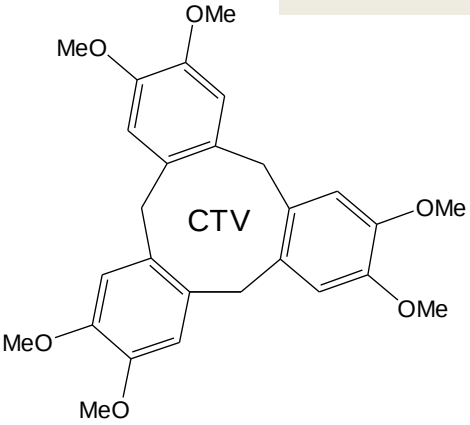
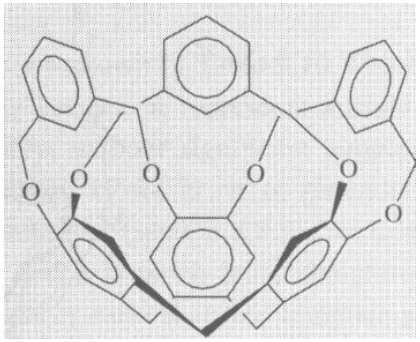
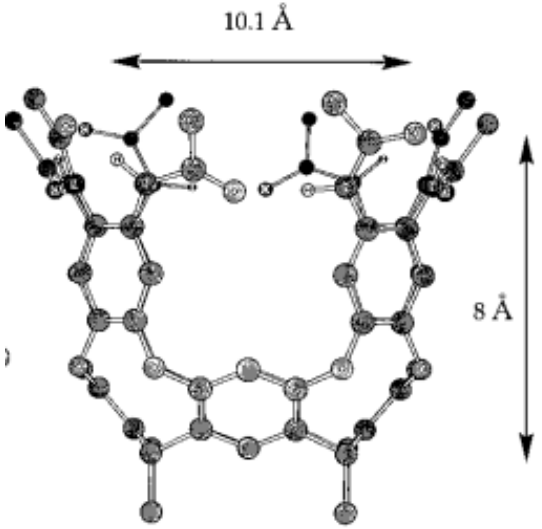
Cavitandi

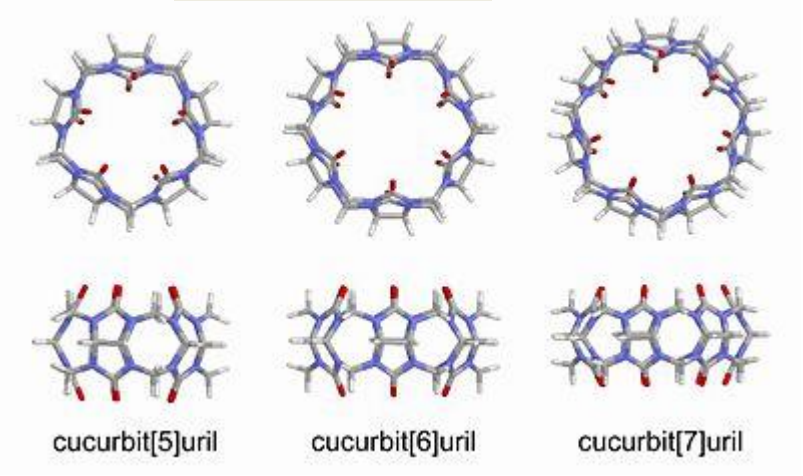
ciclotriveratrilene



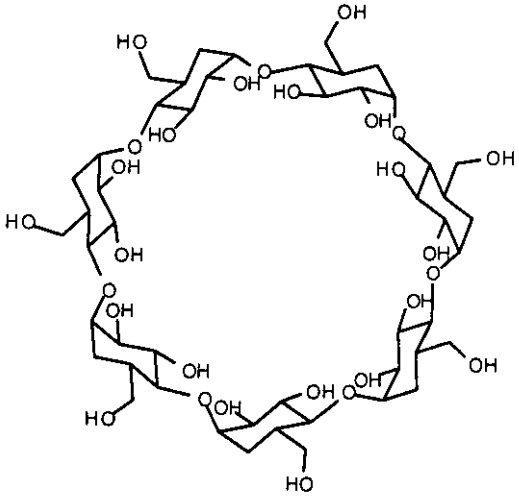


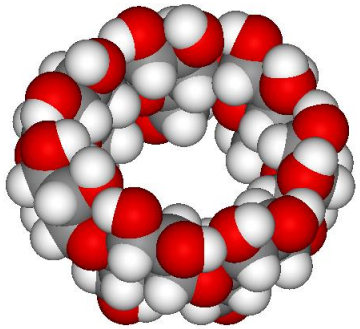


Cucurbiturili



Ciclodestrine





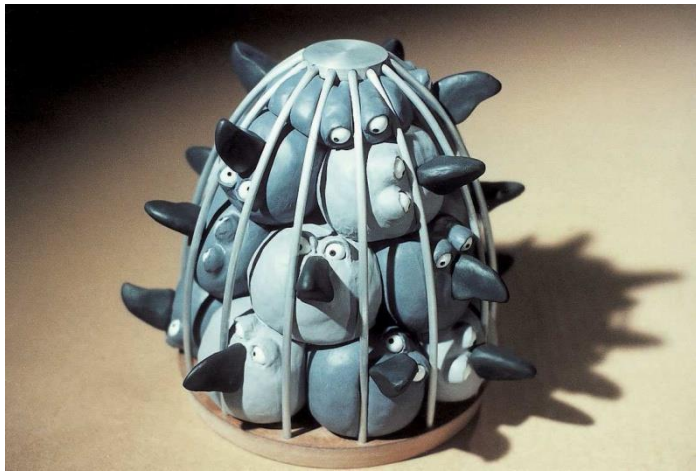
Capsule Molecolari

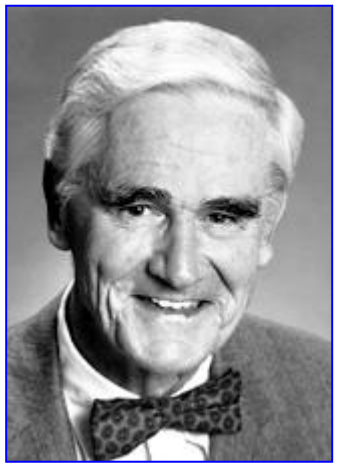
Unione di due cavitandi

Connessione covalente
Legame idrogeno
Legame di coordinazione

Pre-organizzazione

Protezione dal solvente esterno
Rallentamento delle cinetiche di scambio
Stabilizzazione di specie reattive
Reazioni catalitiche
Drug delivery





Carcerando:

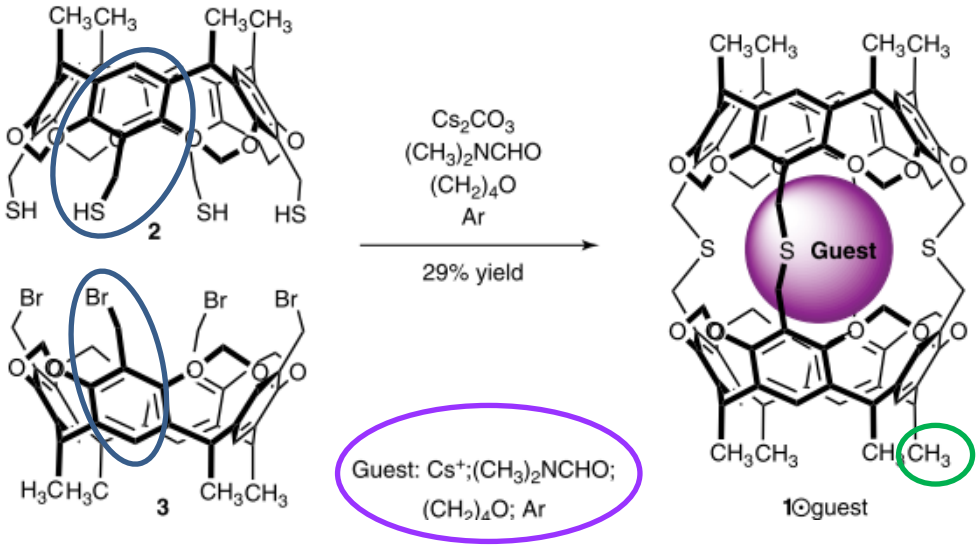
Contenitore molecolare chiuso (capsula) che definisce cavità sferica, i guest sono intrappolati (all'atto della sintesi) entrata e uscita solo per rottura di legame covalente, i.e. velocità di scambio virtualmente nulla

Carcerandi

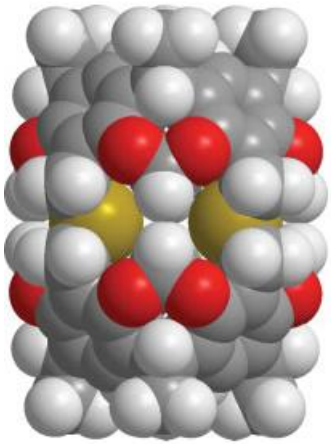
Benzil-tiolo

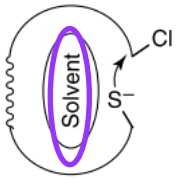
benzil cloruro
(o bromuro)

Alta dliuz



Insolubilità = caratterizz via IR, FAB-MS, analisi elementare, test chimici
FAB-MS dei carciplessi

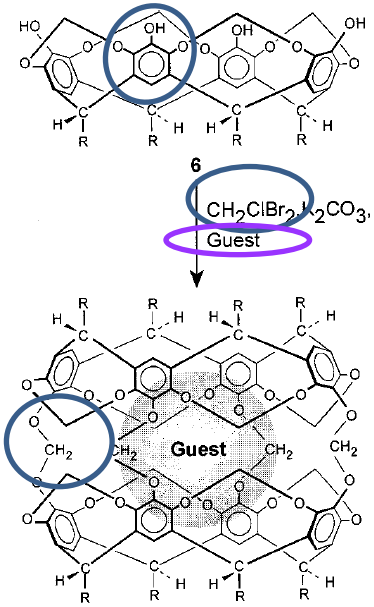


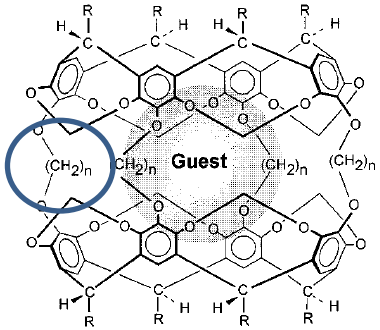


Carcerandi

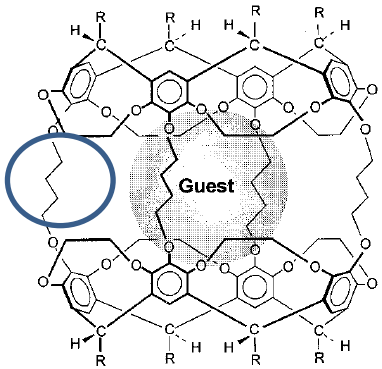
fenolo

bromo-clorometano

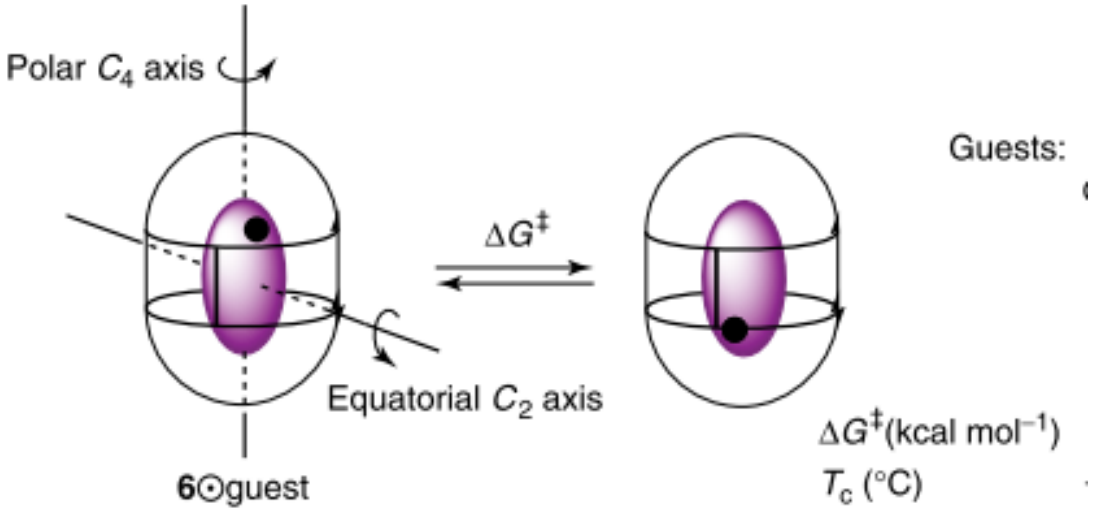


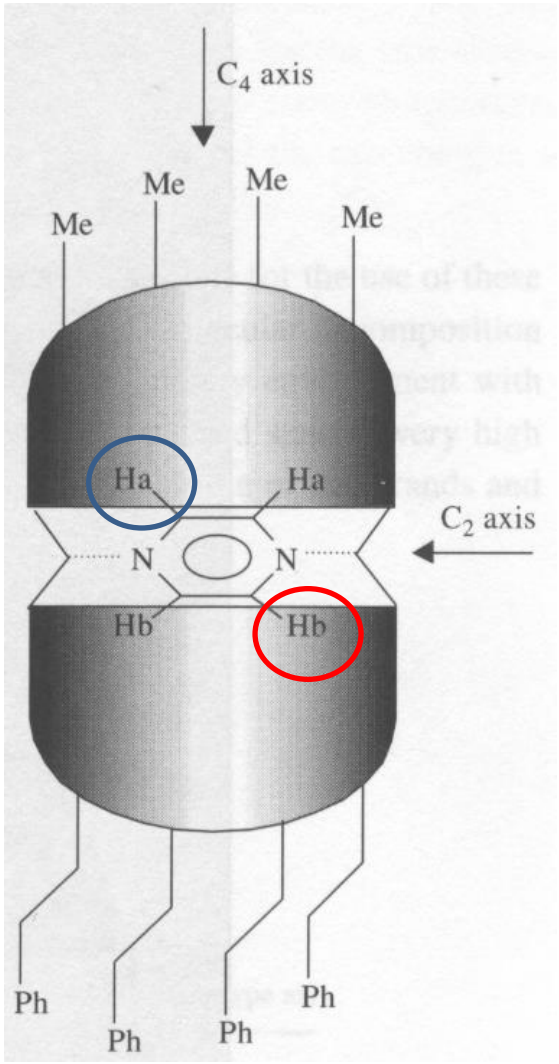


11•Guest n = 2 R = CH_2CH_2Ph
12•Guest n = 3 or $C_{11}H_{23}$



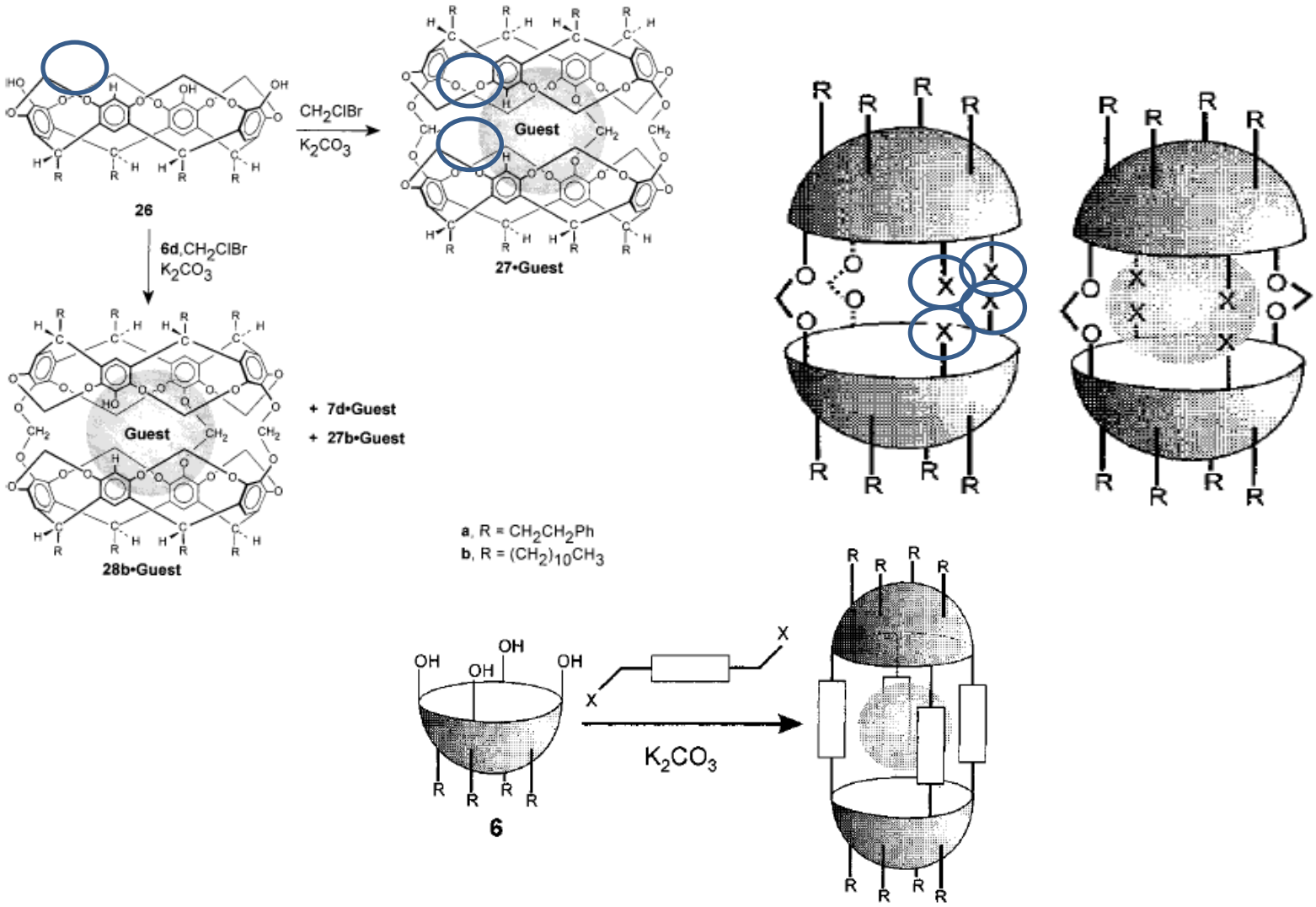
13•Guest R = $(CH_2)_4CH_3$

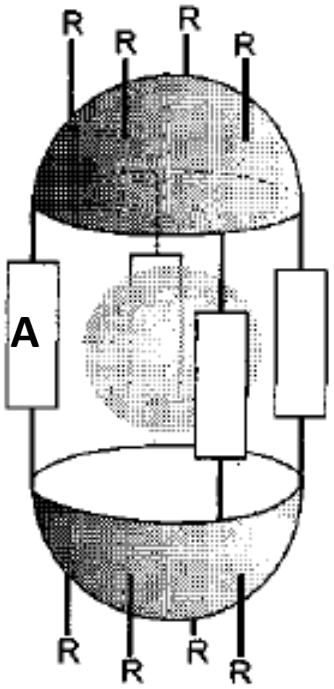

Polar C_4 axis
$\Delta G^{\ddagger}$
Equatorial C_2 axis
6⊙guest
Guests:
$\Delta G^{\ddagger}$(kcal mol^{-1})
T_c (°C)


C4 axis
Me
Me
Me
Me
Ha
Ha
C2 axis
N
N
Hb
Hb
Ph
Ph
Ph
Ph

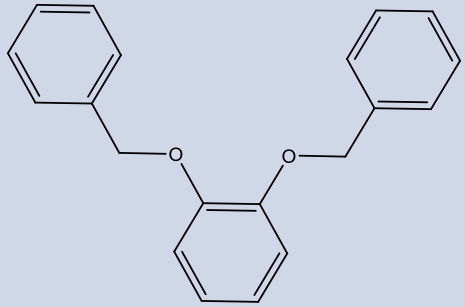
Emicarcerando:

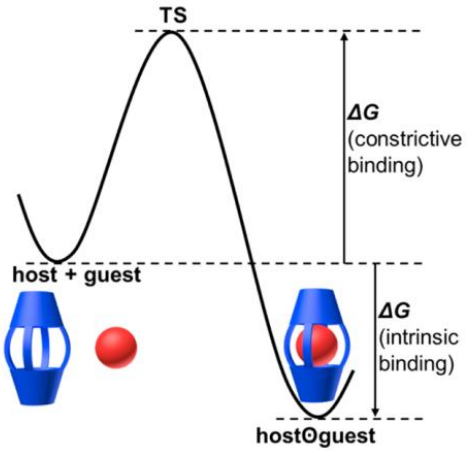
Contenitore molecolare chiuso (capsula) che definisce cavità sferica, i guest sono intrappolati (all'atto della sintesi) - entrata e uscita senza rottura di legame covalente, i.e. velocità di scambio misurabile





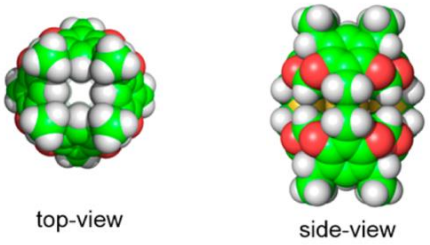
A
$O–CH_2–O$
$S–CH_2–S$
$O–(CH_2)_4–O$
$O–(CH_2)_5–O$
$O–(CH_2)_6–O$
$O–(CH_2)_2O(CH_2)_2–O$

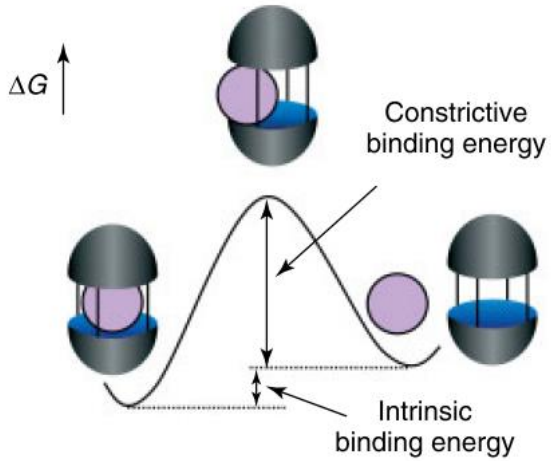





Intrinisic binding, the free energy of complexation, depends on the magnitude of the noncovalent interactions between the guest and the host's inner surface.

