Complexation of *C*-methyl pyrogallarene with small quaternary and tertiary alkyl ammonium cations†‡

Antti Åhman, Minna Luostarinen, Kari Rissanen and Maija Nissinen*

Received (in Montpellier, France) 27th June 2006, Accepted 6th October 2006
First published as an Advance Article on the web 27th October 2006
DOI: 10.1039/b609117b

Complexation properties of pyrogallarene **1** towards small quaternary and tertiary alkyl ammonium cations were studied in gas phase, solution and in solid state. In gas phase both dimeric capsules and monomeric 1 : 1 complexes of all cations $\mathbf{2a}^+$–$\mathbf{d}^+$ are detected but only in the case of $\mathbf{2a}^+$ is the abundance of the capsule form higher than the monomeric 1 : 1 complex. A similar trend is observed in NMR experiments, which reveal a favourable dimeric complex for $\mathbf{2a}^+$ and a weaker dimeric complex for $\mathbf{2b}^+$ but only monomeric complexes for $\mathbf{2c}^+$ and $\mathbf{2d}^+$. Also in solid state, $\mathbf{2a}^+$ and $\mathbf{2b}^+$ form capsules when crystallized from MeOH while $\mathbf{2c}^+$ and $\mathbf{2d}^+$ form dimeric 1 : 1 complexes. As a reference, hetero-conformational dimeric capsule EtOH@$\mathbf{1}_2$ obtained from the crystallization without any guest, is reported. The capsule consists of two directly hydrogen-bonded pyrogallarenes **1**, one in boat conformation and the other in crown conformation, and encloses a molecule of ethanol.

Introduction

Hydrogen-bonded capsules[1–3] as well as open inclusion complexes[2c,4] of artificial receptors have enhanced our current understanding of chemical and biological recognition and self-assembly. For example, size and stereoselective inclusion[5] of guest molecules and catalysis of chemical reactions[6] within a capsule give valuable information of the function of the receptor molecules and biocatalysis.

One family among these capsular and open inclusion complexes is based on resorcinarenes and pyrogallarenes **1**, which are versatile and readily available host compounds.[7] Pyrogallarenes and resorcinarenes are usually all-*cis* configured (r-*ccc*), bowl-shaped cyclic tetramers, which are, due to their favorable shape, π-basic cavity and ability to form multiple hydrogen bonds, suitable for the complexation both in dimeric and open 1 : 1 fashion[2,3,8,9] as well as for the formation of larger complexation assemblies, such as hexameric capsules[10,11] or nanotubes.[12,13]

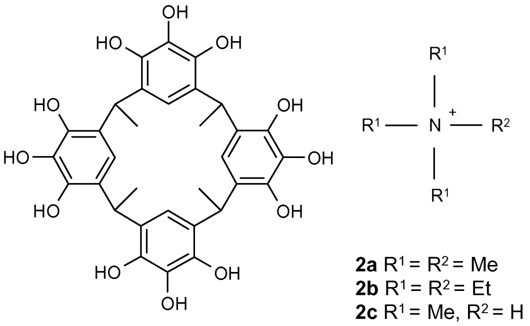
Previous studies in solid state reveal that two halves of dimeric resorcinarene and pyrogallarene capsules are without exception hydrogen bonded to each other *via* mediating solvent molecules or in some cases also *via* spherical halide anions (Cl^- or Br^-).[2,3,8] CH···π and cation–π interactions act as the driving force for the capsule formation since several weak interactions between the aromatic parts of the host and the carbon atoms of the guest are detected. Previous studies emphasize the significance of the cation size for encapsulation, while the effect of the counter anion and solvent is evident for the solid state assembly in general.[2c,d]

In order to compare the complexation properties of pyrogallarenes **1** with earlier results of resorcinarenes[2,12] we studied the complexation of small alkyl ammonium cations $\mathbf{2a}^+$–$\mathbf{d}^+$ with pyrogallarene **1** in solid state, solution and in gas phase (Scheme 1).

Results and discussion

Single crystal X-ray diffraction analysis

Slow crystallization of pyrogallarene **1** with tetramethyl ammoniun chloride (**2a**Cl) from methanol solution in 2 : 1 ratio gives single crystals of a dimeric capsule enclosing the cation with the total composition of $\mathbf{2a}^+@\mathbf{1}\cdot\mathbf{1}^{-0.5}\cdot 0.5Cl^-\cdot 8MeOH$ (Fig. 1). The composition of the crystal is somewhat unusual, since only a half of the chloride anion is found in the asymmetric unit and, additionally, one of the hydroxyls of the other pyrogallarene host is deprotonated with a disorder between protonated OH and deprotonated O^-. The deprotonation is proved by the shorter hydrogen bonding distance of



Scheme 1 Structural formula of *C*-methyl pyrogallarene **1** and alkyl ammonium cations $\mathbf{2a}^+$–$\mathbf{d}^+$.

Nanoscience Center, Department of Chemistry, University of Jyväskylä, P.O. Box 35, FIN-40014 JYU, Finland. E-mail: majoni@cc.jyu.fi; Fax: +358 14 260 4756; Tel: +358 14 260 4242

† Electronic supplementary information (ESI) available: crystallographic data in CIF format. See DOI: 10.1039/b609117b

‡ The HTML version of this article has been enhanced with colour images.

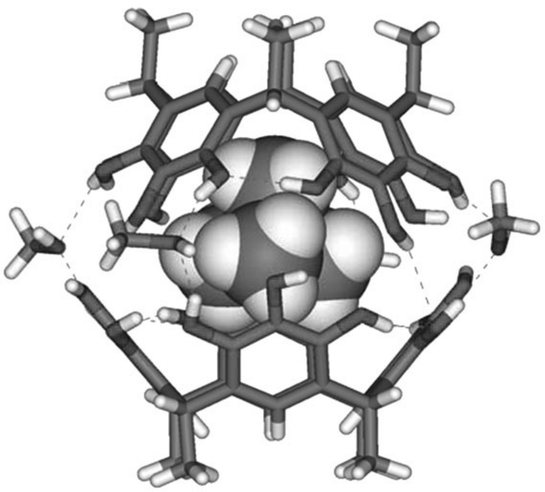


Fig. 1 X-ray crystal structure of the dimeric capsule of pyrogallarene **1** with $\mathbf{2a}^+$ presented as VDW/stick presentation. The capsule halves are linked by hydrogen bonds *via* four methanol molecules. Methanol molecules and the anion, which are not linking pyrogallarenes, are omitted for clarity.

