignment of chemical shifts for selected protons in the **1**·Ag^+ complex by 2D COSY and NOE signal intensities with respect to 8-H and 9-H: −50 °C, CD_2Cl_2:CD_3OD − 4:1 v/v, [**1**] − 5.00 mM, [CF_3SO_3Ag] − 10.0 mM. (B) Changes in the ^1H NMR chemical shift of **1** induced by added Ag^+: the measurement conditions are the same as A. A plus sign (+) denotes a shift to lower magnetic field, whereas a minus sign (−) denotes a shift to higher magnetic field.

Figure 5. Schematic representation of a rope-jumping motion in the **1**·Ag^+ complex.

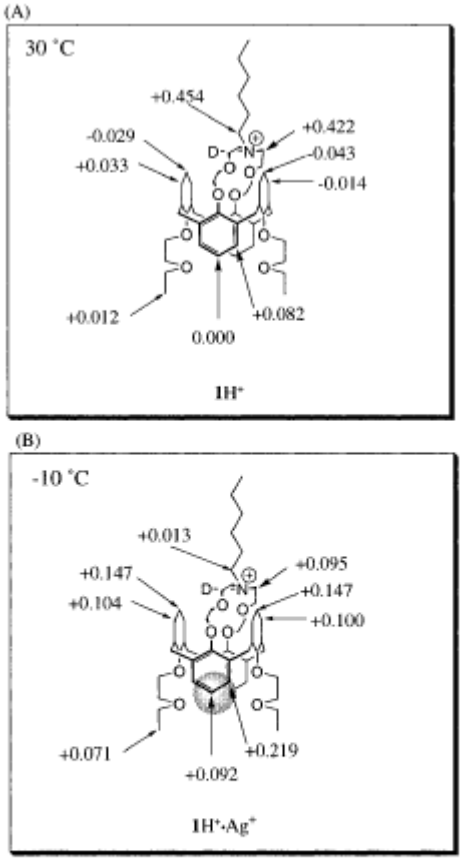


Figure 6. (A) Assignment of chemical shifts for selected protons in $\mathbf{1}H^+$ and changes from those in **1**:30 °C, [**1**] = 5.00 mM, [TFA-*d*] = 600 mM, CD_2Cl_2:CD_3OD = 4:1 v/v. (B) Changes in the ^1H NMR chemical shift of $\mathbf{1}H^+$ induced by added Ag^+ ([CF_3SO_3Ag] = 10.0 mM): the measurement conditions are the same as A. A plus sign (+) denotes a shift to lower magnetic field, whereas a minus sign (−) denotes a shift to higher magnetic field.

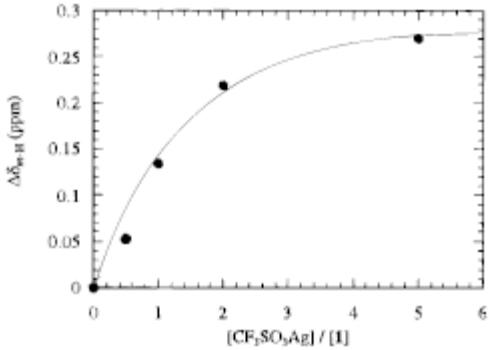


Figure 7. Chemical shift change in δ_{m-H} of $\mathbf{1}H^+$ induced by added CF_3SO_3Ag: 30 °C, [**1**] = 5.00 mM, [TAF-*d*] = 600 mM, CD_2Cl_2:CD_3OD = 4:1 v/v.

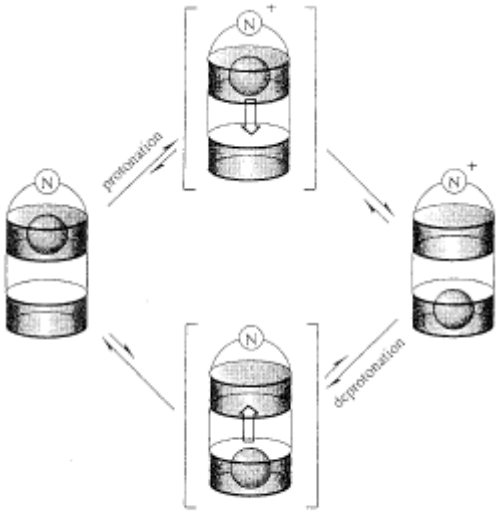


Figure 8. Schematic representation of a reversible metal pumping in a microscopic "molecular syringe" **1** designed from 1,3-alternate calix[4]arene.