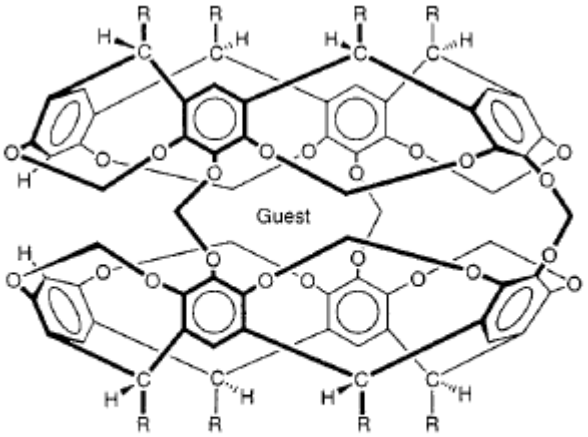
Constrictive binding, activation energy required for a guest to enter the inner cavity of a hemicarcerand through a size restricting portal in the host's skin.





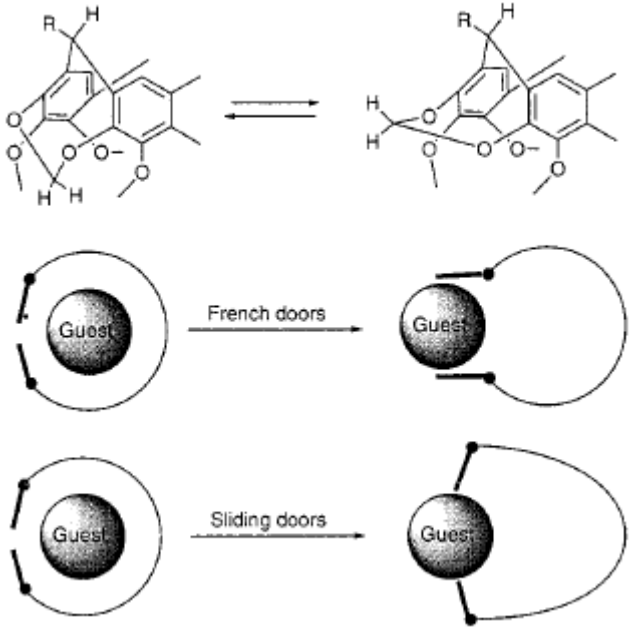
Constrictive binding: aumenta con le dimensioni del guest, diminuisce con le dimensioni dei portali, e con l'aumento della flessibilità dei linker (T).

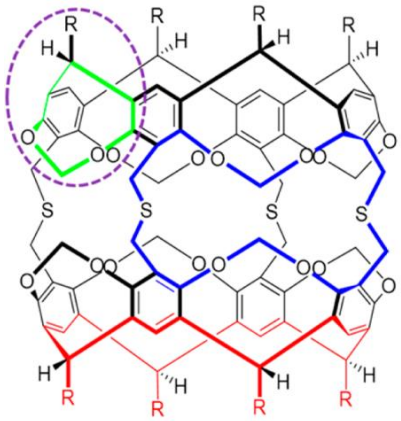
Gate mechanisms (molecular mechanics calculations) – **French door**
chair-to-boat transition of the methylene bridges, calculated barrier 22 kcal/mol.



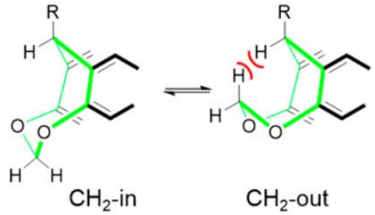
12⊙ Guest

R = CH_2CH_2Ph



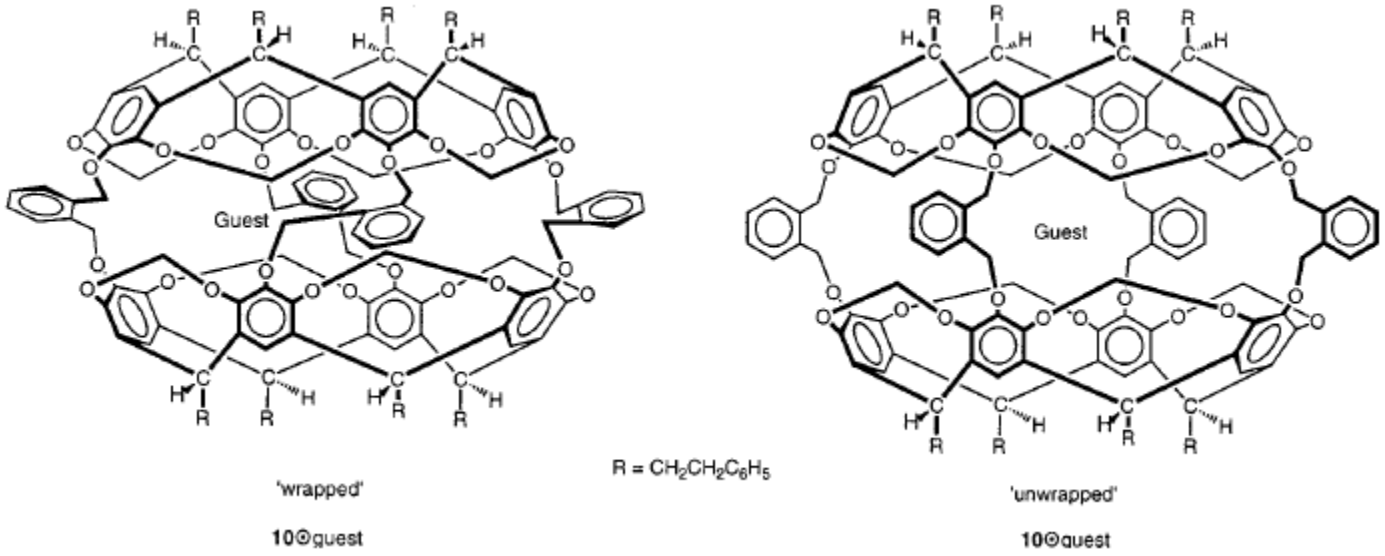


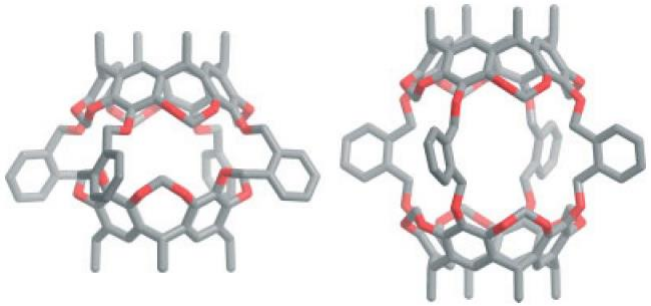
1a. R = $(CH_2)_2Ph$
1b. R = Me

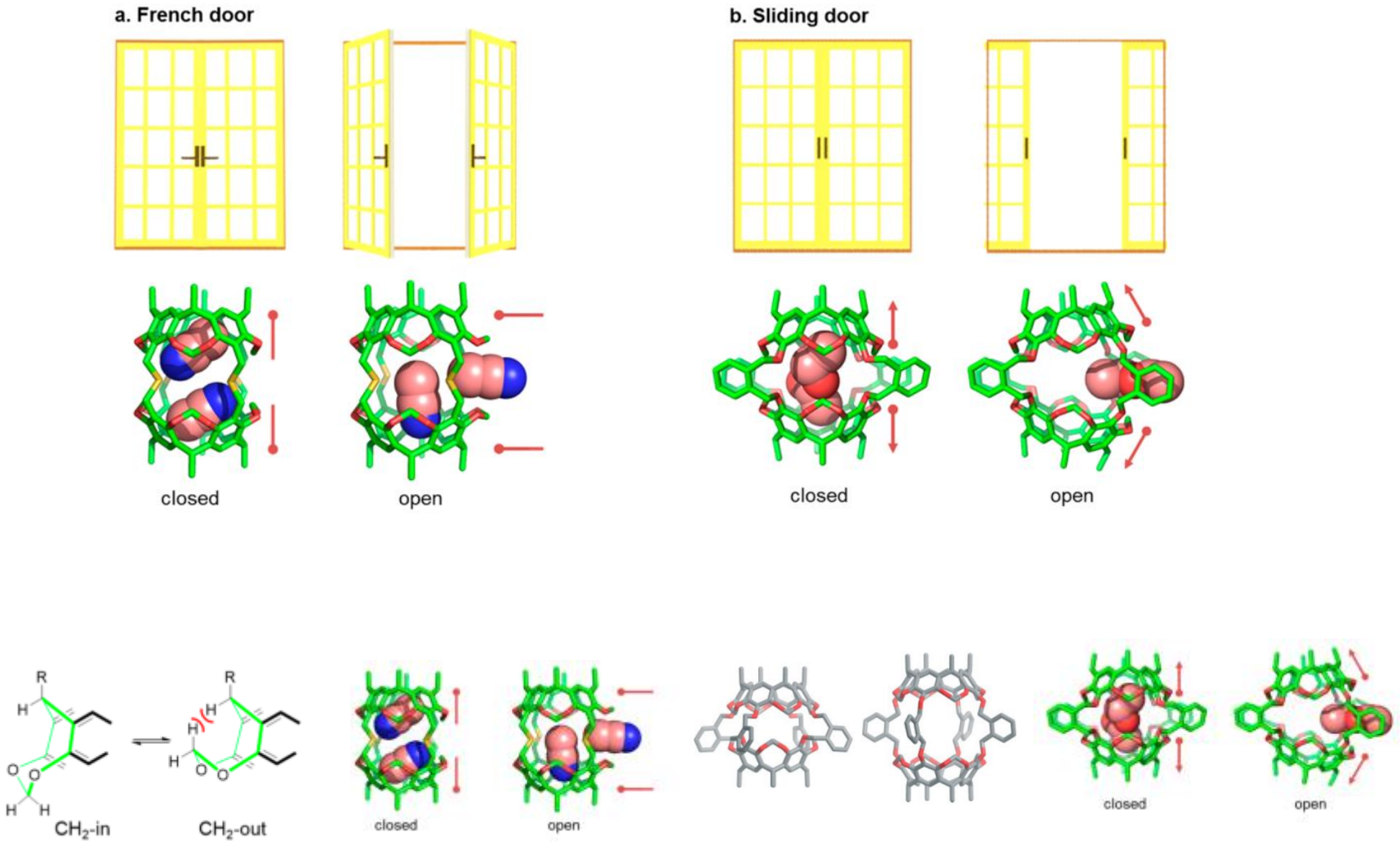


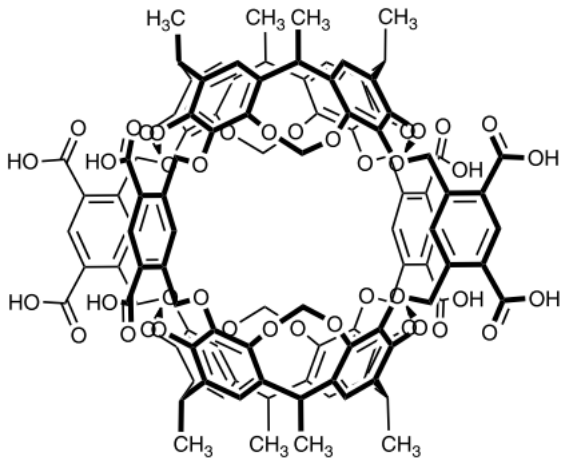
Gate mechanisms (molecular mechanics calculations) – **Sliding door**

twisting and untwisting of the two host cavitands – measured barrier (VT NMR) 12.6 kcal/mol



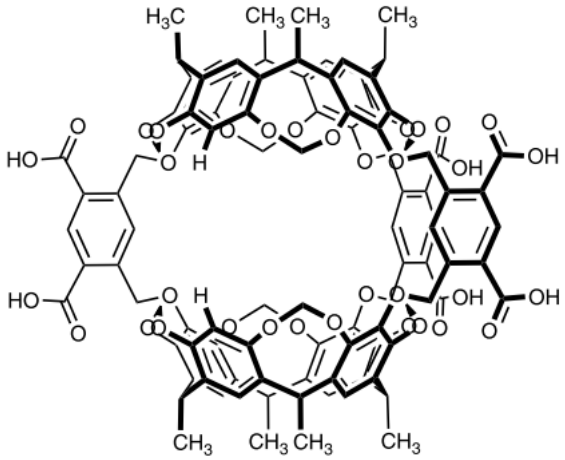



a. French door
b. Sliding door
closed
open
closed
open
R
H
O
O
H
H
CH2-in
CH2-out
closed
open
closed
open

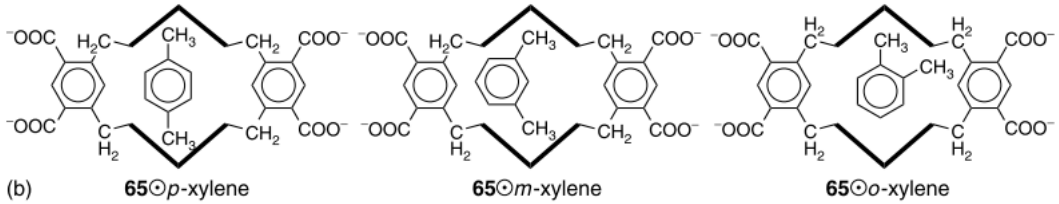


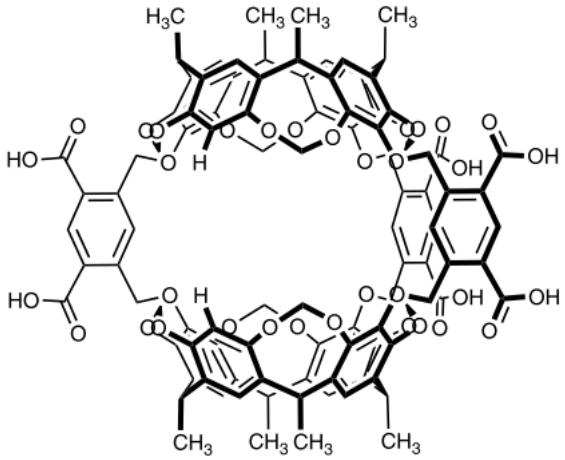
Water soluble octa-acid hemicarcerand:

Hydrophobic effect (higher than cyclodextrines)!