the deprotonated hydroxyl group (2.63 Å *vs.* average of 2.70 Å) and the lack of electron density indicating hydrogen in that particular hydroxyl group. This result is in line with the earlier observation with *C*-ethyl pyrogallarene·$\mathbf{2a}^+$ capsule, in which one of the pyrogallarene hydroxyl groups was similarly deprotonated.[3]

Both capsule-forming molecules of **1** adopt fairly symmetrical crown conformation stabilized by four intramolecular hydrogen bonds in each host molecule. The cation, which is located at the centre of the capsule, interacts with the host molecules *via* CH···π interactions, the shortest distances between the cation carbons (CH_3) and centers of the closest aromatic rings of **1** being 3.70–3.88 Å (Table 1). Capsule halves are in staggered orientation and hydrogen bonded *via* four mediating methanol molecules. Additionally, and differing from resorcinarene capsules[2,8] there is also one direct hydrogen bond of length 3.02(1) Å between the pyrogallarenes owing to the additional hydroxyl group in the 2-position of pyrogallol ring which is in suitable spatial position for direct hydrogen bonding. Despite the direct hydrogen bond the dimensions of the capsule do not differ significantly from the respective values of the resorcinarene capsules,[2] for example, the distance between the planes of the methine bridges of the opposing hosts is 8.67 Å in pyrogallarene capsule and varies from 8.26 to 8.99 Å in resorcinarene capsules.

The packing of the capsules of $\mathbf{2a}^+@\mathbf{1}\cdot\mathbf{1}^{-0.5}\cdot 0.5Cl^-$ is shown in Fig. 2. The capsules form ribbons, in which the lower rim methyl groups of the pyrogallarene are facing the methyl groups of the adjacent pyrogallarene and the ribbons form crossing layers which are at 65° angle to each other.

Several attempts to obtain solid state structure of pyrogallarene **1** with $\mathbf{2b}^+Cl^-$ from methanol solution in 2 : 1 ratio resulted in bad quality crystals and hence the quality of the data was also poor and the results of a low quality structure can only be considered preliminary.[14] However, the low quality structure clearly reveals that also in this case pyrogallarene **1** forms a dimeric complex where cation $\mathbf{2b}^+$ is located inside the capsule. This result is in line with previously reported results of resorcinarene capsules with $\mathbf{2b}^+$.[8a]

Crystallization of **1** with trimethyl ammonium chloride, **2c**Cl, from methanol and triethyl ammonium chloride, **2d**Cl, from methanol–ethanol solution in 2 : 1 molar ratio afforded remarkably similar structures of 1 : 1 inclusion complex, $\mathbf{1}\cdot\mathbf{2c}^+Cl^-\cdot 2MeOH$ and $\mathbf{1}\cdot\mathbf{2d}^+Cl^-\cdot MeOH\cdot EtOH$, respectively (Fig. 3). The position of the cation inside the cavity is similar in both cases. One of the alkyl arms of the cation is situated deeply in the cavity of **1** interacting *via* CH···π interactions with the aromatic rings of the host. The difference between the two structures arises from the interactions of the two remaining alkyl chains. With $\mathbf{2c}^+$ also the other two methyl arms interact with the aromatic walls of the pyrogallarene, but with $\mathbf{2d}^+$ two other ethyl chains show no interactions with the host.

The inspection of the crystal packing of $\mathbf{1}\cdot\mathbf{2c}^+$ and $\mathbf{1}\cdot\mathbf{2d}^+$ reveals that two 1 : 1 complexes are connected to a dimeric assembly by hydrogen bonds from cation N–H to two hydroxyl groups of the adjacent pyrogallarene, two direct hydrogen bonds between pyrogallarenes and hydrogen bonds mediated by chloride (Fig. 3). In addition, the dimer of $\mathbf{1}\cdot\mathbf{2c}^+$ shows

Table 1 Selected dimensions and weak interaction distances in the X-ray crystal structures

Structure/ Distance [Å]	$\mathbf{2a}^+@\mathbf{1}\cdot\mathbf{1}^{-0.5}\cdot 0.5\ Cl^-$	$\mathbf{1}\cdot\mathbf{2c}^+Cl^-$	$\mathbf{1}\cdot\mathbf{2d}^+Cl^-$	$EtOH@\mathbf{1}_2$
Intramolecular O–H···O[a]	2.63(1)–2.75(2)	2.624(4)–2.709(4)	2.658(5)–2.748(6)	2.732(5)–2.761(5)
Intermolecular O–H···O[a]	3.02(1)	2.964(5)	2.858(5)	2.954(5)–3.102(5)
Intermolecular O–H···O to solvent[a]	2.67(1)–2.75(1)	2.822(4)	—	—
Intermolecular O–H···X^- to anion[a]	—	3.057(3)–3.072(3)	3.080(4)–3.272(7)	—
N–H···O (cation to **1**)	—	2.780(5)–3.059(5)	2.846(5)–2.986(6)	—
CH···π (the closest cation C to the closest aromatic ring centroid of **1**)	3.70	3.34	3.60	3.72
Capsule height[b]	8.67	—	—	8.77
Capsule/molecule width[c]	6.70/6.97 for molecule A; 6.72/6.84 for molecule B	6.72/6.91	6.72/6.92	5.13 (boat) 6.83/6.88 (crown)
Dihedral angles between the adjacent pyrogallol rings/°	67.0/79.5 for molecule A; 65.8/73.5 for molecule B	65.8/74.0	67.9/75.5	6.6/187.1 (boat) 70.4/77.9 (crown)

[a] Distances given as O···O or O···X^- distances. [b] Defined as a distance between the planes formed by the methine bridges of **1**. [c] Distance between the centroids of the opposite aromatic rings of **1**.