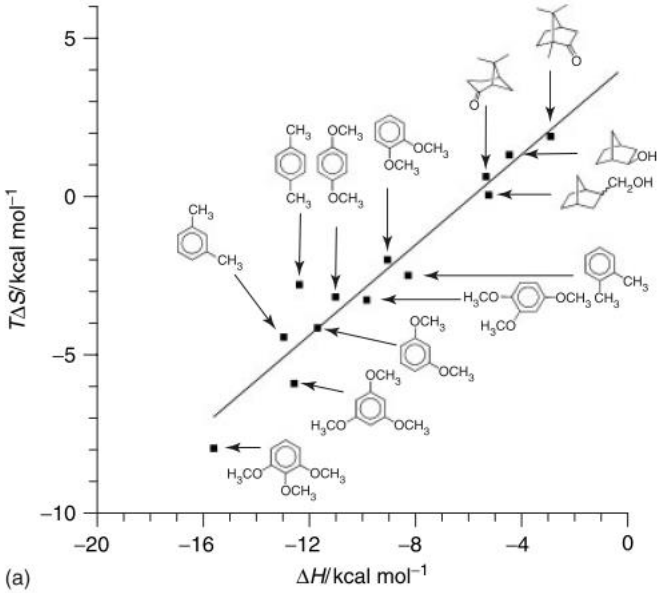


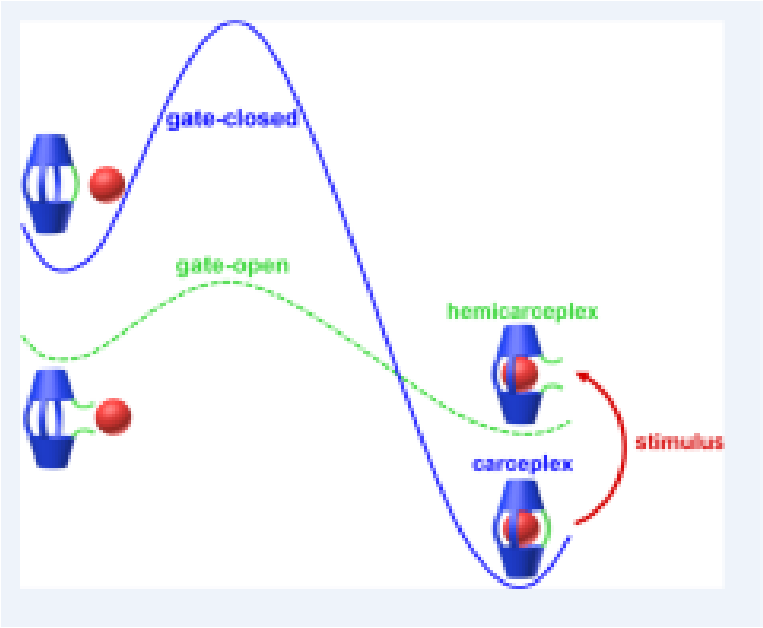
CH-π interactions for isomeric xylenes or dimetoxybenzenes direct the order of affinity: meta > para >> ortho





CH-π interactions for isomeric xylenes or dimetoxybenzenes direct the order of affinity: meta > para >> ortho




gate-closed
gate-open
hemicarceplex
stimulus
carceplex

Angewandte International Edition Chemie

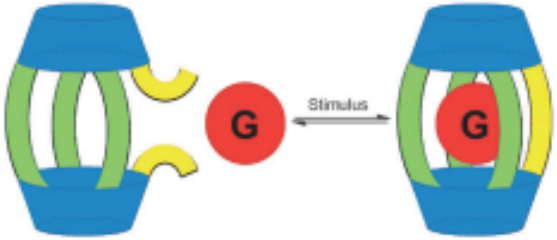
Host–Guest Chemistry

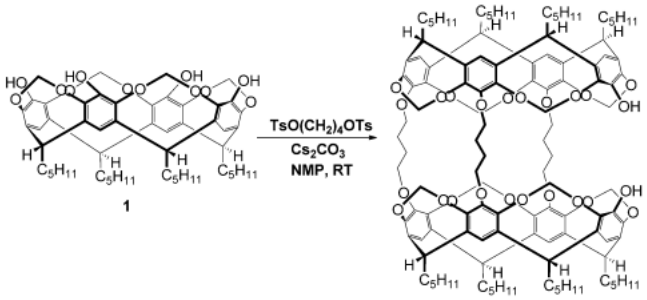
DOI: 10.1002/anie.201205376

Reversible Photochemically Gated Transformation of a Hemicarcerand to a Carcerand**

*Hao Wang, Fang Liu, Roger C. Helgeson, and Kendall N. Houk**

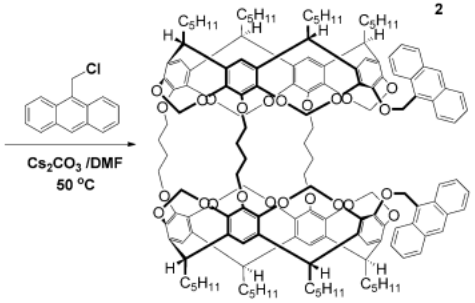
Angew. Chem. Int. Ed. **2013**, *52*, 655–659



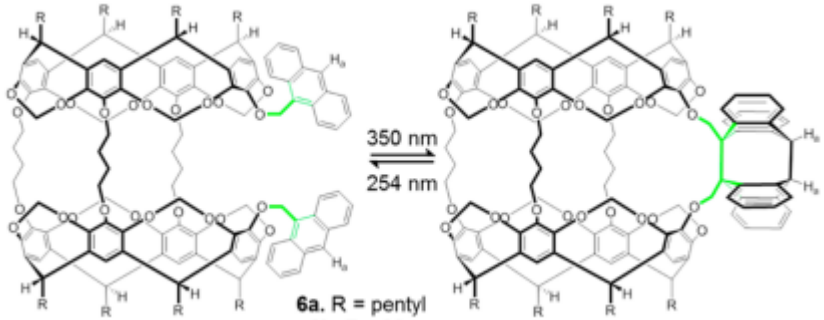


1

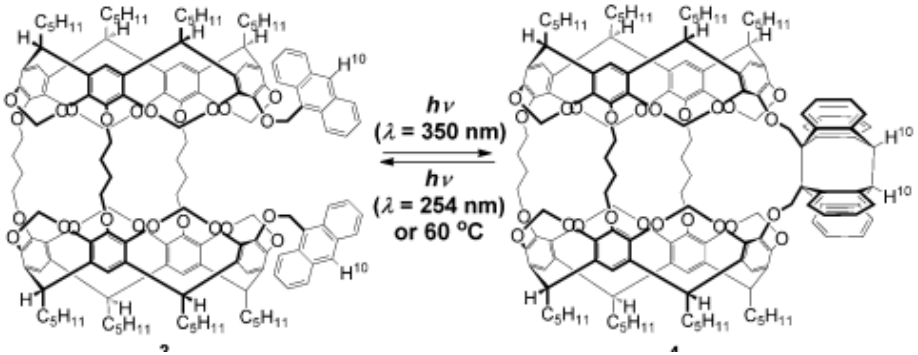
2



3



6a. R = pentyl
6b. R = Me



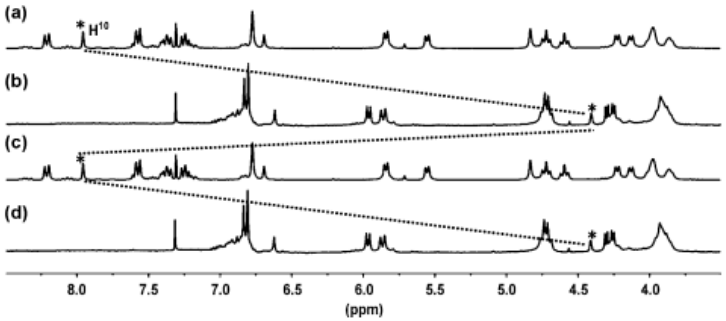
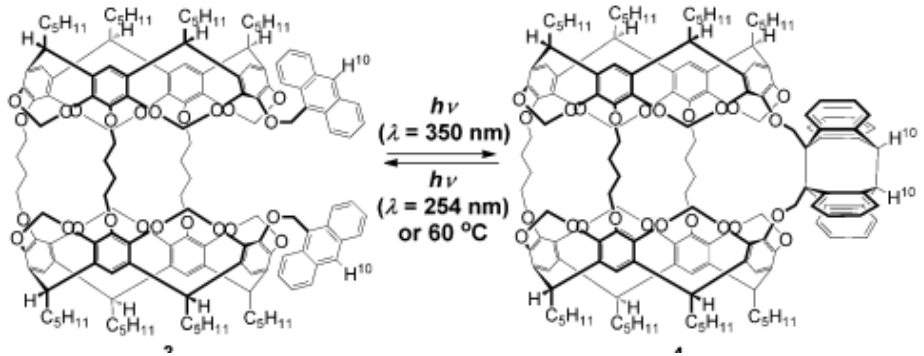
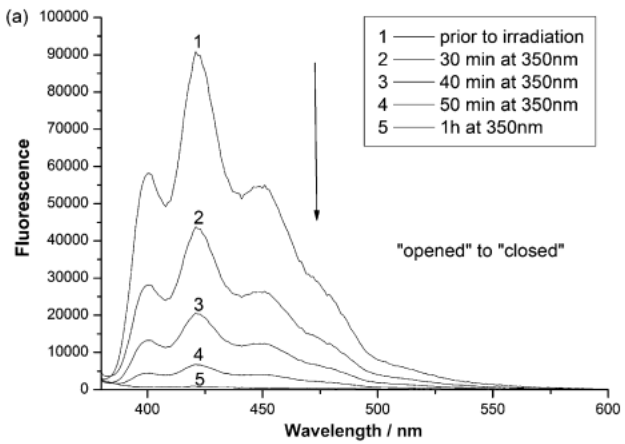
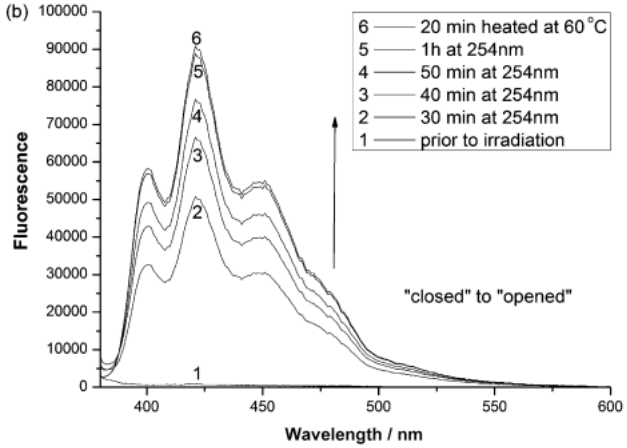
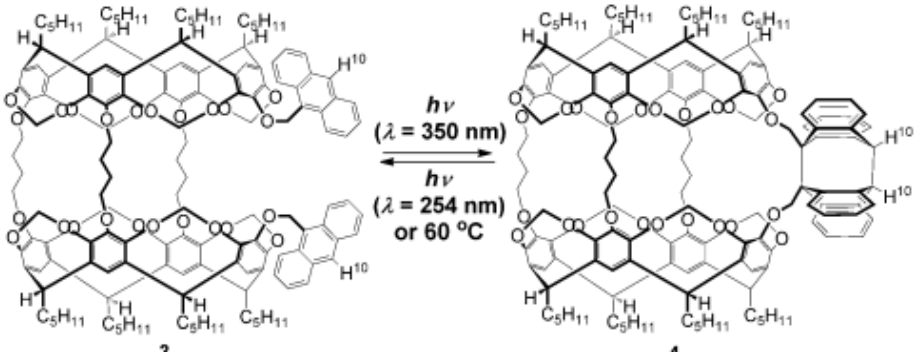


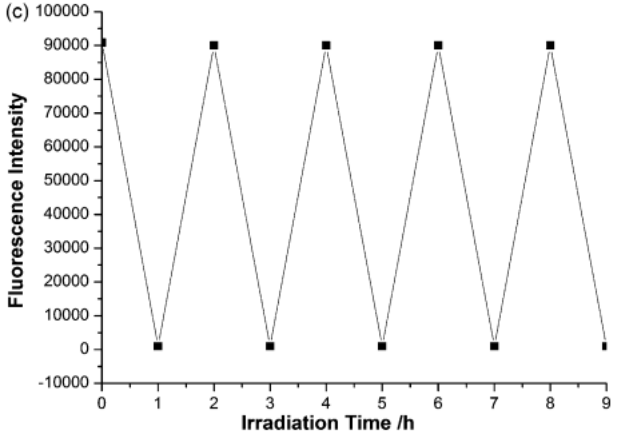
Figure 3. Partial ^{1}H NMR spectra (400 MHz, $CDCl_3$) of a) host **3** b) irradiation of host **3** with light at 350 nm for 1 h, c) irradiation of b with light at 254 nm for 1 h or heating at 60°C for 20 min, d) irradiation of c with light at 350 nm for 1 h.

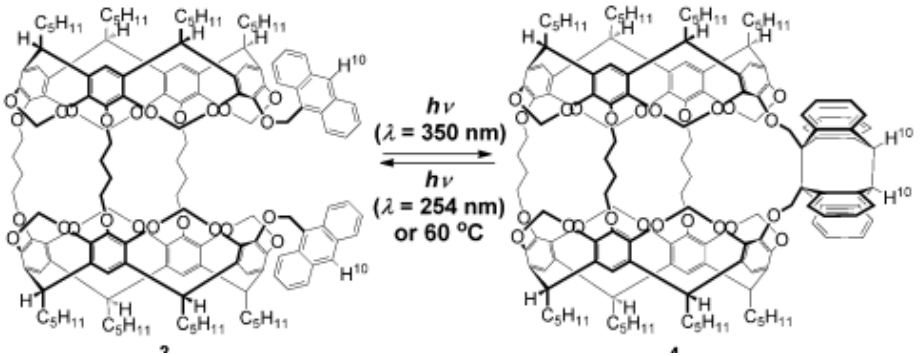

hν
(λ = 350 nm)
hν
(λ = 254 nm)
or 60 °C


(a)
Fluorescence
Wavelength / nm
1 —— prior to irradiation
2 —— 30 min at 350nm
3 —— 40 min at 350nm
4 —— 50 min at 350nm
5 —— 1h at 350nm
"opened" to "closed"

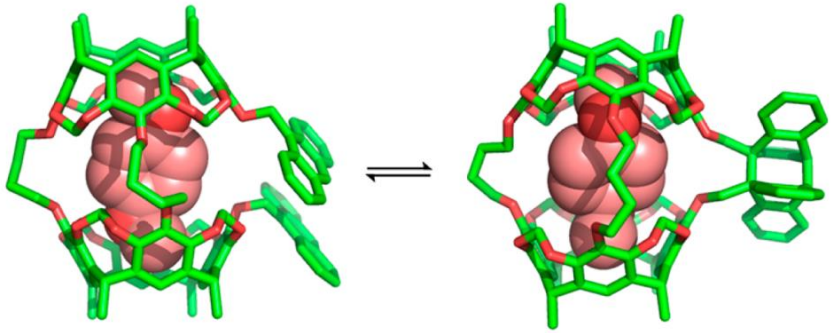

(b)
Fluorescence
Wavelength / nm
6 —— 20 min heated at 60 °C
5 —— 1h at 254nm
4 —— 50 min at 254nm
3 —— 40 min at 254nm
2 —— 30 min at 254nm
1 —— prior to irradiation
"closed" to "opened"


hν
(λ = 350 nm)
hν
(λ = 254 nm)
or 60 °C


(c)
Fluorescence Intensity
Irradiation Time /h
100000
90000
80000
70000
60000
50000
40000
30000
20000
10000
0
-10000
0
1
2
3
4
5
6
7
8
9



The progress of the photodimerization was also monitored by thin-layer chromatography, which showed only one band after completion of the photodimerization. Photodimer 4 was purified after photolysis at 350 nm. In the high-resolution mass spectrum the molecular ion of photoproduct 4 has the same mass as the parent open-state host 3.



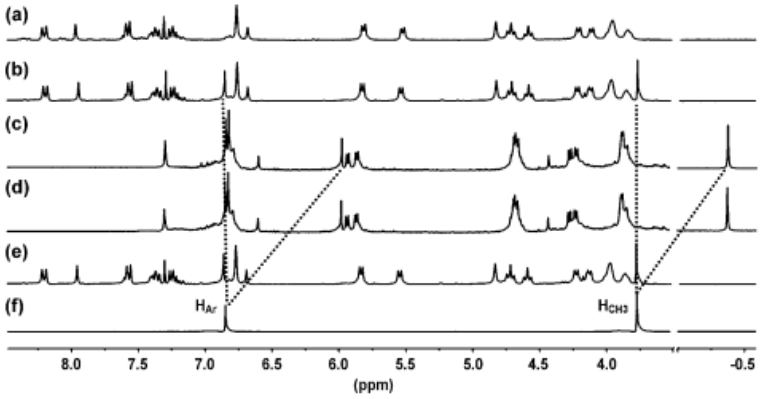
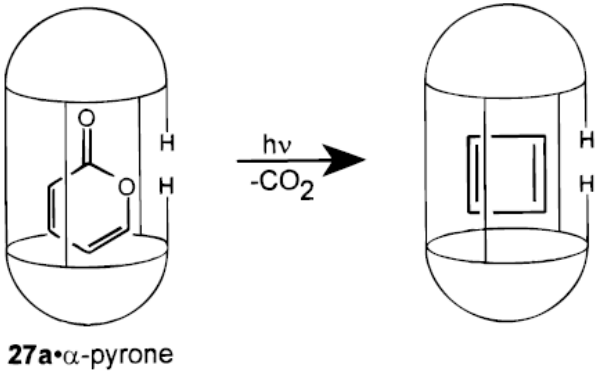


Figure 6. Partial ^{1}H NMR spectra (400 MHz, $CDCl_3$) of a) host **3** b) addition of 1 equiv of 1,4-$(MeO)_2C_6H_4$ into host **3** solution without irradiation, c) **4** ⊙ 1,4-$(MeO)_2C_6H_4$,[16] d) c after 4 weeks in dark and RT, e) irradiation of c with light at 254 nm for 1 h or heating at 60 °C for 20 min, f) guest 1,4-$(MeO)_2C_6H_4$.

The Ph_2O mixture was irradiated at 350 nm for 1 h and then poured into 10 mL of MeOH. The precipitate was dissolved in $CDCl_3$ and the ^{1}H NMR spectrum was recorded (F. 6c). The methyl signal of the guest showed a shift from 3.78 to 0.37 ppm ($\Delta\delta$ = 4.15 ppm), and the anthracene peaks of 3 disappeared (F. 6c). This indicates that after the gate of 3 is closed, a carceplex is formed between the carcerand 4 and the guest. MALDI mass spectra indicate formation of this carceplex. The carceplex 4@G can stay in the dark at ambient temperature more than 4 weeks without detectable release of the guest molecule (F. 6d). As a result, the activation energy for decomplexation in the open state 3@G and the incarcerated guest can egress easily. The gate-opened hemicarcerand is then almost exclusively filled with the solvent $CDCl_3$

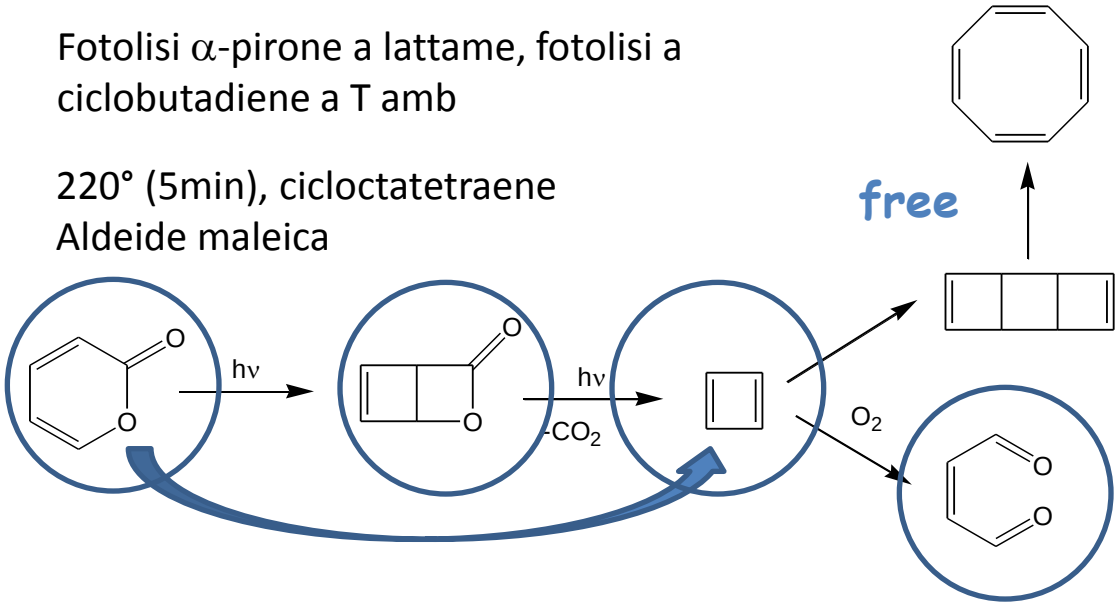


27a•α-pyrone

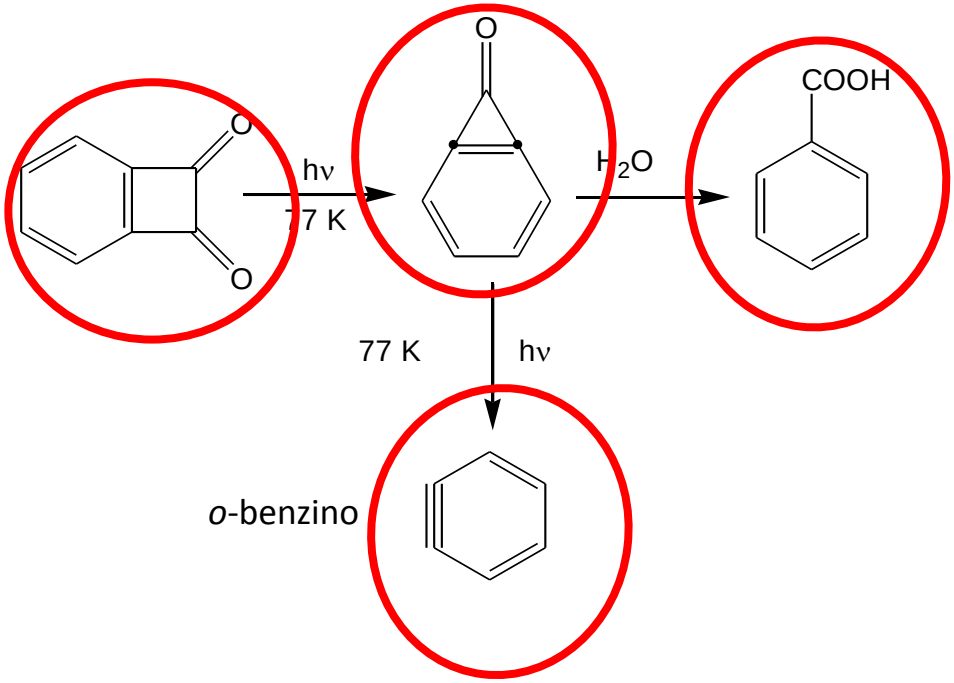
8K - matrice gas inerte congelato

Fotolisi α-pirone a lattame, fotolisi a ciclobutadiene a T amb

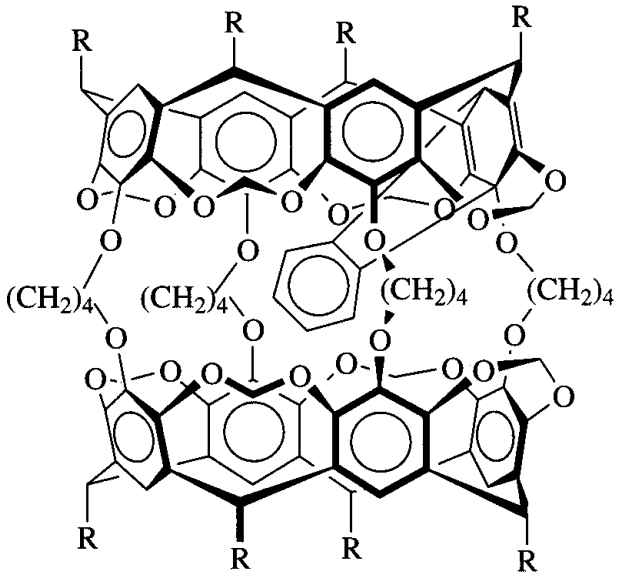
220° (5min), cicloctatetraene
Aldeide maleica

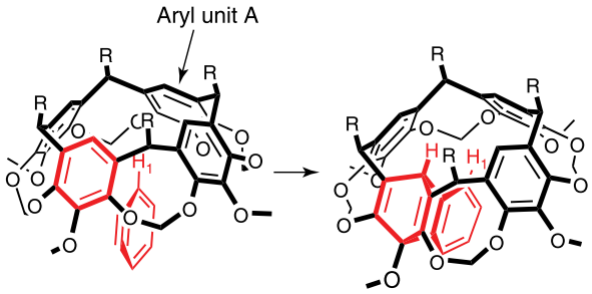


Benzociclobutendione Benzociclopropenone



^{1}H e ^{13}C NMR a bassa T





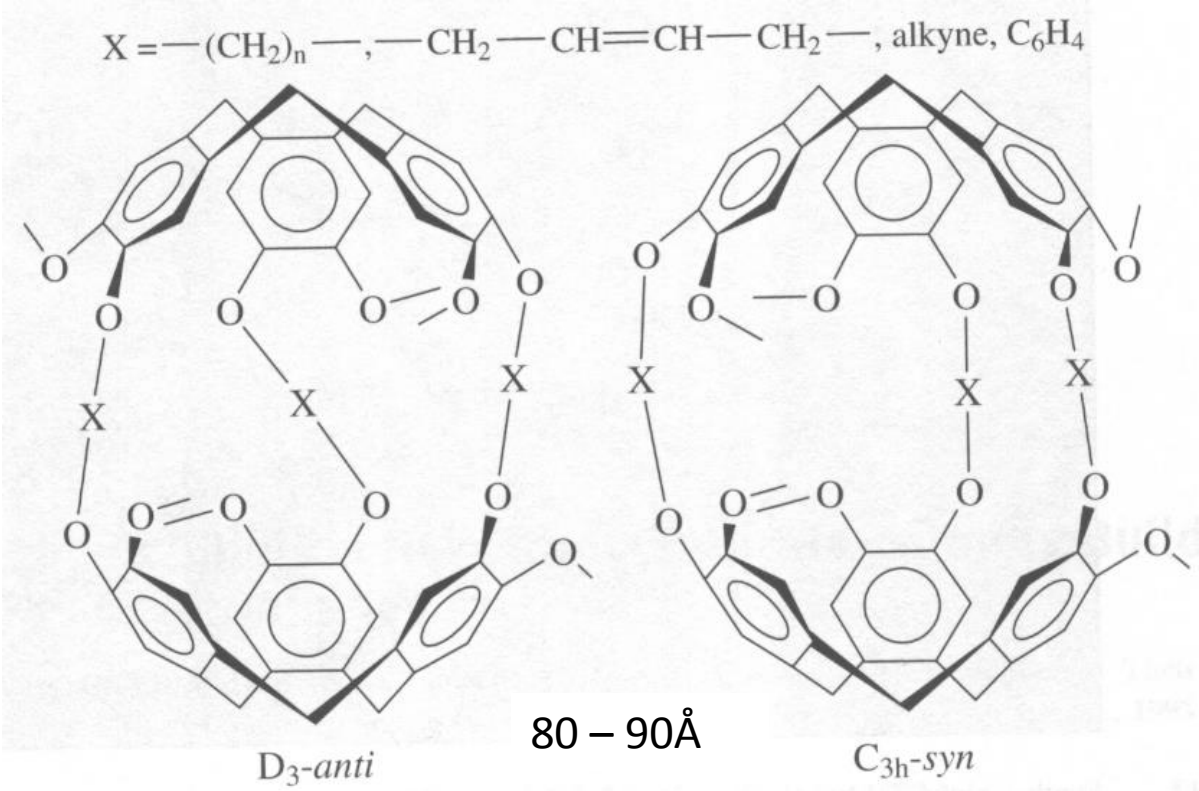
First containers with the ability to permanently encapsulate a signle molecule;
Strong contributions to what is perhaps the most exciting application of molecular containers:

use as molecular reaction flasks (or “nanoreactor”) in which otherwise fleeting species or labile intermediates can be generated and gain longevity at room temperature.

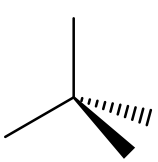
We anticipate future use of hemicarciplex in the following fields:

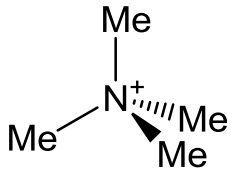
catalysis
drug and radiation delivery
release systems
separation science
guest-indicator systems,
light-electrical switches
memory storage devices
scavenging impurities for water purification

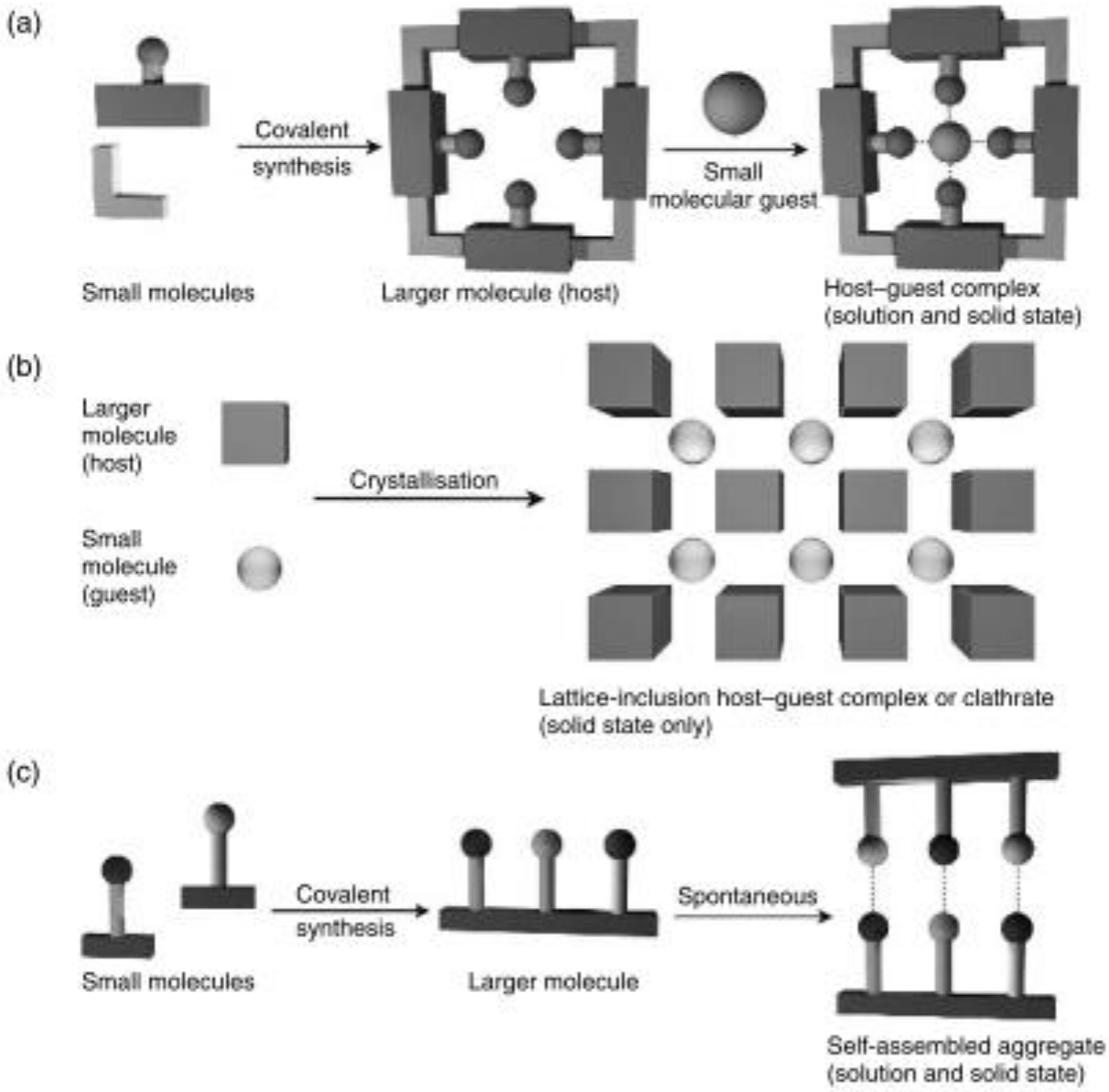
Criptofani



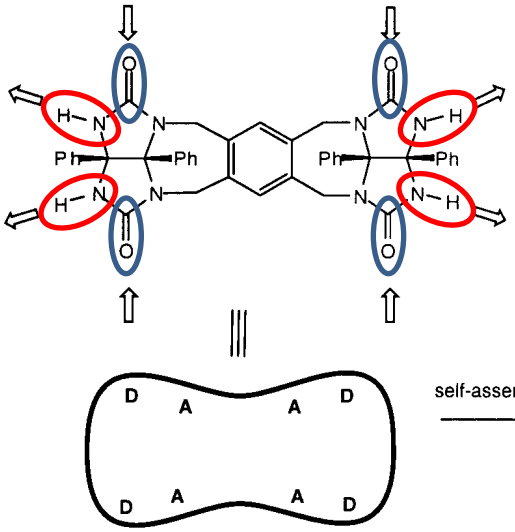
80 – 90Å



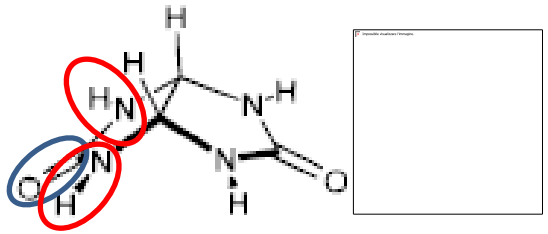



(a)
Covalent
synthesis
Small
molecular guest
Small molecules
Larger molecule (host)
Host–guest complex
(solution and solid state)
(b)
Larger
molecule
(host)
Small
molecule
(guest)
Crystallisation
Lattice-inclusion host–guest complex or clathrate
(solid state only)
(c)
Covalent
synthesis
Spontaneous
Small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