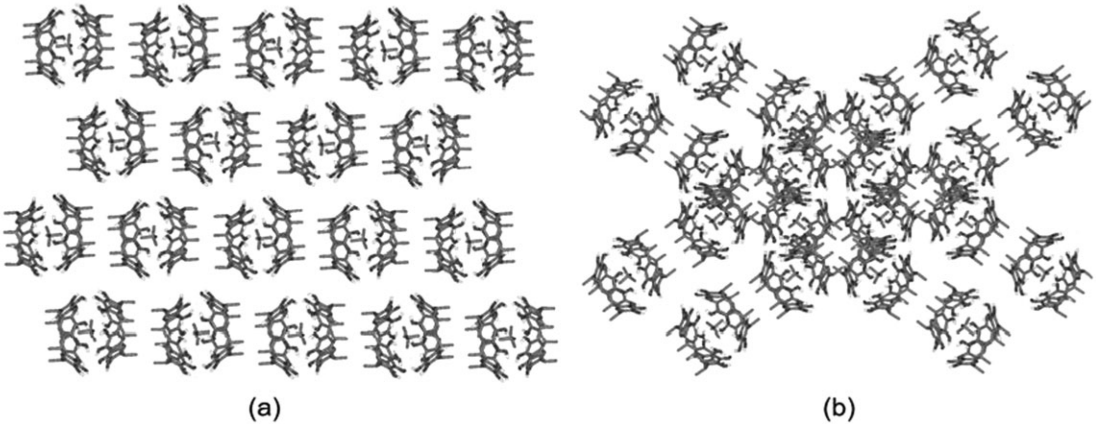


Fig. 2 Crystal packing of capsules of **1** with **2a**$^+$ showing (a) layers formed by sequential pyrogallarene capsules (b) crossing layers at 65° angle to each other. Solvent molecules, anions and hydrogen atoms attached to carbons are omitted for clarity.

altogether four methanol mediated hydrogen bonds, while no solvent mediated bonds are observed in **1** · **2d**$^+$.

The probable reason for the formation of this shifted-type of capsule-like dimer instead of typical directly facing capsule is the non-spherical shape and hydrogen-bonding ability of the cation, which clearly directs the orientation of host molecules in respect to each other.

The major difference between the two complexes arises from the crystal packing of dimeric assemblies (Fig. 4). 2(**1** · **2c**$^+$ · Cl$^-$) dimers form layers in which they are hydrogen bonded to each other *via* chloride anions, while 2(**1** · **2d**$^+$ · Cl$^-$) dimers are placed next to each other with the methyl groups of pyrogallarenes pointing toward each other and forming dimer ribbons running in two directions throughout the crystal.

To get a reference how the host **1** alone behaves in similar crystallization conditions, we crystallized **1** from small polar alcohols and alcohol–water mixtures. To our great surprise the crystallization of **1** from ethanol–water mixture gave unique, directly hydrogen-bonded hetero-conformational capsule where one pyrogallarene **1** is in crown and the other in boat conformation. The diminished cavity is occupied by a disordered ethanol molecule, which is hydrogen bonded to one of the pyrogallarene hydroxyls of the molecule in boat conformation (Fig. 5). To our knowledge this is the very first example of the simultaneous crystallization of two different conformations of resorcinarene-type molecules in the same crystal, as well as the first example of hetero-conformational capsule, which, in addition, is the first truly directly hydrogen-bonded resorcinarene-type dimeric capsule without any mediating solvent or anionic species.

The formation of this type of novel capsule relates to the optimal hydrogen bonding and effective crystal packing. The change of the conformation of one of the hosts is needed to fulfill these requirements and therefore all four intramolecular hydrogen bonds of other pyrogallarene are replaced by intermolecular hydrogen bonds and the conformation changes from crown to boat. Similar types of guest induced conformational change caused by the replacement of intramolecular hydrogen bonds by intermolecular interactions to guests have earlier been detected in open inclusion complexes.[15]

The molecule in boat conformation is described by the two parallel pyrogallol rings (6.5° dihedral angle and 5.13 Å

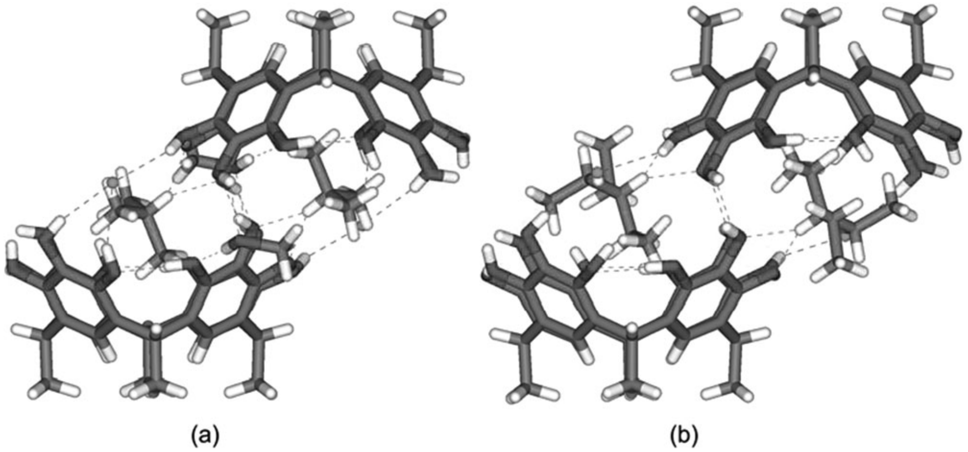


Fig. 3 X-ray crystal structures of dimeric assemblies of (a) 2(**1** · **2c**$^+$ · Cl$^-$) and (b) 2(**1** · **2d**$^+$ · Cl$^-$) connected *via* hydrogen bonds. Solvent molecules, which are not linking host molecules, are omitted for clarity.