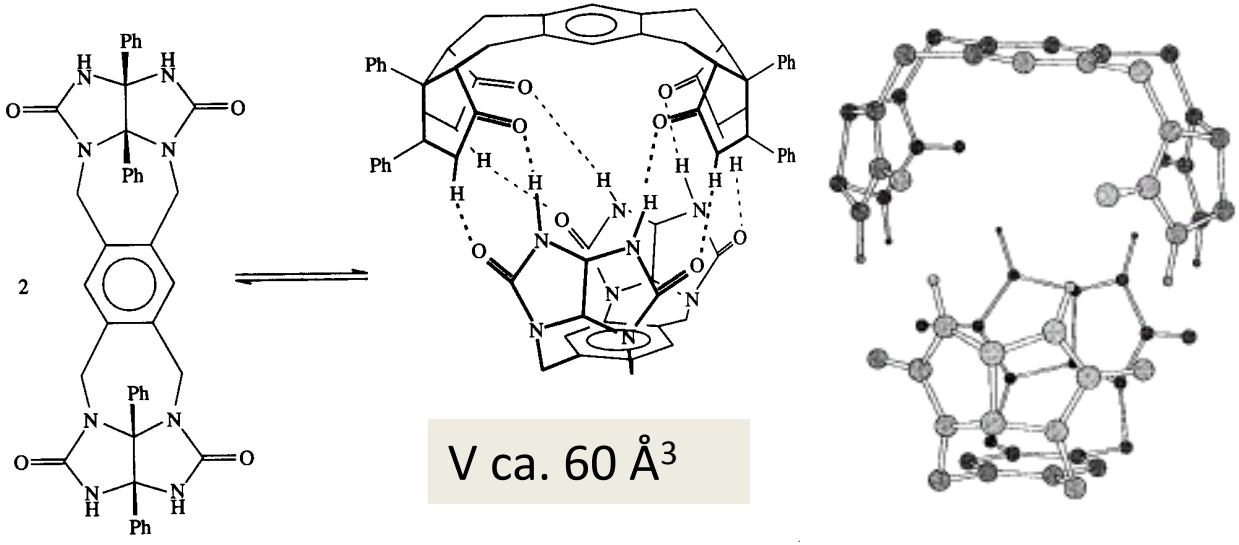
Tennis-ball



The formation of a molecular tennis ball

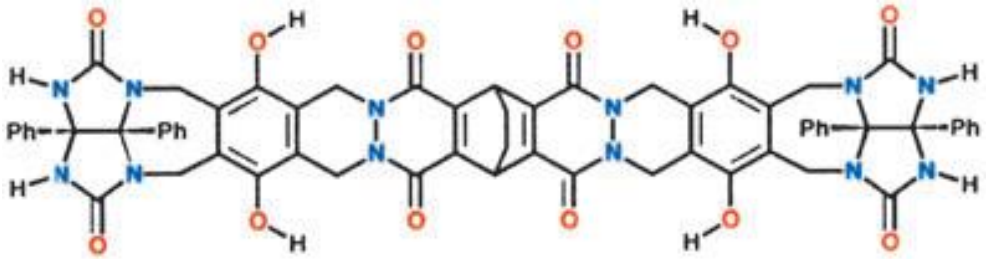


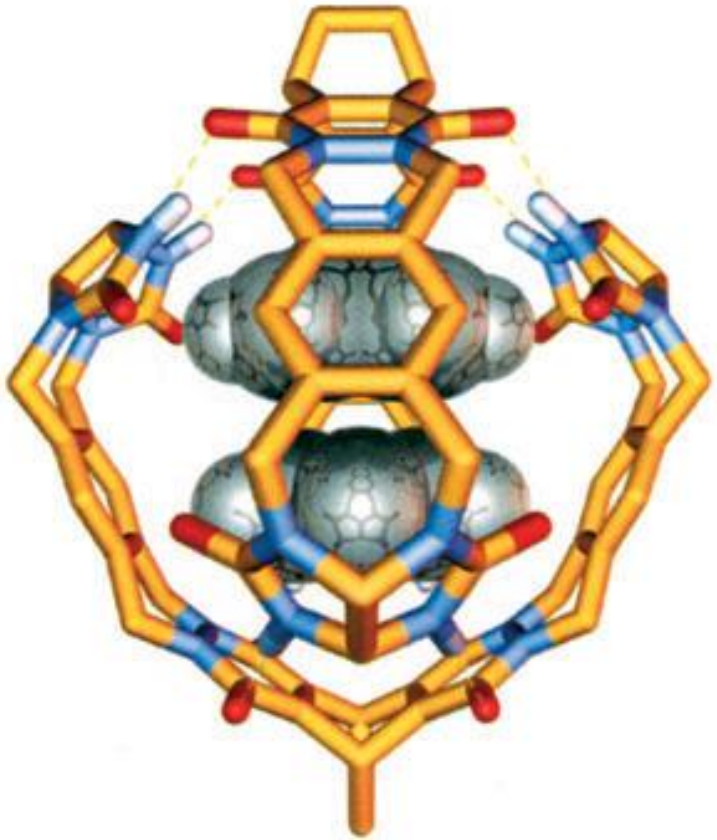
unità glicolurile



V ca. 60 Å^3

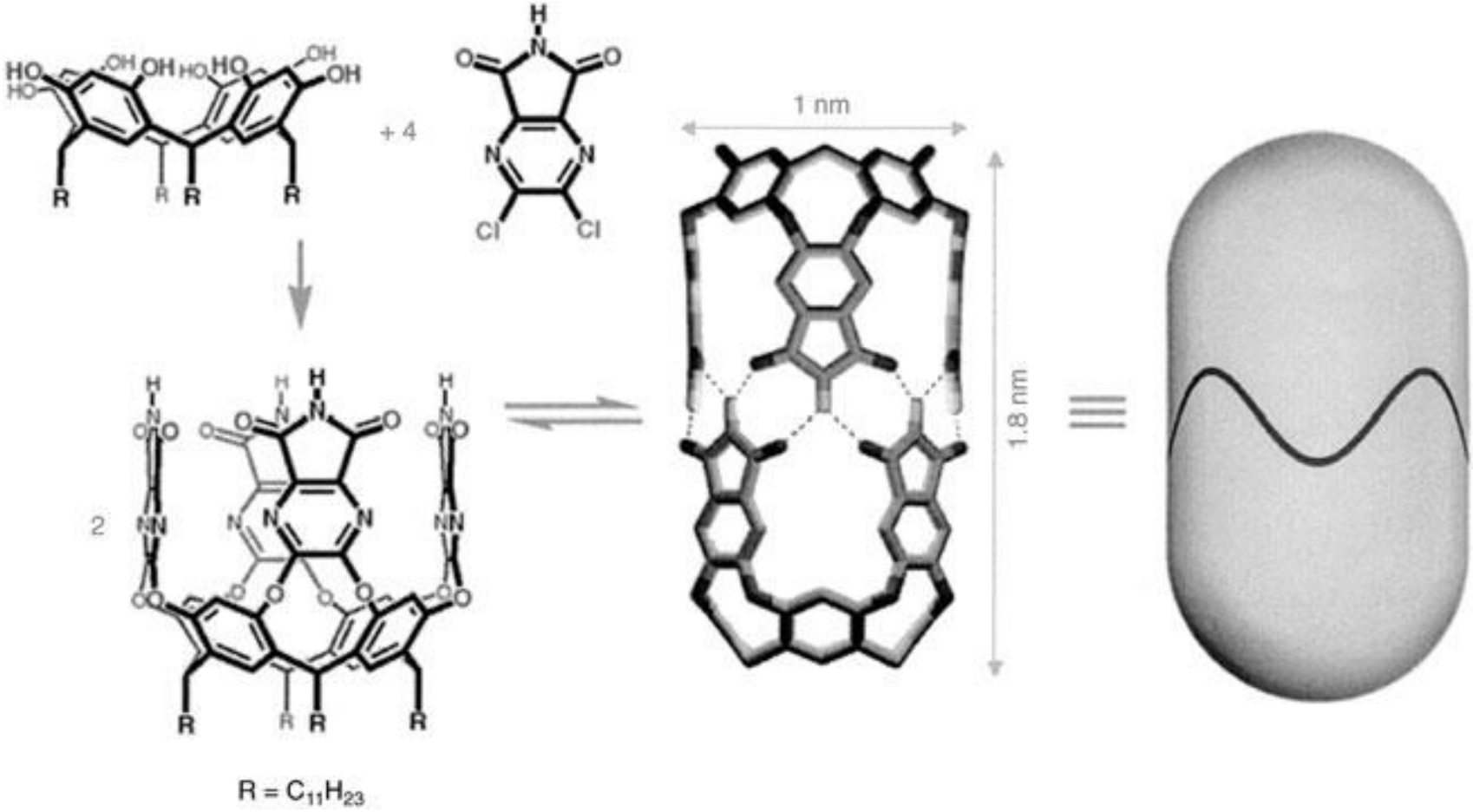
Soft-ball





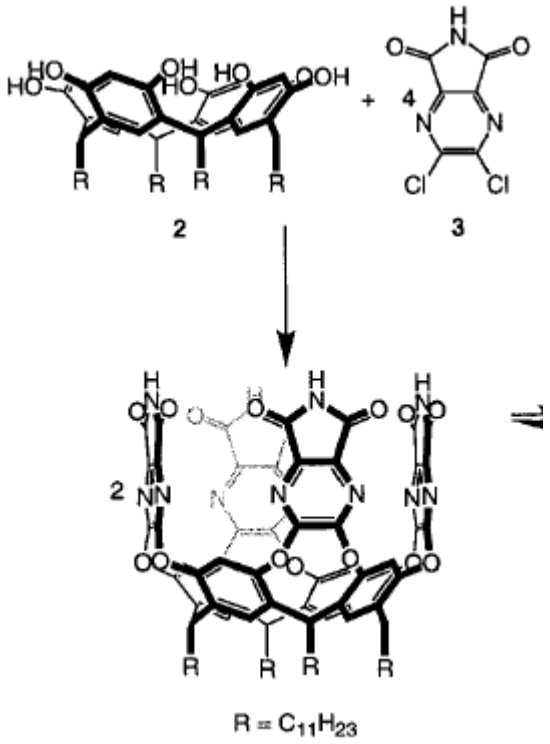
V ca. 400 Å^3

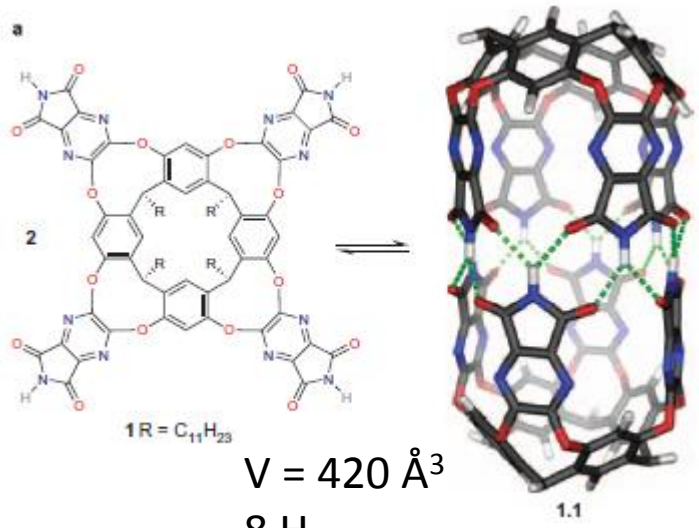
Molecular Cylinder



V *ca.* 420 Å^3

Molecular Cylinder

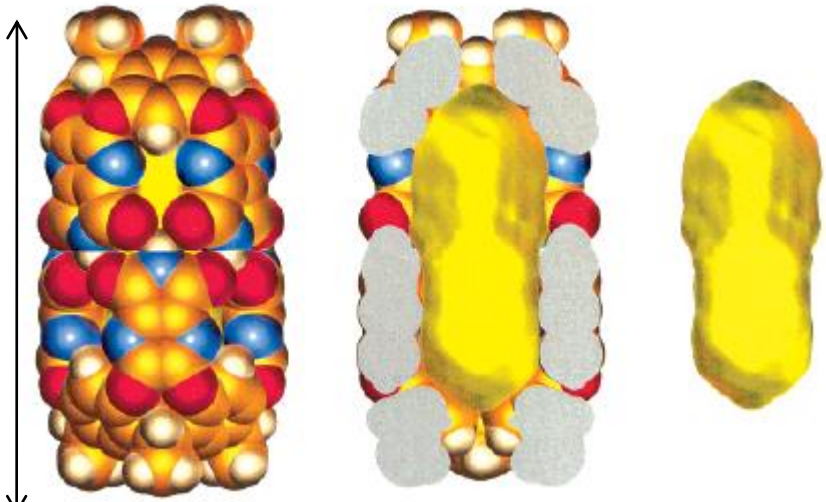




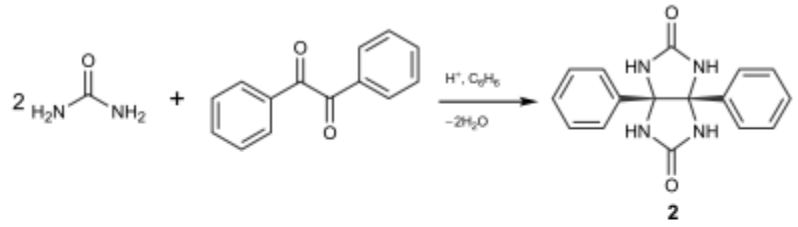
V = 420 Å^3

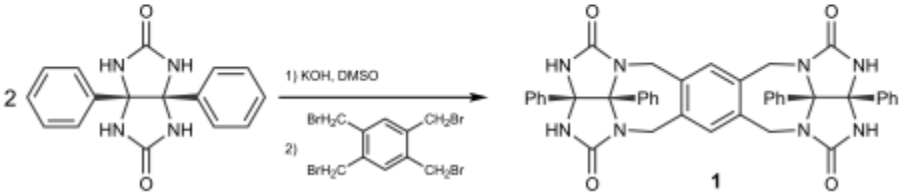
8 H

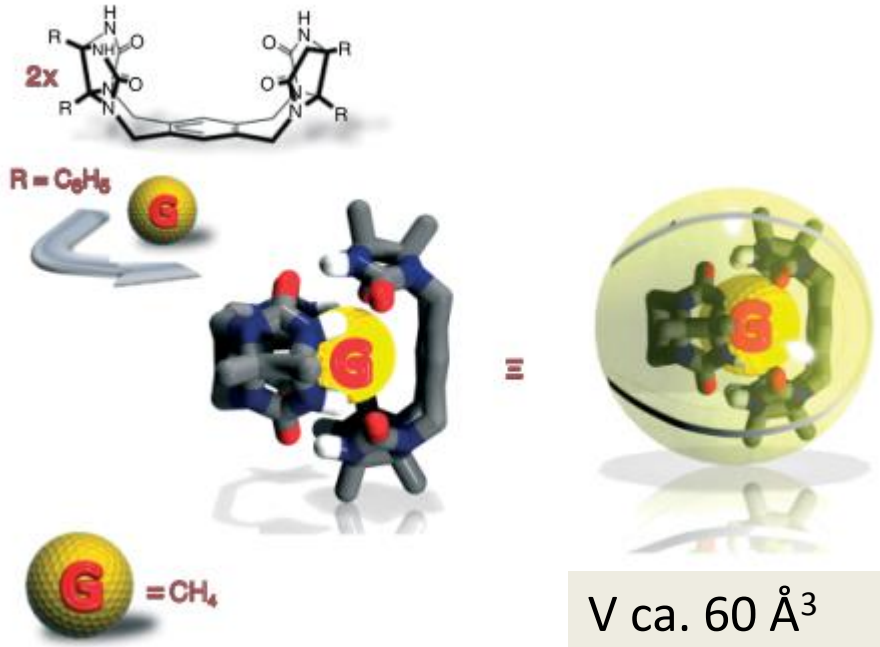
16 Å



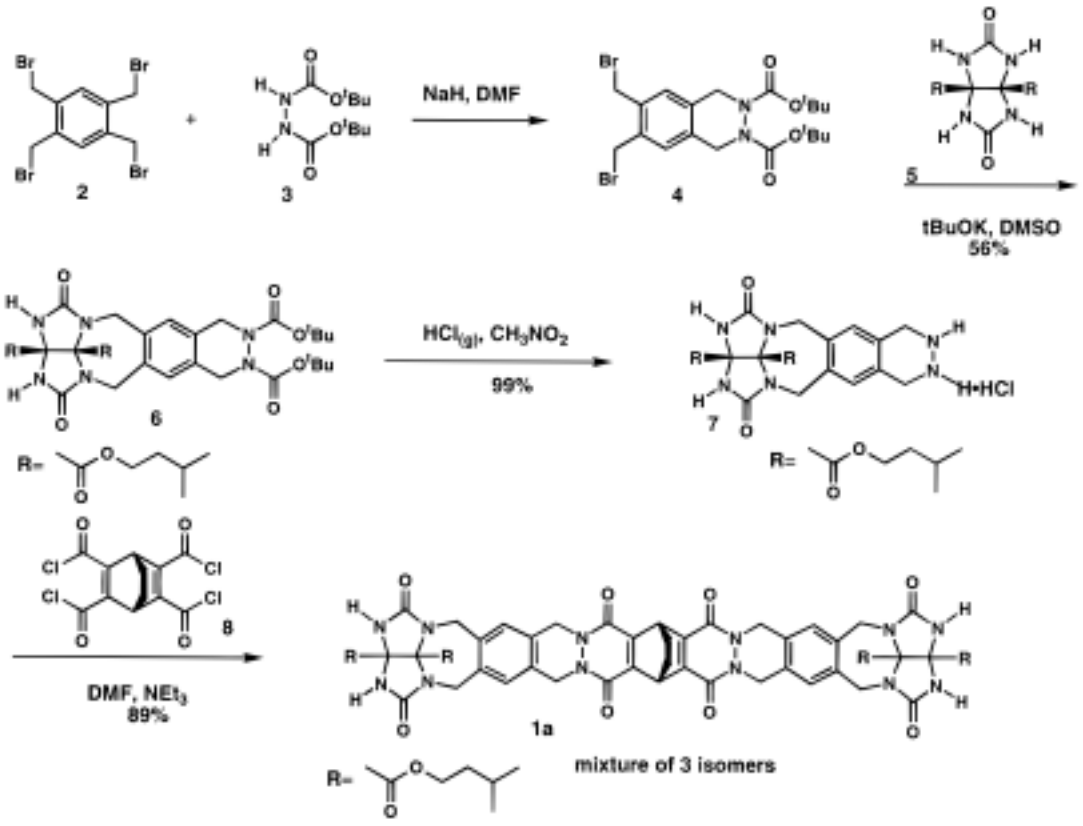
12 Å

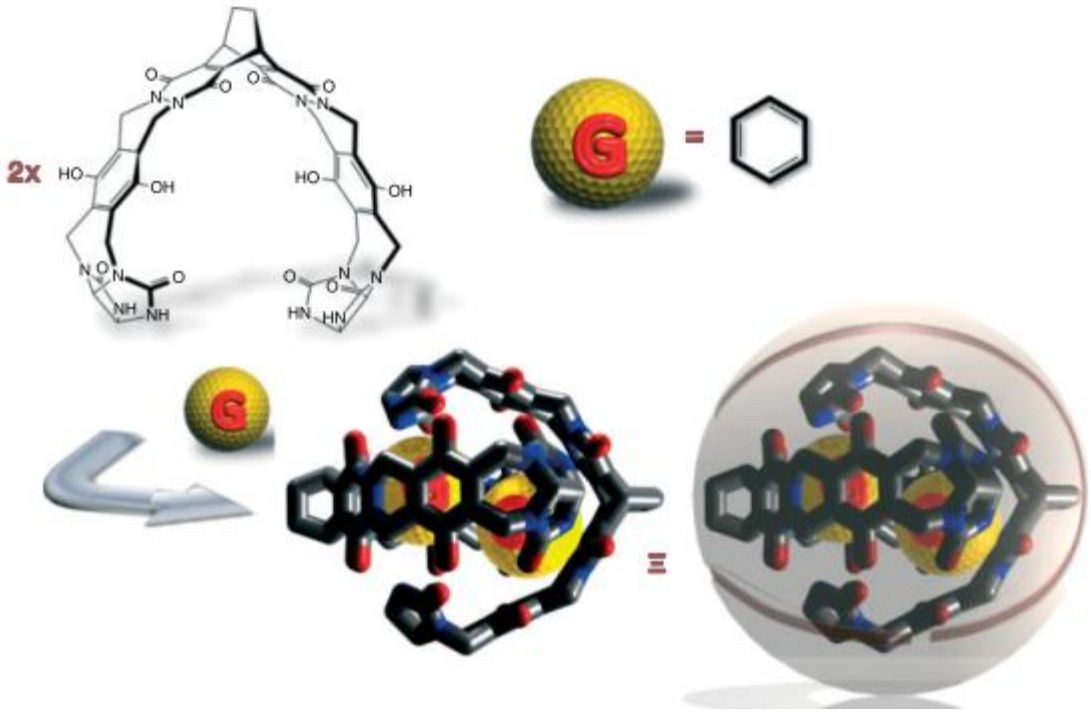

2
+
H+, C6H6
-2H2O
HN
NH
O
2


2
1) KOH, DMSO
2)
BrH2C
CH2Br
Ph
1

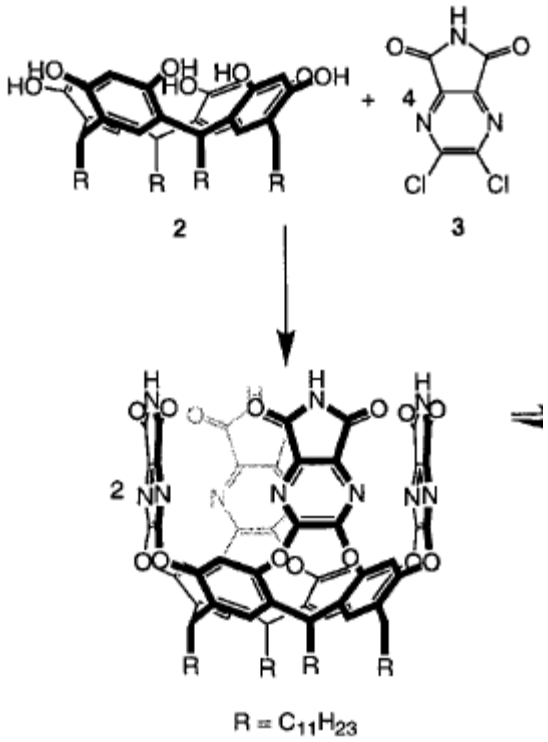

2x
R = C6H5
G
= CH4

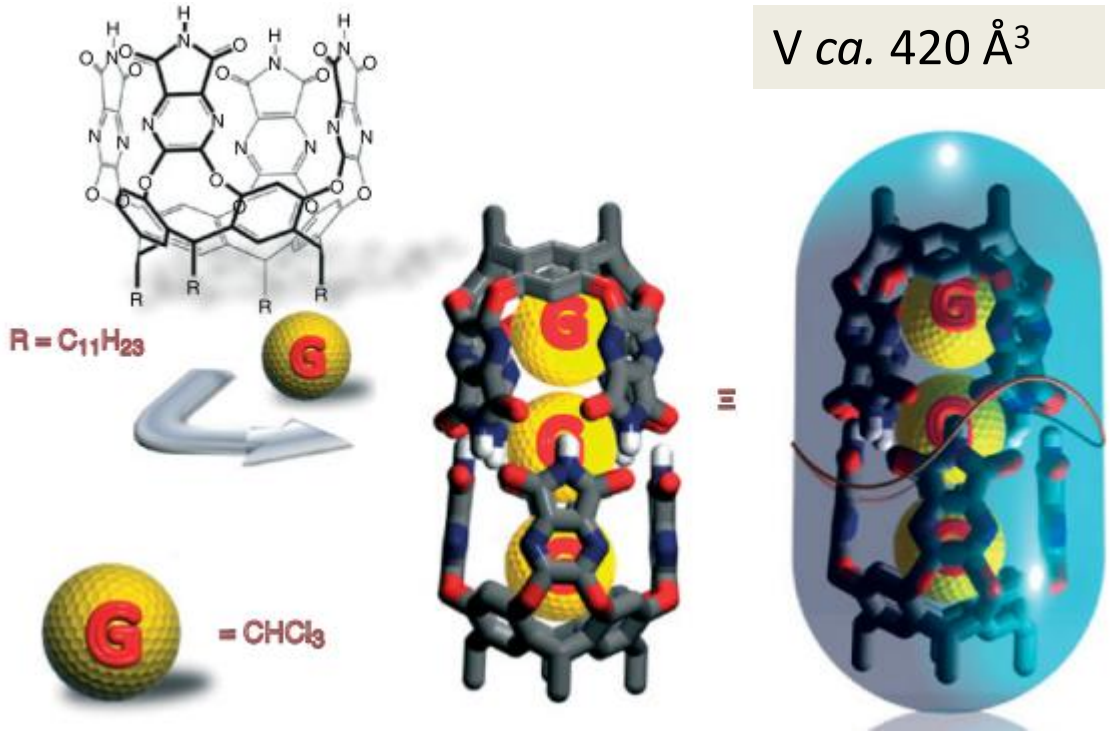
V ca. 60 Å^3


Br
Br
Br
Br
2
3
NaH, DMF
4
5
tBuOK, DMSO
56%
6
HCl(g), CH3NO2
99%
7
H•HCl
R=
8
DMF, NEt3
89%
1a
mixture of 3 isomers
R=