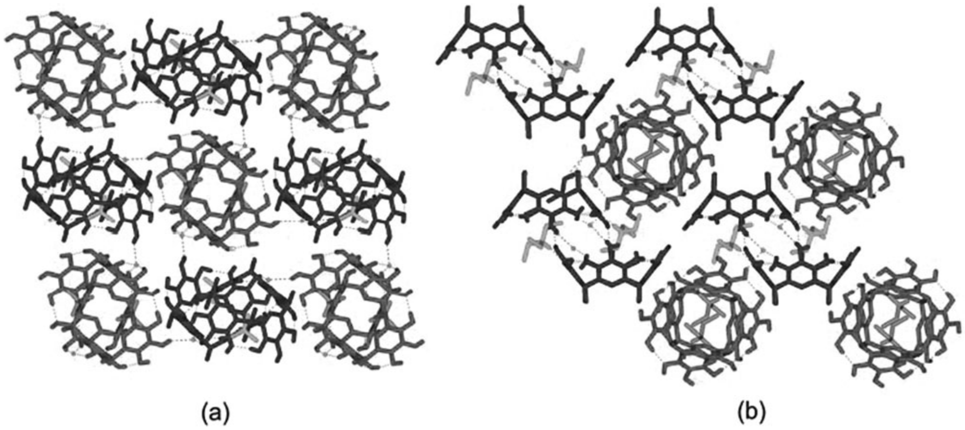


Fig. 4 Crystal packing of (a) $2(\mathbf{1}\cdot\mathbf{2c}^{+}\cdot\mathrm{Cl}^{-})$ and (b) $2(\mathbf{1}\cdot\mathbf{2d}^{+}\cdot\mathrm{Cl}^{-})$. Solvent molecules and hydrogen atoms attached to carbons are omitted for clarity.

centroid-to-centroid distance) while the other two opposing rings are nearly coplanar and bent towards the lower rim of the pyrogallarene core. The other capsule forming pyrogallarene molecule remains in crown conformation and is, as usual, stabilized by four intramolecular hydrogen bonds of length 2.73–2.76 Å. Its cone shaped cavity also efficiently nests the molecule of ethanol.

Investigation of the crystal packing reveals that pyrogallarenes in boat conformation are connected to each other *via* multiple hydrogen bonds and π···π interactions (closest C to C distance 3.47 Å) so that capsules form very tight continuous chains emphasizing the significance of the closest packing and stabilising effect of π-stacking interactions in addition to hydrogen bonding (Fig. 6). The chains are further interloced to a zipper-like packing motif.

The other important reason for the unusual formation of a hetero-conformational capsule can be reasoned by comparing the sizes and shapes of the guests. Roughly spherical and symmetrical guest $\mathbf{2a}^{+}$ fits perfectly into the crown-shaped cavity of host **1** and being symmetrical, it is able to withdraw yet another host for dimer formation. More ellipsoidal shape and hydrogen bonding ability of $\mathbf{2c}^{+}$ and $\mathbf{2d}^{+}$, on the other hand, seems to induce the formation of a paired assembly. In hetero-conformational capsule EtOH@$\mathbf{1}_2$ the shape of the guest is roughly linear and the size is smaller than the size of the studied cations, so a true directly hydrogen-bonded capsule can form and no mediating hydrogen bonds are needed at all. It is also noteworthy to realize that ethanol as a neutral molecule is still a good enough guest for encapsulation and no reinforcing cationic interactions are required in this case.

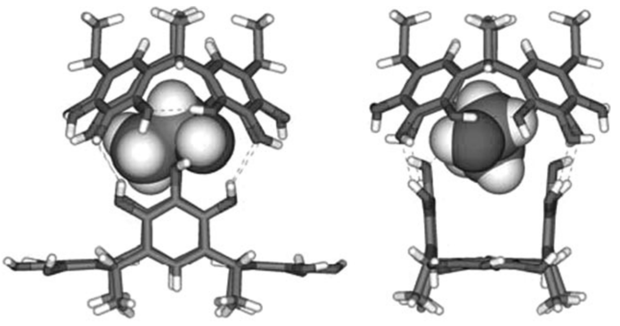


Fig. 5 X-ray crystal structure of directly hydrogen-bonded heterodimeric capsule EtOH@$\mathbf{1}_2$ shown as WDV/stick presentation, two views. Solvent molecules, except for ethanol inclusion, are omitted for clarity.

NMR spectroscopic studies

Encapsulation and open inclusion complexes in solution. The crystal structure of $\mathbf{2a}^{+}@\mathbf{1}\cdot\mathbf{1}^{-0.5}\cdot 0.5\mathrm{Cl}^{-}\cdot 8\mathrm{MeOH}$, investigations in gas phase (below) and former investigations with *C*-ethyl pyrogallarene[8] suggest that pyrogallarene **1** forms dimeric capsules with $\mathbf{2a}^{+}$ in methanol solution, although the respective experiments with *C*-ethyl resorcinarene did not show any sign of capsule formation in solution.[2d] The addition of **2a**Cl to the solution of **1** in methanol-d_4 at 303 K did not change the ^{1}H NMR spectrum of pyrogallarene **1** but induced a shift for the resonance of the methyl protons of $\mathbf{2a}^{+}$ were detected ($\Delta\delta = -1.87$ ppm) indicating shielding effects of aromatic rings of the host cavity.

At 213 K exchange of components became slow on the NMR time scale and the integration of the signals at different host–guest ratios clearly shows that cation $\mathbf{2a}^{+}$ is complexed by **1** in 1 : 2 ratio (Fig. 7). This observation can either mean the formation dimeric (2 : 1 host–guest ratio) or hexameric (6 : 3 host–guest ratio) capsule. However, hexameric capsules in this case are very unlikely, since methanol solution have been reported to be too polar solvent for hexameric pyrogallarene capsules.[10d] Additionally, small alkyl ammonium cations are known to form 1 : 1 and 1 : 2 complexes with high affinity,[2,3,8,9] and the formation of hexameric 6 : 3 would, as a matter of fact, mean three positively charged cations packed in a small volume with high charge density.

In the presence of 4 equiv. of **1** per 1 equiv. of $\mathbf{2a}^{+}$, the signals of both free and complexed pyrogallarene are found in a 1 : 1 ratio (Fig. 7b) and a strong up-field shift of the protons of $\mathbf{2a}^{+}$ ($\Delta\delta = -3.79$ ppm) indicates dimeric capsular structure. Addition of salt ($\mathbf{2a}^{+} : \mathbf{1} > 1 : 2$) leads to the appearance of an open inclusion 1 : 1 complex, whose components are in fast exchange, and to the reduction of the amount of the dimeric capsule (Fig. 7c–e), which indicates that the 1 : 1 complex is favored when an excess of the guest is used.