V ca. 400 Å^3



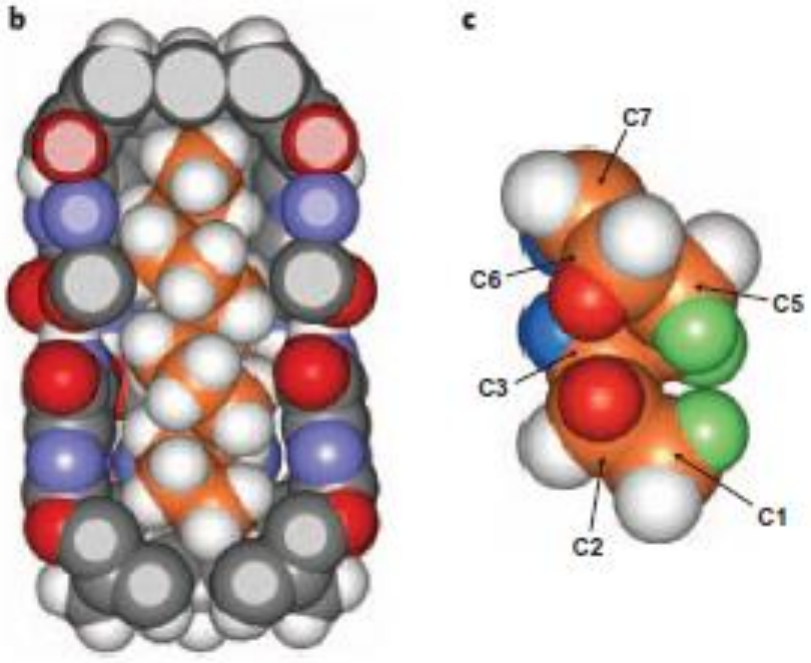


V *ca.* 420 Å^3

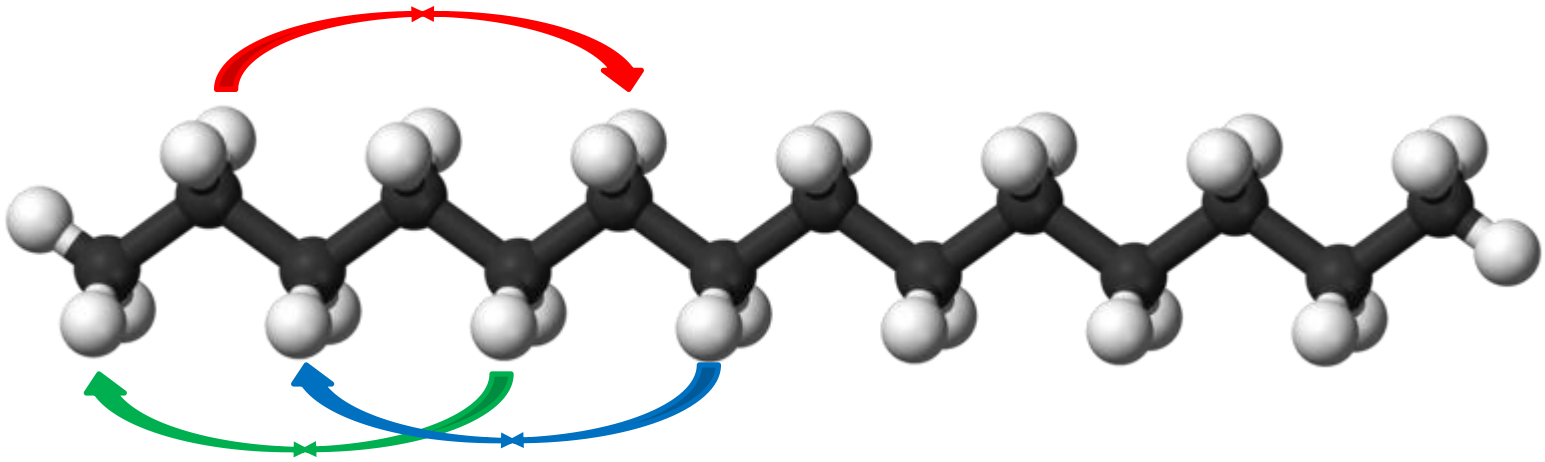
From molecular mechanics calculations:

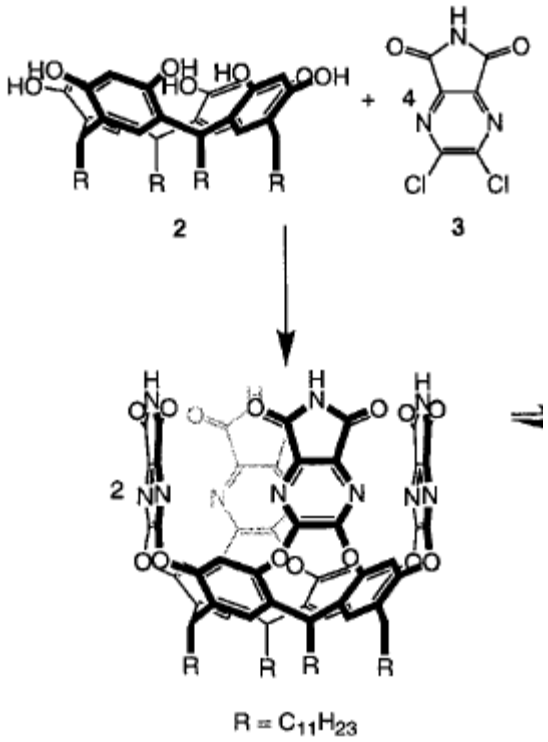
the encapsulated guest(s) occupy approximately 55% of the available space (same occupancy inside most weakly interacting organic solvents).

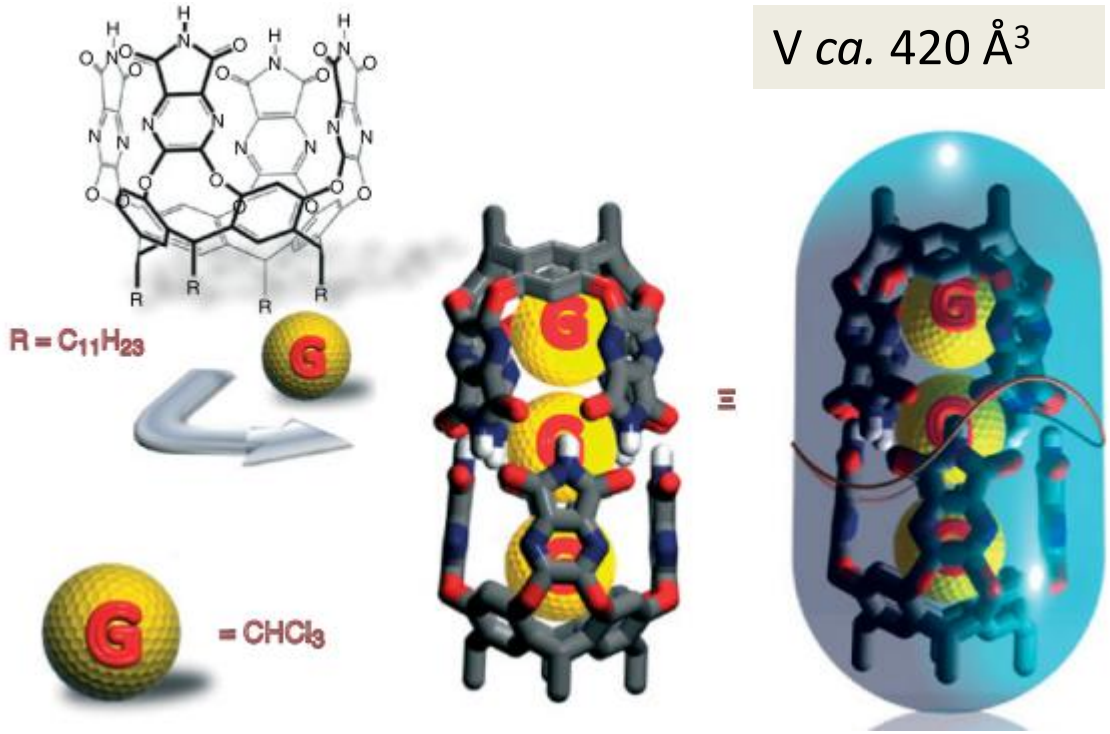
Stability deacreases at higher or lower space occupancy.



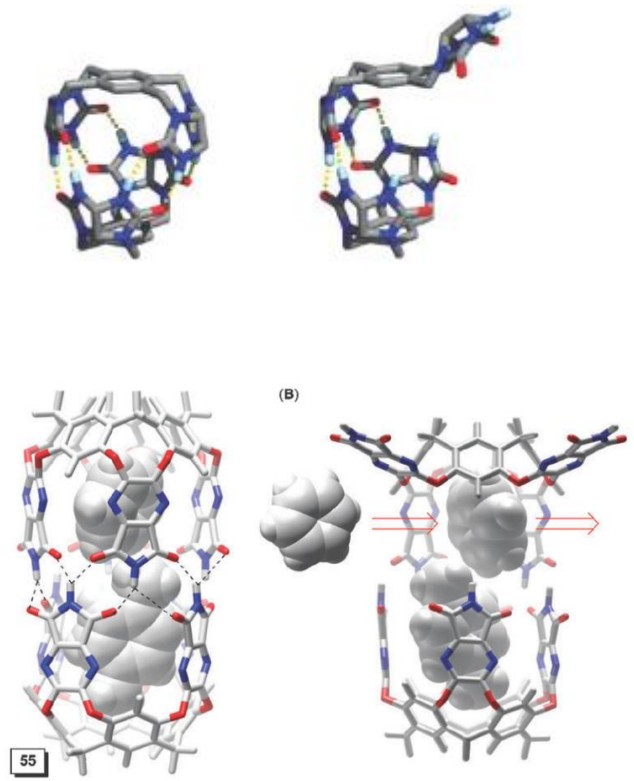
Model structure: incapsulation of coiled alkanes - tetradecane

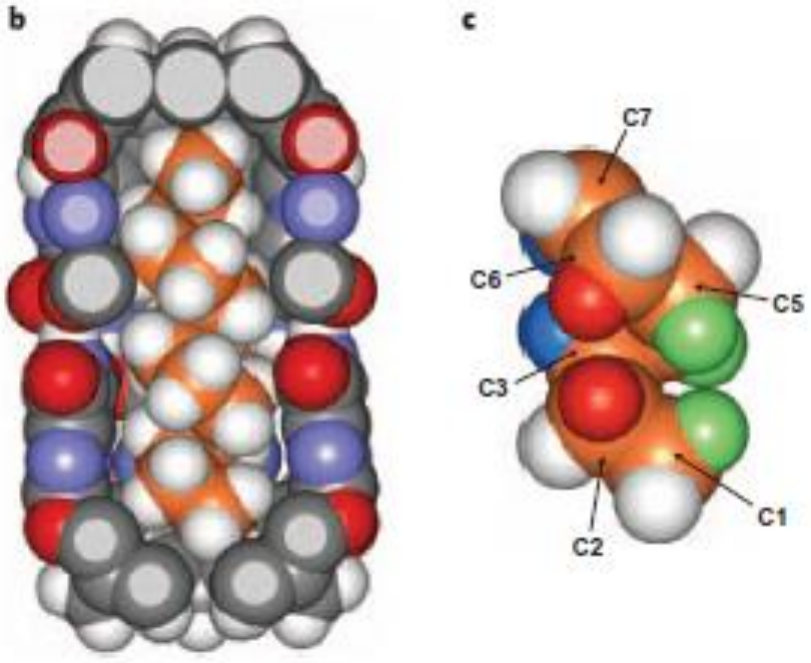




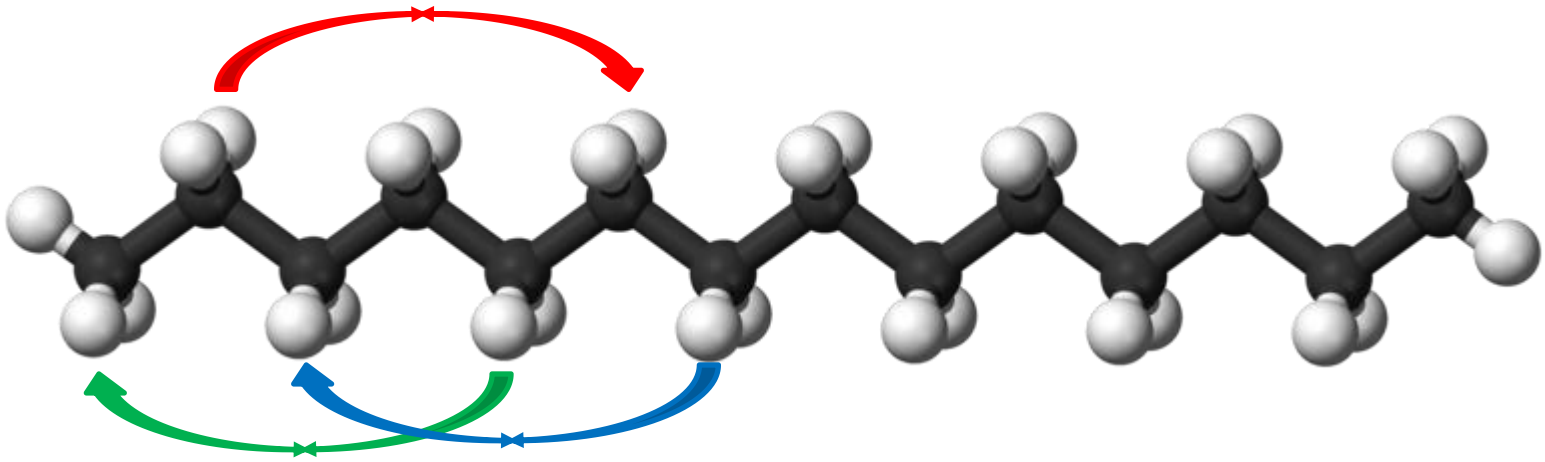


V *ca.* 420 Å^3


(B)
55



Model structure: incapsulation of coiled alkanes - tetradecane

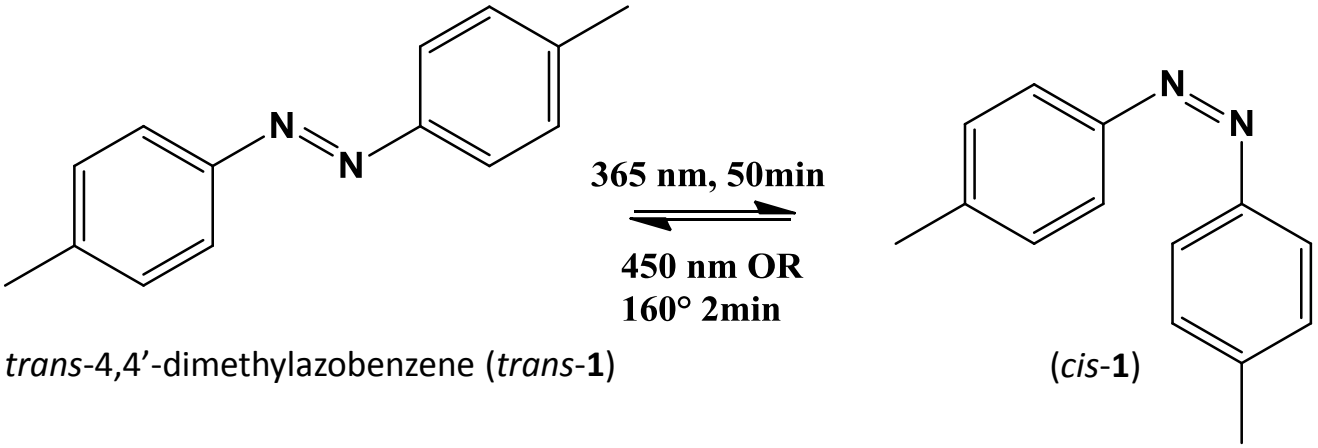


Host–Guest Chemistry

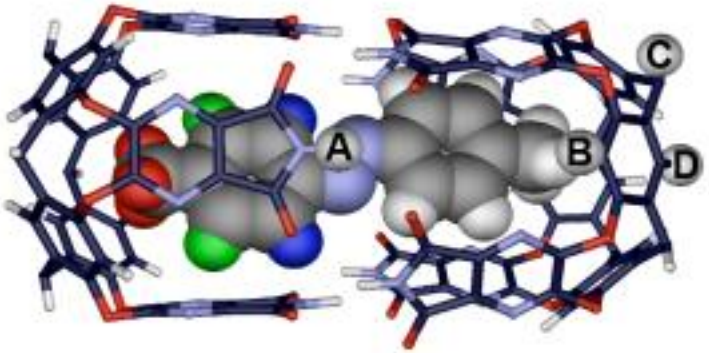
Angew. Chem. Int. Ed. 2010, 49, 3192 –3195

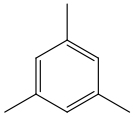
Photochemical Control of Reversible Encapsulation

*Henry Dube, Dariush Ajami, and Julius Rebek, Jr.**

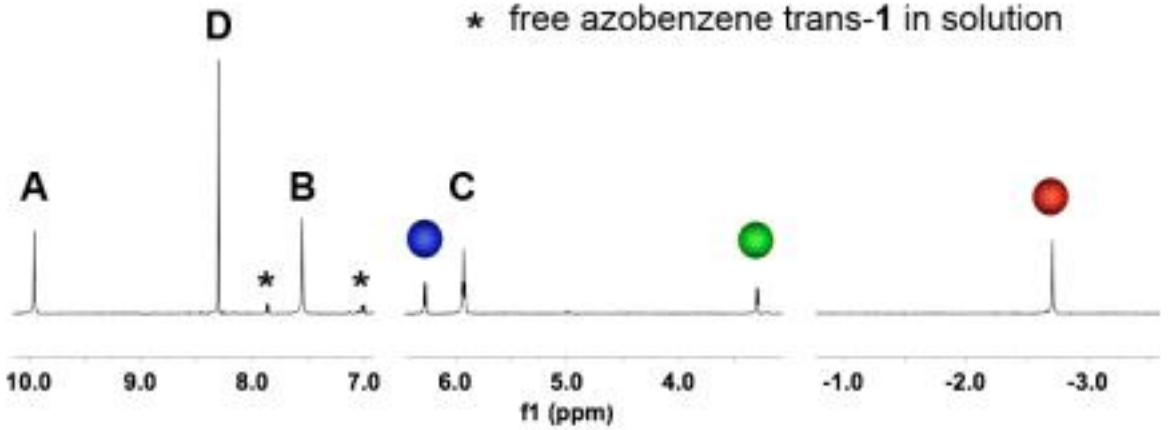


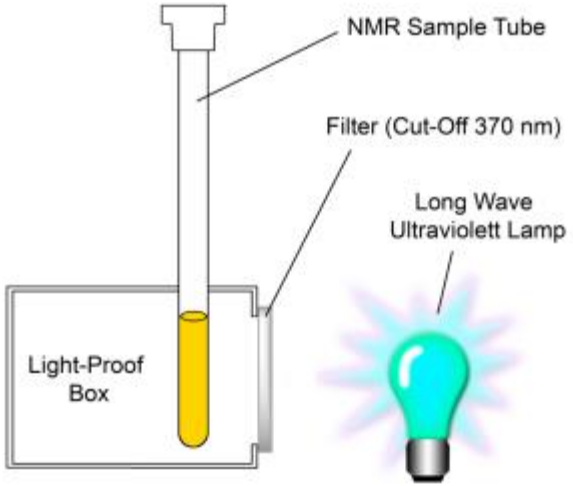
trans-4,4'-dimethylazobenzene (*trans*-**1**) (*cis*-**1**)

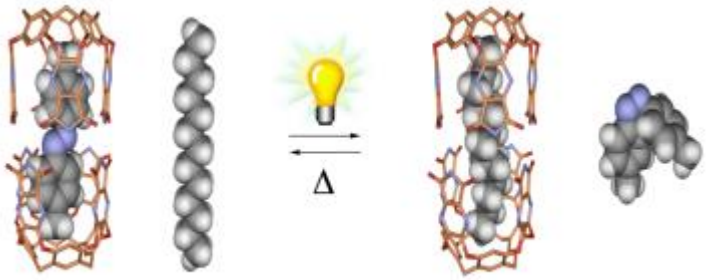


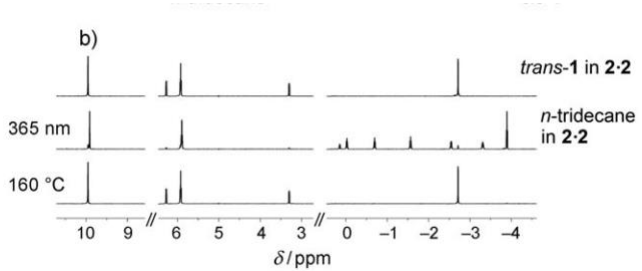


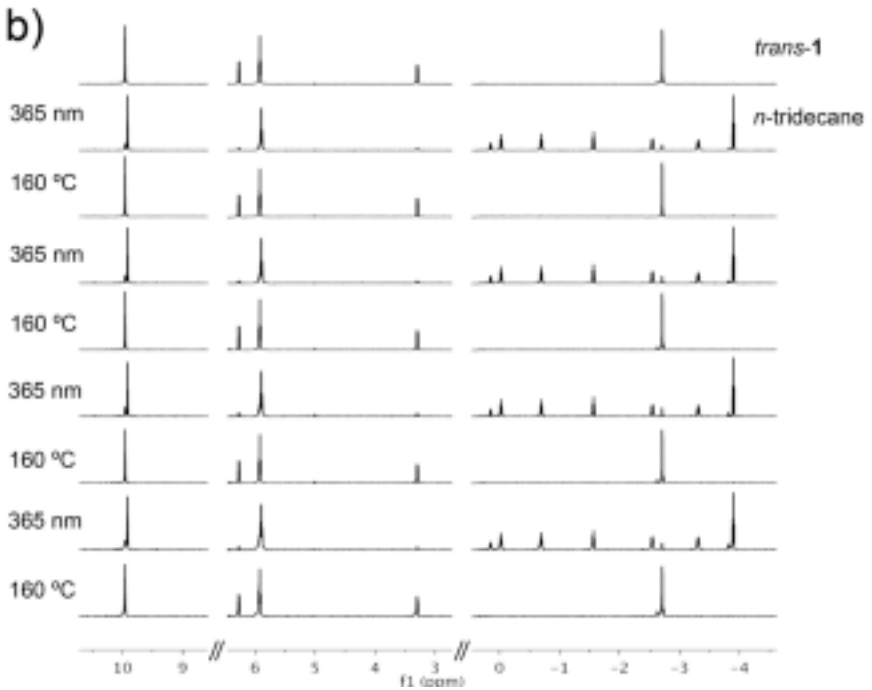
[D_{12}]mesitylene




NMR Sample Tube
Filter (Cut-Off 370 nm)
Long Wave
Ultraviolett Lamp
Light-Proof
Box

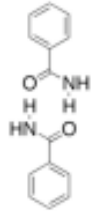

Δ


b)
trans-1 in 2·2
365 nm
n-tridecane
in 2·2
160 °C
10 9 6 5 4 3 0 −1 −2 −3 −4
δ / ppm

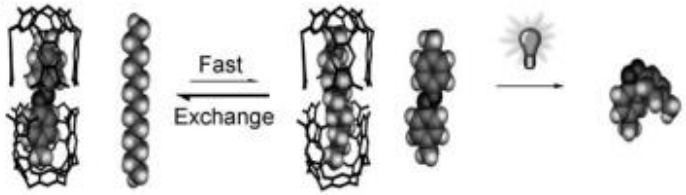

b)
trans-1
365 nm
n-tridecane
160 °C
365 nm
160 °C
365 nm
160 °C
365 nm
160 °C
10 9 6 5 4 3 0 -1 -2 -3 -4
f1 (ppm)

Guest =

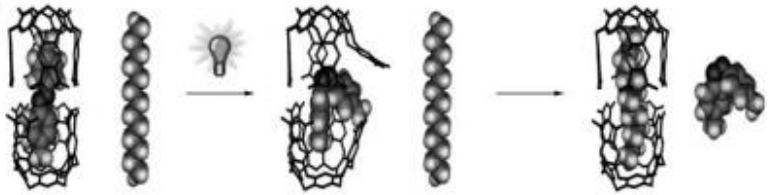
Guest =



a)



b)



Breakout

J. AM. CHEM. SOC. 2010, 132, 9984–9985

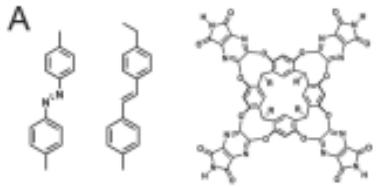
J|A|C|S COMMUNICATIONS

Published on Web 07/07/2010

Supramolecular Control of Fluorescence through Reversible Encapsulation

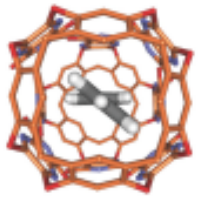
Henry Dube,[‡] Mark R. Ams,[†] and Julius Rebek, Jr.*[,‡]

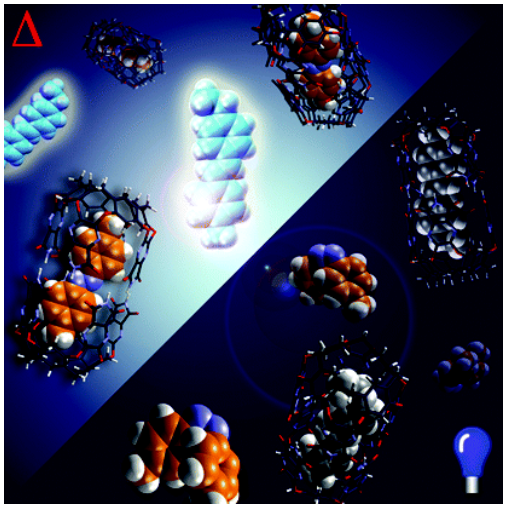
A

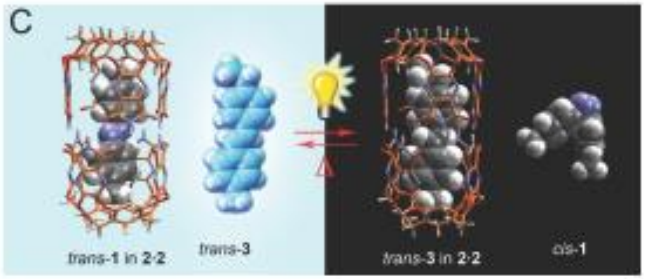


trans-**1** *trans*-**3** **2** R = $C_{11}H_{23}$

B







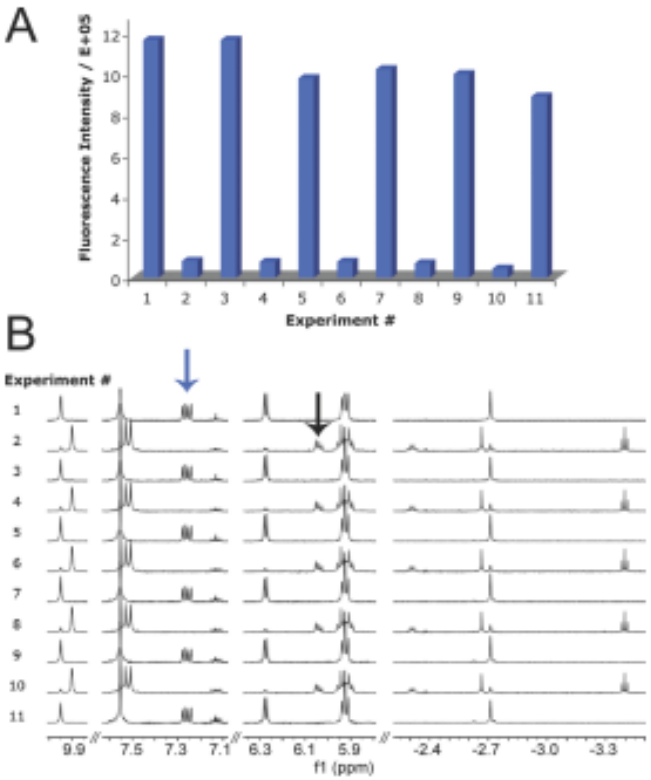
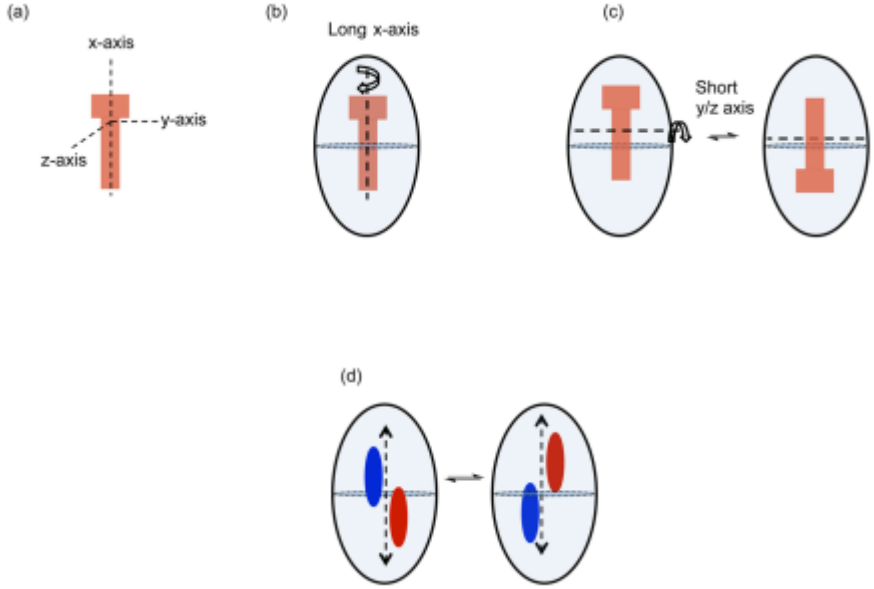
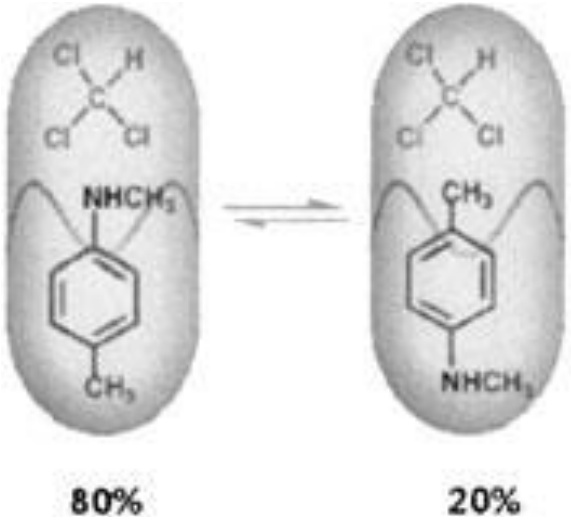


Figure 2. Reversible fluorescence intensity switching by light and heat. Five cycles of guest exchange and concomitant fluorescence change are shown. The numbers shown correspond to paired experiments for fluorescence measurement and ^{1}H NMR spectra. Odd experiment numbers indicate heating steps (160 °C for 2 min); even numbers indicate irradiation steps (365 nm for 50 min at 20 °C). (A) Fluorescence measured at 388 nm on excitation at 318 nm. (B) Corresponding ^{1}H NMR spectra for each step. The blue arrow indicates proton signals of free *trans*-**3** in solution; the black arrow indicates two aromatic proton signals of encapsulated *trans*-**3**.


(a)
x-axis
y-axis
z-axis
(b)
Long x-axis
(c)
Short
y/z axis
(d)

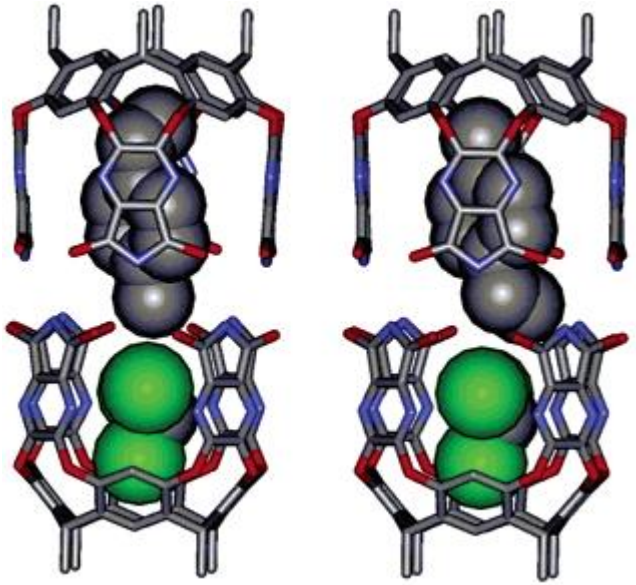
Social Isomers



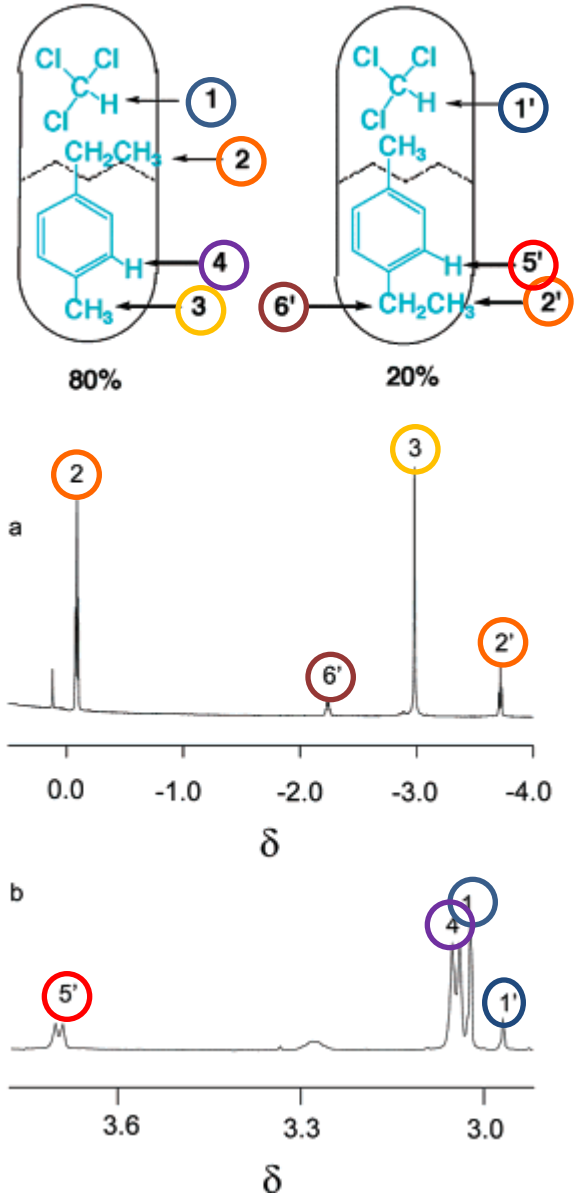
Cloroformio ed N-metil-*para*-toluidina, no interconversione

Social Isomers:

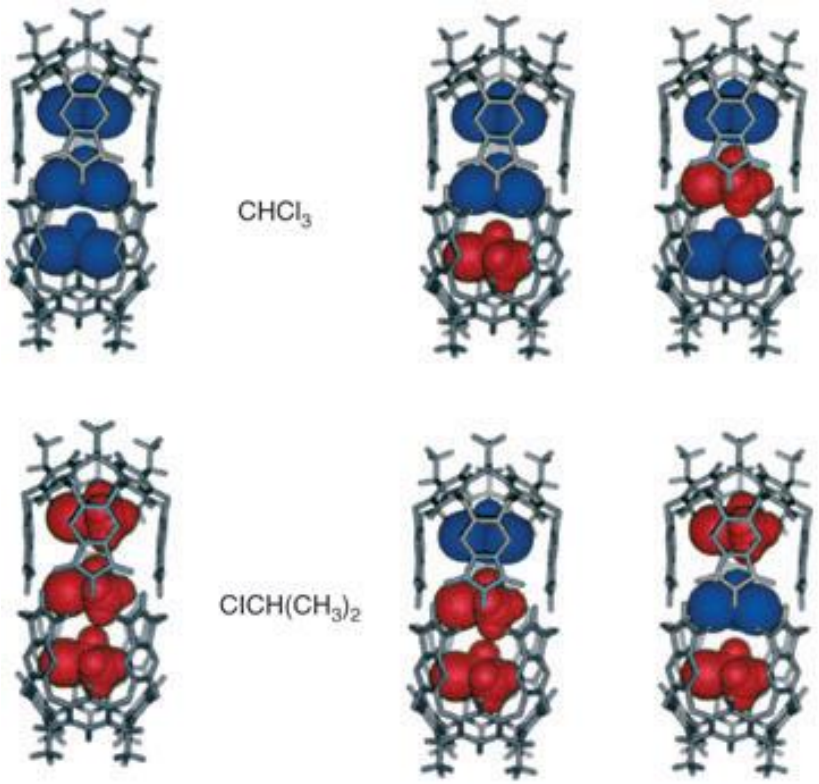
The orientational preference of one guest depends on the presence of the co-guest.



MM optimized structures:
cloroformio e *para*-etiltoluene



Constellation Isomers



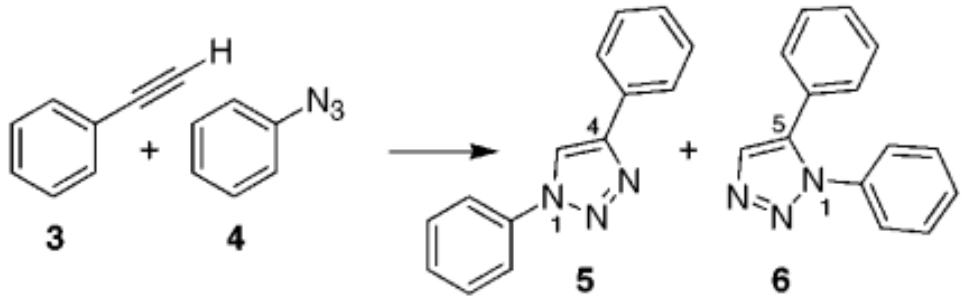
MM optimized structures:
cloroformio e *iso*-propilcloruro

In addition to being able to preserve highly labile species, they may serve as catalysts and accelerate reactions inside their inner cavity by either concentrating the reactants leading to higher effective concentrations or TS stabilization or by preorganising them inside the capsule.

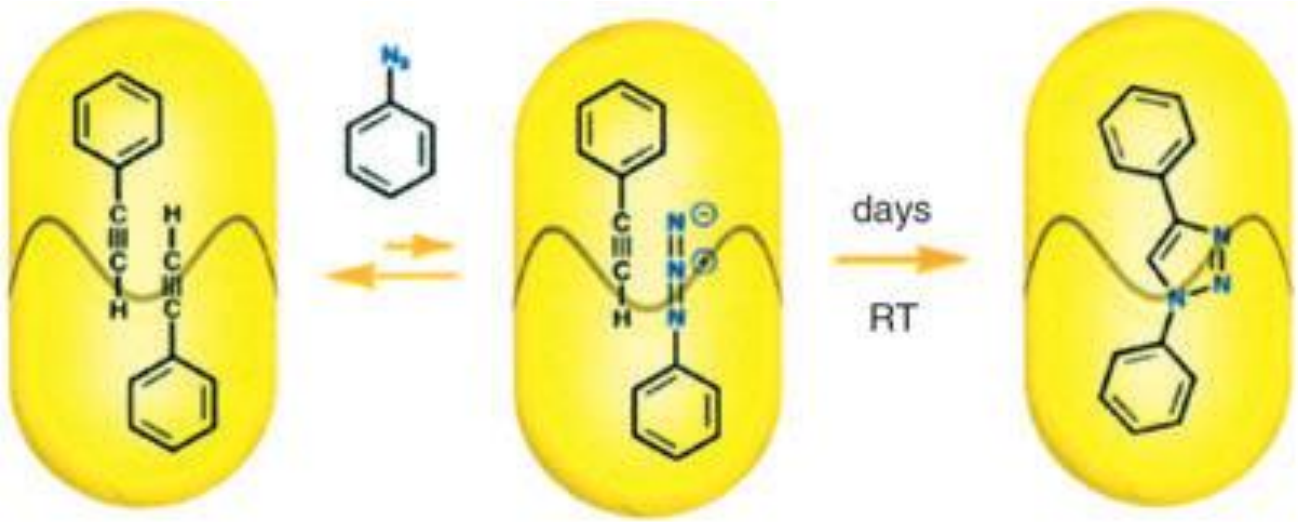
They may create a micro-environment in which two encapsulated reactants are held together in a orientation that differs from their most reactive arrangment in solution (or gas phase) leading to products that are disfavoured in equivalent solution phase reactions.