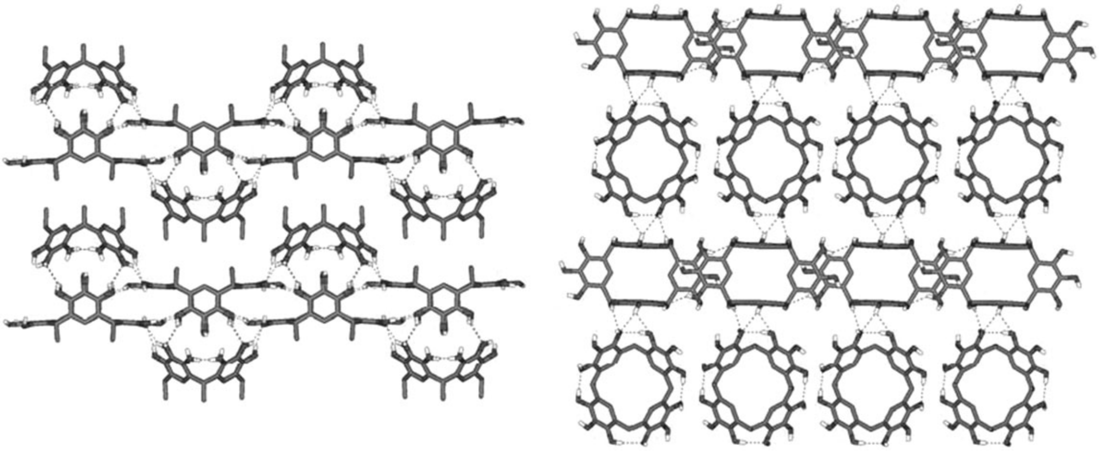


Fig. 6 Crystal packing of EtOH@$\mathbf{1}_2$ showing hydrogen bonded and π-stacked continuous chains, which further form zipper-like motifs, two views. Solvent molecules and hydrogen atoms of C are omitted for clarity.

As expected on the basis of solid state and gas phase studies pyrogallarene **1** can form dimeric capsules also with $\mathbf{2b}^+$ in methanol solution, but not as willingly as $\mathbf{2a}^+$ and hence 1 : 1 stoichiometry is favored. The addition of **2b**Cl to the solution of **1** in methanol-d_4 at 303 K did not change ^{1}H NMR spectrum of pyrogallarene **1** and weaker induced shifts for the resonances of the methylene and methyl protons of $\mathbf{2b}^+$ ($\Delta\delta = -0.92$ ppm and -0.78 ppm, respectively) are observed than with $\mathbf{2a}^+$. At 213 K the exchange of components is still fast and hence the dilution experiments were made at 195 K, where the exchange becomes slow at NMR time scale.

In the presence of 4 equiv. of **1** per 1 equiv. of $\mathbf{2b}^+$, the shoulder of the signal of the methine bridge and broadening of the aromatic proton signal indicate the presence of free and complexed pyrogallarene. Strong upfield shift of the protons of $\mathbf{2b}^+$ ($\Delta\delta = -3.69$ and -1.75 ppm), which are comparable to the shifts of $\mathbf{2a}^+$, indicate the formation of a dimeric capsule also in this case (Fig. 8a). When the amount of **1** is increased in respect to the amount of $\mathbf{2b}^+$ (Fig. 8b; 2 : 1 ratio) two singlets for methine bridge, a slight broadening of the signal of the aromatic proton and appearance of guest peaks at 0.22 and 1.73 ppm ($\Delta\delta = -1.52$ and -0.98 ppm) indicate also the presence of 1 : 1 complex. The ratio of 1 : 1 complex and capsule is 2 : 1 which indicates that capsule formation is weaker than in the case of $\mathbf{2a}^+$ which gave only capsule form in the same host-to-guest ratio. Further addition of the salt ($\mathbf{2a}^+ : \mathbf{1} > 1 : 1$) led to the appearance of the signal of the free salt and disappearance of signal of dimeric capsule (Fig. 8c–e). This difference in NMR behavior between $\mathbf{2a}^+$ and $\mathbf{2b}^+$ hints that $\mathbf{2b}^+$ is indeed already too large to be efficiently encapsulated inside two pyrogallarene hosts.

Trimethyl ammonium $\mathbf{2c}^+$ and triethyl ammonium $\mathbf{2d}^+$ cations did not show any signal for dimeric capsules with **1** in methanol-d_4 and only the formation of 1 : 1 complex was observed. At 213 K the spectrum of a methanol-d_4 solution containing **1** and $\mathbf{2c}^+$ in a 4 : 1 molar ratio reveals upfield shift for the methyl ($\Delta\delta = -2.12$ ppm which is approximately half of the corresponding shift of the $\mathbf{2a}^+$) protons of the cation while there was no change in the spectrum of **1**. In the same conditions up-field shifts for the methyl and methylene protons of the $\mathbf{2d}^+$ cation are -1.20 ppm and -1.63 ppm, respectively. This indicates the formation of an open monomeric complex that is in fast exchange with its components.

Mass spectrometric studies

Mass spectra of pyrogallarene–alkyl ammonium cation mixtures in 1 : 1 ratio in methanol gave peaks representing both 1 : 1 and 2 : 1 pyrogallarene–ammonium ion complexes, which is in line with the mass spectrometric studies of resorcinarene complexes.[2b] When the ratio of pyrogallarene to ammonium ion was increased to 2 : 1 the abundance of capsule in respect to monomeric complex was increased as well, which together with NMR titration results and former investigation with resorcinarenes in gas phase[16] indicates that the ratio of the guest and host controls the formation of dimeric capsules. Fig. 9a presents the mass spectrum of 2 equiv. of **1** mixed with 1 equiv. of **2a**Cl. The peak at m/z 682 corresponds to the monomeric complex $[\mathbf{1}\cdot\mathbf{2a}]^+$ and m/z 1290 to the dimeric capsule $[\mathbf{2a}@\mathbf{1}_2]^+$. Only in the case of $\mathbf{2a}^+$ was the amount of the capsule form higher than that of the monomeric complex, which is in good agreement with X-ray structural and NMR results. Respectively, other spectra of 2 : 1 pyrogallarene–ammonium ion ratio are shown in Fig. 9b–d.

The competition studies between the equimolar amounts of cations $\mathbf{2a}^+$–$\mathbf{d}^+$ and host **1** are shown in Fig. 10a. Monomeric complexes form with all cations ($\mathbf{1}\cdot\mathbf{2a}^+ > \mathbf{1}\cdot\mathbf{2b}^+ \approx \mathbf{1}\cdot\mathbf{2c}^+ > \mathbf{1}\cdot\mathbf{2d}^+$) and dimeric capsules were detected with cations $\mathbf{2a}^+$, $\mathbf{2b}^+$ and $\mathbf{2c}^+$, but not for $\mathbf{2d}^+$ ($\mathbf{2a}^+@\mathbf{1}_2 \gg \mathbf{2b}^+@\mathbf{1}_2 \approx \mathbf{2c}^+@\mathbf{1}_2$). The competition experiment reveals that host **1** has the highest affinity for cation $\mathbf{2a}^+$ both as a monomeric complex and in capsule form. The lowest affinity for monomeric complex was detected with $\mathbf{2d}^+$ and in these conditions it did not form capsules at all. The abundances of 1 : 1 complexes and capsules of $\mathbf{2b}^+$ and $\mathbf{2c}^+$ were almost equal which corresponds to the results of ^{1}H NMR experiments in methanol solutions at 303 K where upfield shifts of monomeric complexes of $\mathbf{2b}^+$ and $\mathbf{2c}^+$ with **1** were same order of magnitude. Also the competition studies support the earlier results with resorcinarenes.[2b]

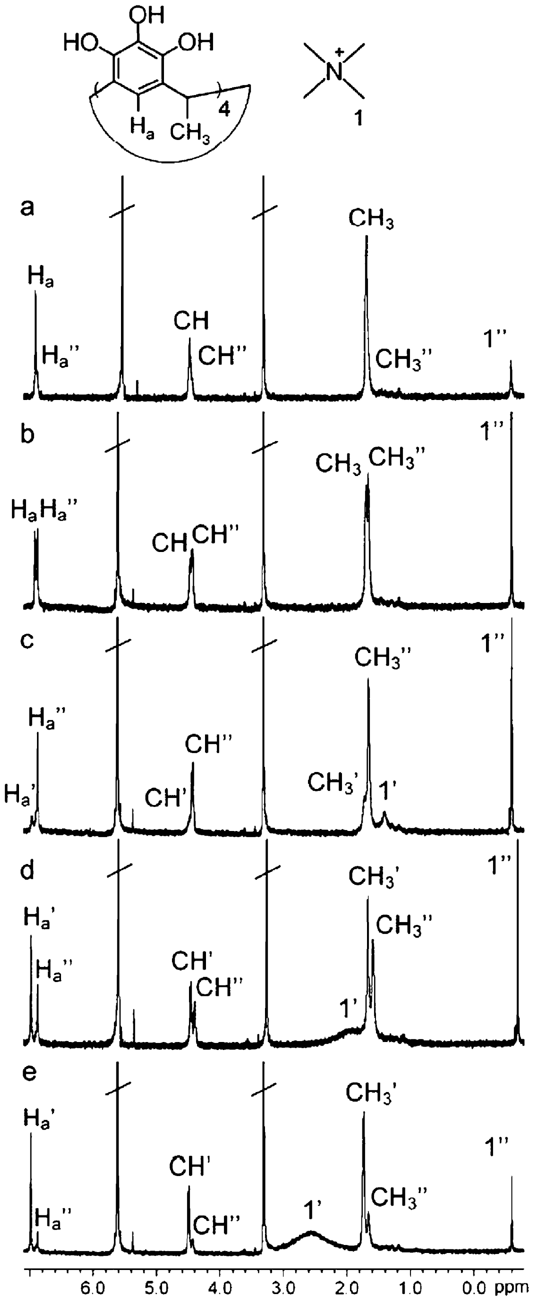


Fig. 7 ^{1}H NMR spectra of **2a**Cl and **1** in methanol-d_4 at 213 K. No apostrophe = free host or guest, ′ = host or guest in 1 : 1 complex and ″ = host or guest in capsule. **2a**Cl: **1**; (a) 1 : 8, (b) 1 : 4, (c) 1 : 2, (d) 1 : 1, (e) 2 : 1.

Relative stability of the capsules was also studied in methanol solution with equimolar amounts of cations **2a**$^+$–**d**$^+$ and host **1**. Different voltages of the sample cone were used to induce ion source fragmentation. Increasing sample cone from 15 V to 35 V led to the reduction of the **2b**$^+$@**1**$_2$ relative to **2a**$^+$@**1**$_2$ while the relative abundancies of **2c**$^+$@**1**$_2$ and **2a**$^+$@**1**$_2$ stayed almost unchanged (Fig. 10b and c). This is line with NMR results which show that dimeric capsule **2a**$^+$@**1**$_2$ is more stable than **2b**$^+$@**1**$_2$ in methanol-d_4 solution due to the more suitable size of the guest.

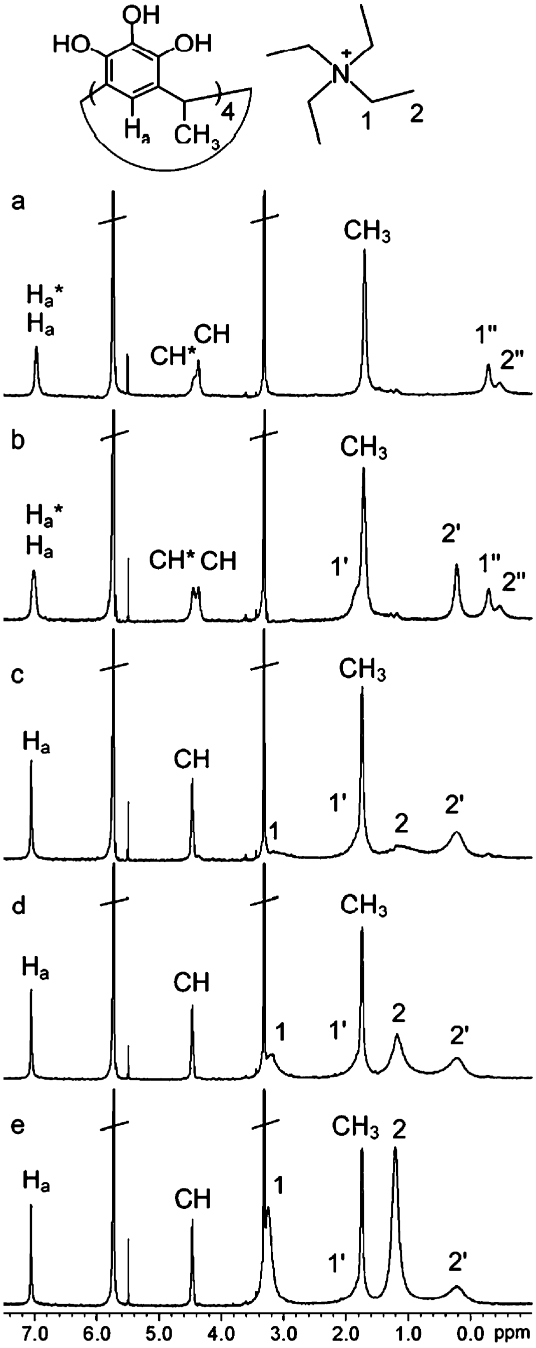


Fig. 8 ^{1}H NMR spectra (500 MHz) of **2b**Cl and **1** in methanol-d_4 at 195 K. * = complexed host, ′ = guest in 1 : 1 complex and ″ = guest inside capsule. **2b**Cl : **1**; (a) 1 : 4, (b) 1 : 2, (c) 1 : 1, (d) 2 : 1, (e) 4 : 1.