Reattività nelle capsule molecolari

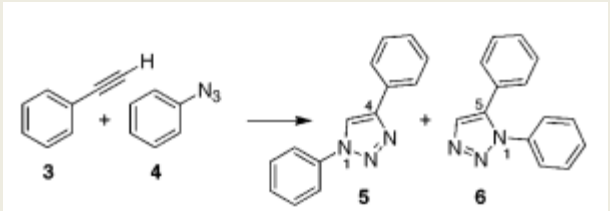
Cicloaddizione 1,3 regioselettiva di fenilacetilene e fenilazide



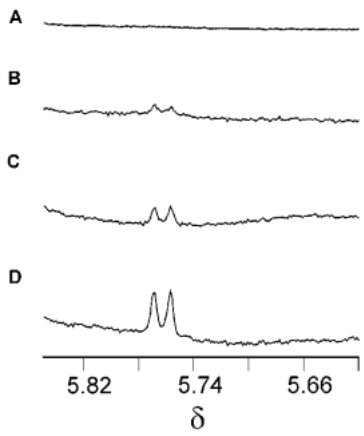
Reattività nelle capsule molecolari

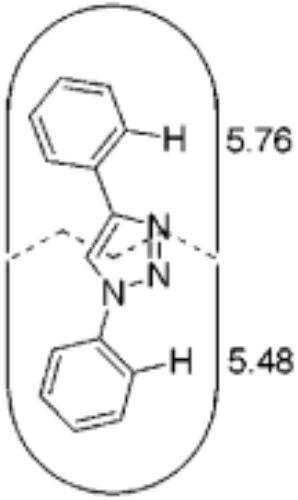


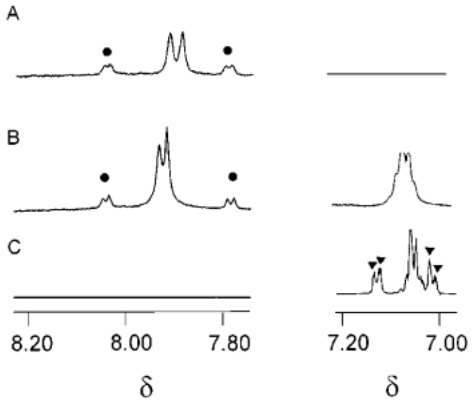
Cicloaddizione 1,3 regioselettiva di fenilacetilene e fenilazide:

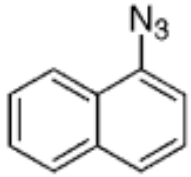


Volume definito = [ ] 4M vs mM
Tempo di contatto = 1 s vs 1 ns
Solvatazione fissa

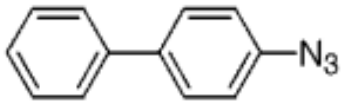








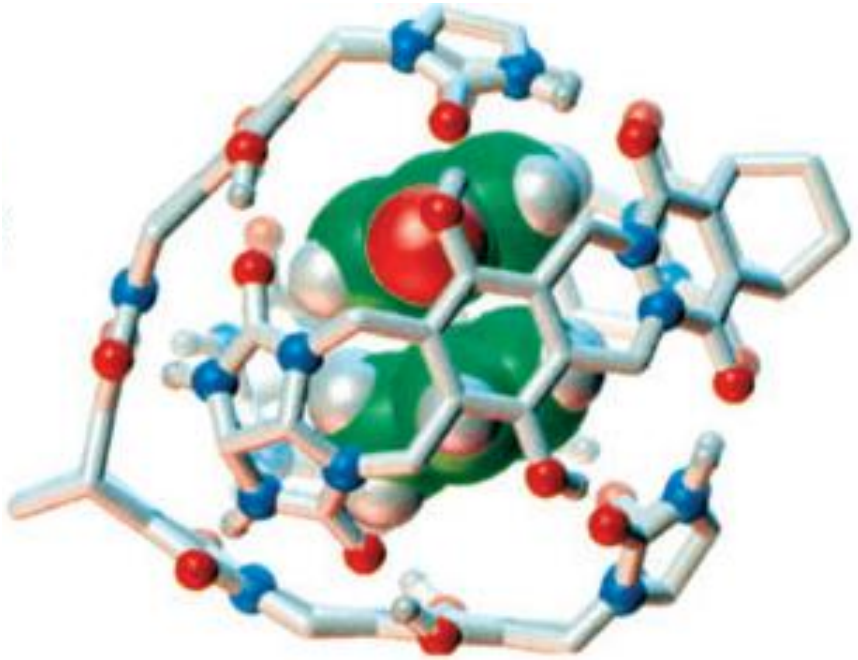
7



8

Reattività nelle capsule molecolari

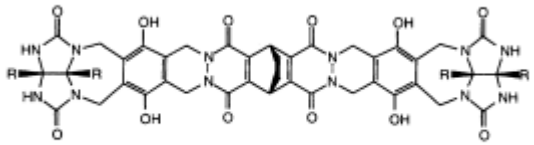
Cicloaddizione Diels-Alder acceleraz di ca. 200 volte
[ ] = 5M
Solvatazione
Tempo di contatto



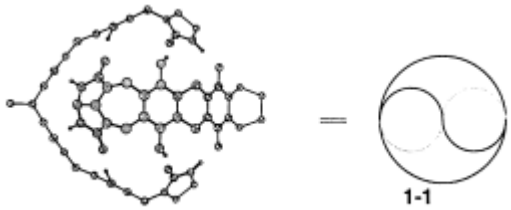
Acceleration of a Diels–Alder reaction by a self-assembled molecular capsule

Jongmin Kang & Julius Rebek Jr

NATURE · VOL 385 · 2 JANUARY 1997

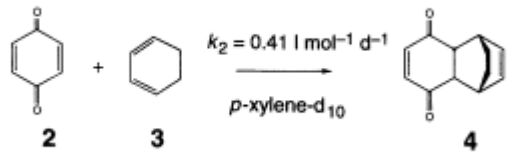


1 R = 4-*n*-heptylphenyl



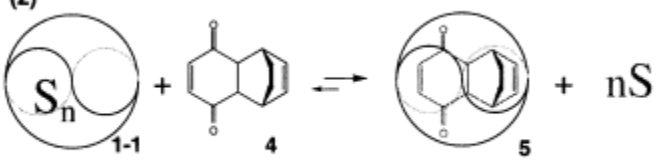
1-1

(1)



2 **3** **4**

(2)



S = *p*-xylene-d_{10}

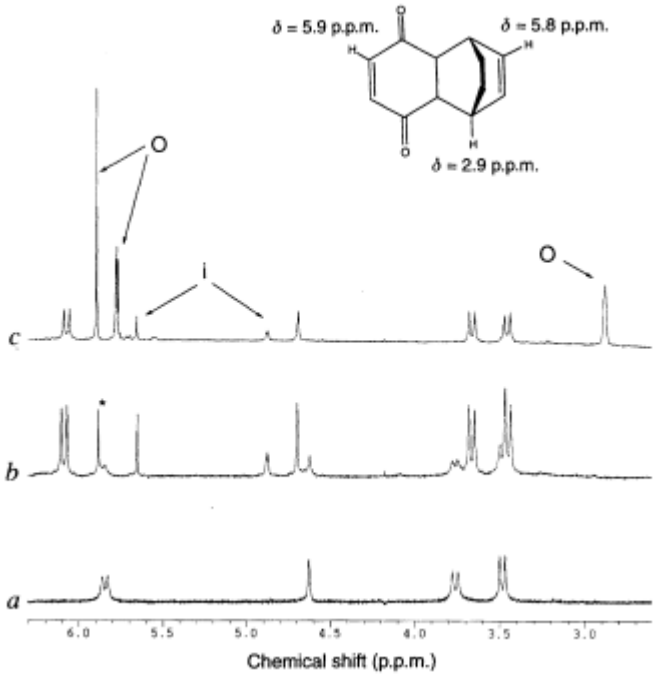
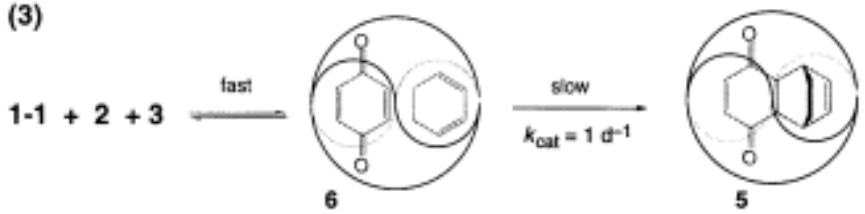


FIG. 2 Proton NMR spectra of **1-1** and its encapsulation complex with the adduct **4** in *p*-xylene-d_{10}. Signals of the guest inside the capsule and outside (free) are labelled with 'i' and 'o', respectively. The signal designated with an asterisk represents chloroform. *a*, Compound **1-1** alone. *b*, Compound **1-1** with 0.7 equiv. of Diels–Alder adduct **4** added; all of the latter is encapsulated and separate signals are observed for the complex **5** and solvated dimer **1-1**. *c*, Compound **1-1** with 6 equiv. of Diels–Alder adduct **4** added; all of the capsule is occupied as complex **5** and separate signals are observed for free and encapsulated adduct **4**. Assignments for resonances of free **4** are shown on the structure.

(3)



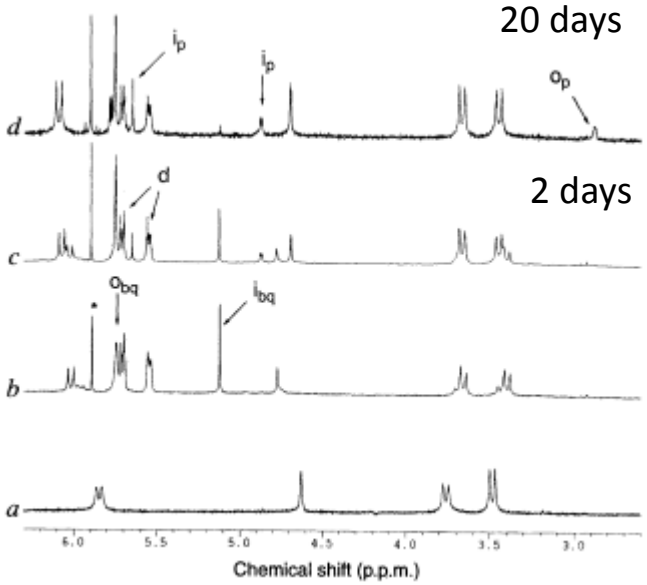


FIG. 3 Changes in the proton NMR spectra of **1-1** during the reaction of *p*-benzoquinone **2** and 1,3-cyclohexadiene **3** in *p*-xylene-d_{10}. The signals for *p*-benzoquinone(bq) and Diels–Alder product (p) inside and outside are designated as 'i' and 'o' respectively. Signals from cyclohexadiene are designated as 'd'. The signal designated with an asterisk represents chloroform impurity. *a*, Compound **1-1** alone. *b*, Shortly after 4 equiv. of *p*-benzoquinone and 4 equiv. of 1,3-cyclohexadiene were added to the solution of **1-1**. *c*, The reaction mixture after 2 days. *d*, The reaction mixture after 19 days, showing evidence of released product and **5** as the principal species.

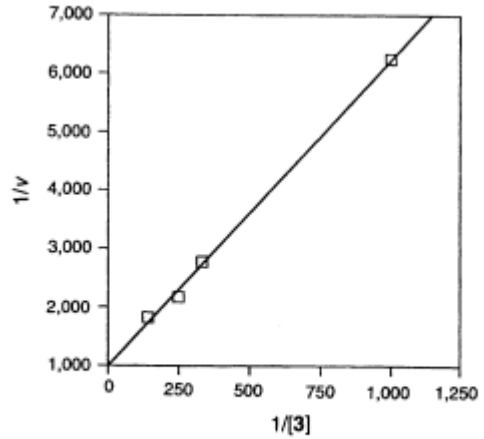
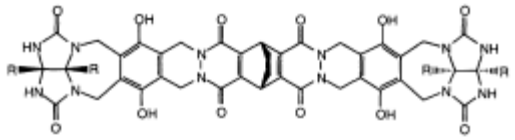
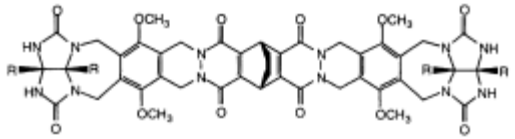


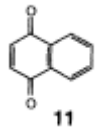
FIG. 4 Lineweaver–Burke plot of the reaction rates, *V*, of **2** with **3** in the presence of **1-1**. The concentrations of 1,3-cyclohexadiene **3** were changed with a constant concentration (4 mM) of *p*-benzoquinone.



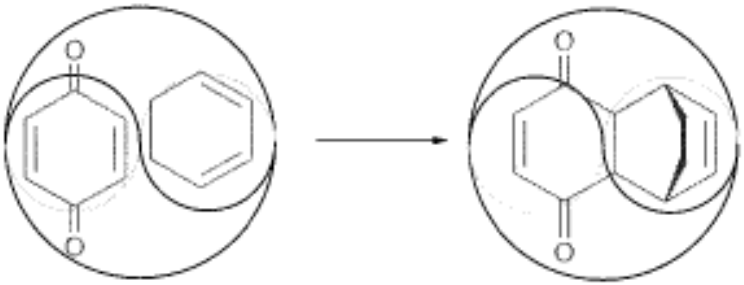
9 R = 4-*n*-heptylphenyl

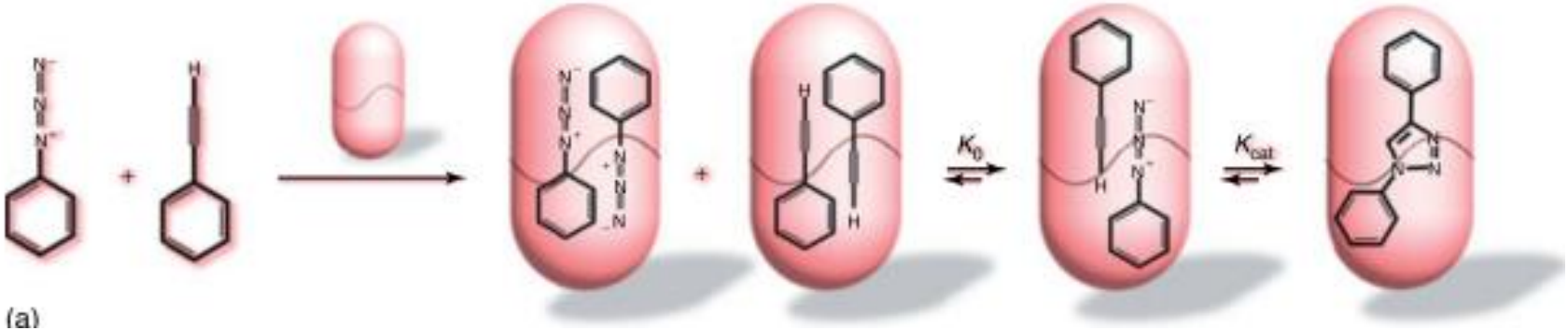


10 R = 4-*n*-heptylphenyl



11



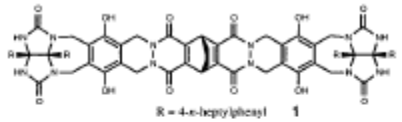


(a)

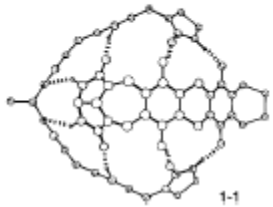
Self-Assembled Molecular Capsule Catalyzes a Diels–Alder Reaction

J. Am. Chem. Soc. 1998, *120,* 7389–7390

Jongmin Kang, Javier Santamaria, Göran Hilmersson, and Julius Rebek, Jr.*

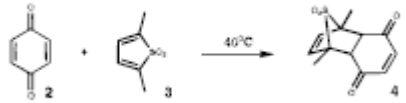


R = 4-n-heptylphenyl 1



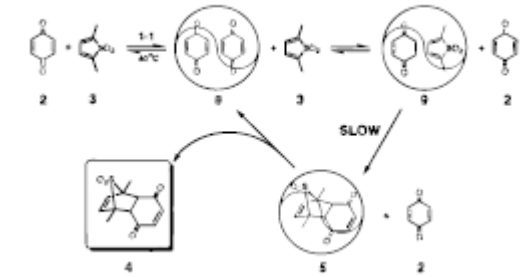
1-1

Scheme 1



Scheme 2

Scheme 3



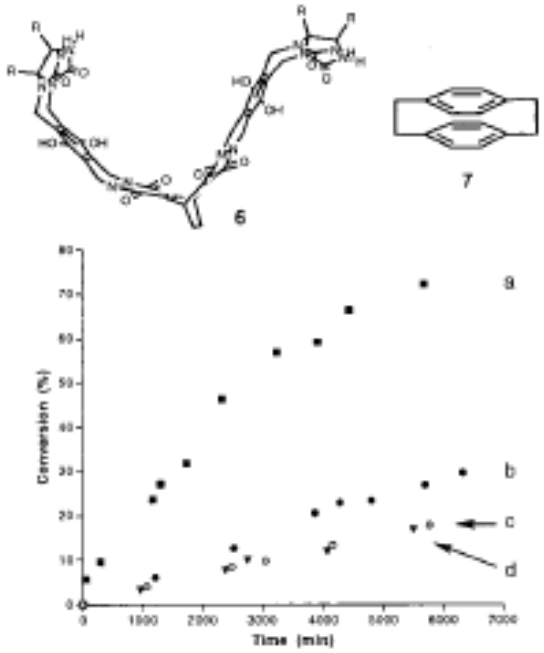


Figure 2. Comparative study of the formation of the Diels−Alder adduct along the time: (a) catalyzed reaction; (b) reaction inhibited with 1 equiv (with respect to the softball) of [2,2]paracyclophane (**7**); (c) background reaction; (d) use of S-shaped isomer **6** instead hydroxy softball.

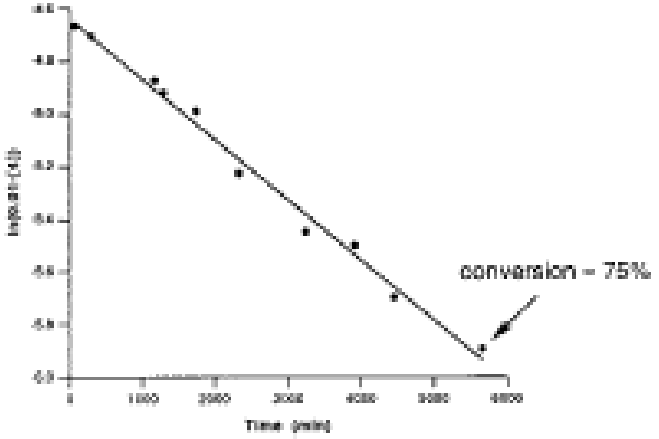
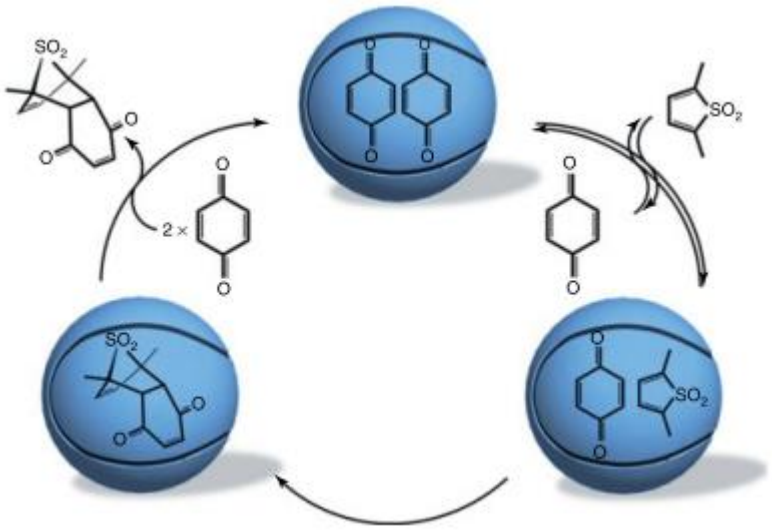


Figure 3. Logarithmic plot of the formation of the Diels−Alder adduct using hydroxy softball as catalyst. It shows linearity over 75% conversion. The experiment has been performed in *p*-xylene-d_{10} at 40 °C, with concentrations of 10 mM for the reactants and 1 mM for the capsule.


SO2
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