Conclusions

In solid state pyrogallarene **1** forms dimeric capsules with tetraalkyl ammonium cations **2a**$^+$ and **2b**$^+$ which is in accordance with the earlier reported capsules of closely related resorcinarenes.[2,3,8a,b] Capsule-like dimeric assemblies of **2c**$^+$ and **2d**$^+$ are more open than tetraalkyl ammonium capsules and their formation is also governed by hydrogen bonding ability of the guest.

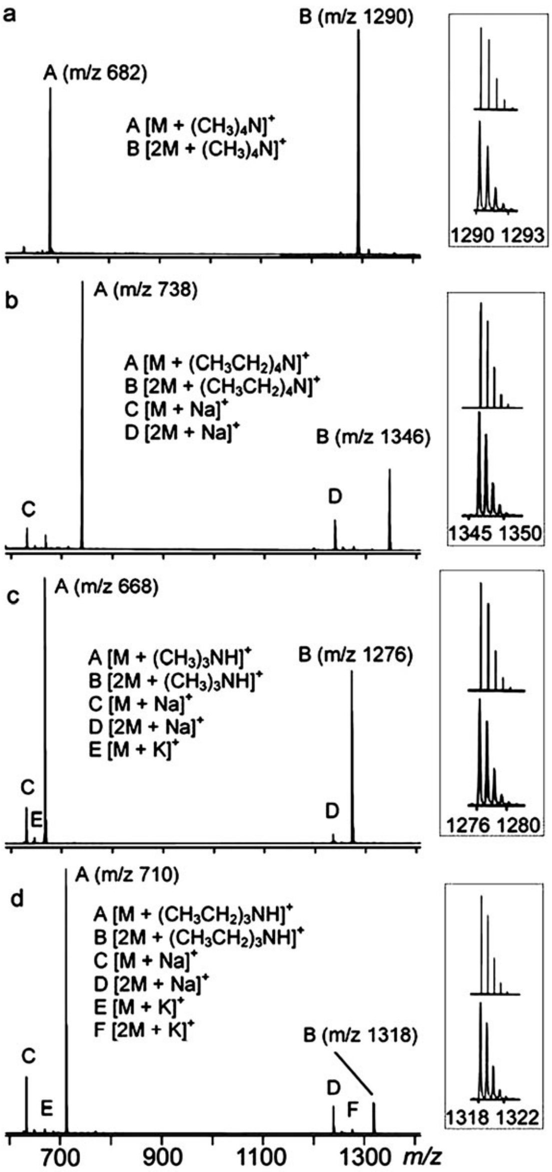


Fig. 9 ESI spectra of pyrogallarene **1** with alkyl ammonium ion **2a**$^+$–**d**$^+$ in 2 : 1 ratio. The inserts show the experimental isotope patterns (curves) of dimeric capsules (B) and those calculated on the basis of the natural abundance (line spectra), which agree well with each other.

NMR titration experiments show that both **2a**$^+$ and **2b**$^+$ form dimeric capsules also in methanol-d_4 solution, but capsule formation of **2b**$^+$ is considerably weaker than that of **2a**$^+$, which emphasizes the sensitivity of the guest size for the efficient encapsulation. The titration experiments of **2c**$^+$ and **2d**$^+$ showed only the formation of 1 : 1 complexes.

In gas phase both capsule and 1 : 1 complex were detected for all cations **2a**$^+$–**d**$^+$ but only in the case of **2a**$^+$ was the abundance of capsule form higher than that of the monomeric 1 : 1 complex. The competition studies between the equimolar amounts of cations **2a**$^+$–**d**$^+$ in gas phase show that host **1** has the highest affinity for cation **2a**$^+$ both as a monomeric complex and especially in capsule form.

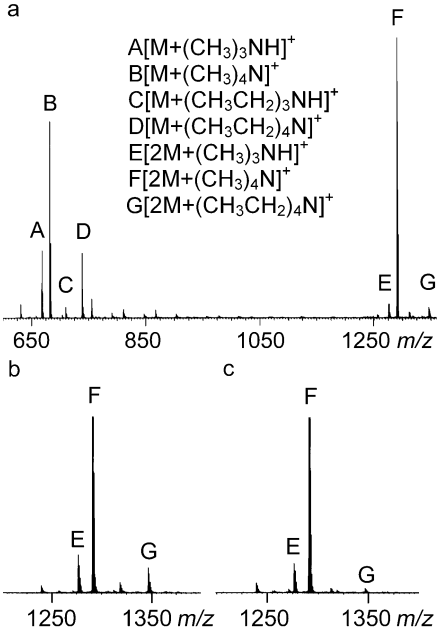


Fig. 10 ESI spectrum of pyrogallarene **1** with alkyl ammonium ions **2a**$^+$–**d**$^+$ (a) and relative abundance of dimeric capsules in soft (b) and harder (c) ionization conditions.

In general it can be concluded on the basis of NMR studies that the affinity of the pyrogallarene **1** towards the capsule formation especially with **2a**$^+$ is greater than that of earlier much studied resorcinarenes.[2] Otherwise solid state and gas phase behavior of pyrogallarene **1** is comparable to the behavior of the resorcinarenes emphasizing the significance of the cation size for the type of the complex formed. These results are complemented by the novel hetero-conformational capsule, which underlines the versatility of pyrogallarene **1** as a building block for crystal engineering studies and brings out the unusual effect of the neutral, roughly linear guest as a template for encapsultion.

Experimental

Single crystal X-ray diffraction

Data were recorded on a Nonius Kappa CCD (**2a**$^+$@**1**$\cdot$**1**$^{-0.5}$, **1**$\cdot$**2c**$^+$ and **1**$\cdot$**2d**$^+$) or Nonius Kappa Apex II (EtOH@**1**$_2$) diffractometer using graphite monochromatized MoK$_\alpha$ radiation [λ(MoK$_\alpha$) = 0.710 73 Å] and temperature of 173.0 ± 0.1 K. The data were processed with Denzo-SMN v0.97.638.[17] The structures were solved by direct methods (SHELXS-97[18]) and refinements based on F^2, were made by full-matrix least-squares techniques (SHELXL-97[19]). The hydrogen atoms were calculated to their idealized positions with isotropic temperature factors (1.2 or 1.5 times the C temperature factor) and refined as riding atoms.

In the structure **2a**$^+$@**1**$\cdot$**1**$^{-0.5}\cdot$0.5Cl$^-$ only a half of the chloride anion was found in the asymmetric unit and it was disordered with a methanol molecule (occupancies 0.5 : 0.5). Additionally, one of the hydroxyls of the other host was partially deprotonated with a disorder between protonated

Table 2 Experimental data for the X-ray diffraction studies on complexes $\mathbf{2a}^+@\mathbf{1}\cdot\mathbf{1}^{-0.5}$, $\mathbf{1}\cdot\mathbf{2c}^+$, $\mathbf{1}\cdot\mathbf{2d}^+$ and EtOH@$\mathbf{1}_2$

	$\mathbf{2a}^+@\mathbf{1}\cdot\mathbf{1}^{-0.5}$	$\mathbf{1}\cdot\mathbf{2c}^+$	$\mathbf{1}\cdot\mathbf{2d}^+$	EtOH@$\mathbf{1}_2$
Formula	$C_{32}H_{32}O_{12}\cdot C_{32}H_{31.5}O_{12}\cdot (CH_3)_4N^+\cdot 0.5\cdot Cl^-\cdot 8CH_3OH$	$C_{32}H_{32}O_{12}\cdot (CH_3)_3NH^+Cl^-\cdot 2CH_3OH$	$C_{32}H_{32}O_{12}\cdot (CH_3CH_2)_3NH^+Cl^-\cdot CH_3OH\cdot CH_3CH_2OH$	$2C_{32}H_{32}O_{12}\cdot 3CH_3CH_2OH$
Formula weight	1564.85	768.2	824.3	1355.4
Crystal system	Monoclinic	Monoclinic	Monoclinic	Monoclinic
Space group	$P2_1/n$ (No. 14)	$P21/c$ (No. 14)	$C2/c$ (No. 15)	$C2/c$ (No. 15)
a/Å	15.2741(8)	13.9176(7)	21.228(1)	28.6719(6)
b/Å	23.811(1)	15.1093(9)	25.343(1)	14.5214(5)
c/Å	21.702(1)	18.653(1)	17.9561(5)	20.4197(6)
β/°	91.297(2)	109.008(2)	122.883(2)	131.685(2)
V/Å^3	7891.0(8)	3708.5(4)	8112.1(6)	6349.3(3)
Z	2	4	8	4
$\mu(\mathrm{MoK}_\alpha)$/mm^{-1}	0.119	0.174	0.164	0.109
No. of refl. measured	48118	23613	27871	9463
No. of independent refl.	12515	7254	7814	5779
R_{int}	0.2204	0.1278	0.088	0.064
R/R_w/%[a]	14.89/27.42	8.37/15.49	10.21/22.96	9.42/21.98
GOF	1.036	1.095	1.111	1.111

[a] For $I > 2\sigma I$.

OH and deprotonated O$^-$. Five methanol molecules were refined isotropically and four of them were disordered as follows: MeOH 1: occupancy factor 0.75 and carbon disordered over two positions with site occupancy factors 0.35 : 0.40; MeOH 2: disordered over two positions with occupancies of 0.4 : 0.6; MeOH 3: carbon disordered over two positions with occupancies of 0.4 : 0.6; MeOH 4: oxygen disordered over two positions with occupancies of 0.25 : 0.75. The fifth methanol was refined anisotropically with occupancy factor 0.75.

In the structure $\mathbf{1}\cdot\mathbf{2d}^+Cl^-$ chloride was disordered over two positions with site occupancy factors 0.5 : 0.5. Ethanol was refined isotropically and its oxygen was disordered over two positions (0.75 : 0.25). The methanol molecule was disordered over two positions (0.5 : 0.5). Residual electron density of 1.19 and 1.11 was detected near disordered Cl$^-$.

In the structure EtOH@$\mathbf{1}_2$ ethanol molecule was disordered over two positions with site occupancy factors 0.5 : 0.5 and its oxygen was refined isotropically.

The crystal data and collection parameters are compiled in Table 2.§

NMR experiments

NMR experiments were performed in methanol-d_4 by adding a 60 mM solution of corresponding alkyl ammonium chloride salt ($\mathbf{2a}^+$–$\mathbf{d}^+$) to a 5 mM solution (0.5 ml) of the pyrogallarene **1**. The ^{1}H spectra were measured with Bruker Avance 400 and Bruker Avance DRX 500 (400 and 500 MHz for ^{1}H) equipped with temperature regulation.

ESI-TOF mass spectra

The mass spectrometric studies were performed with a Micromass LCT ESI-TOF instrument equipped with a Z geometry electrospray ion source. The samples were introduced into the ion source as methanol solutions of **1** (50 μM) and the salts of cations $\mathbf{2a}^+$–$\mathbf{d}^+$ (50 or 25 μM) using 1 : 1 and 2 : 1 pyrogallarene–alkyl ammonium ion molar ratio at flow rates of 10–20 μL min^{-1}.

The highest intensities were achieved with a capillary voltage of 4500 V at a source temperature of 80 °C and a desolvation temperature of 120 °C. Other selected source parameters were as follows: Sample cone voltage: 10–33 V, extraction cone voltage: 6 V, flow of gone gas: 10 L h^{-1}, flow of desolvation gas: 150 L h^{-1}.

Acknowledgements

Financial support of Academy of Finland (proj. no. 211240; MN and AÅ) and TEKES (proj. no. 40476/01; KR and ML) are gratefully acknowledged. We thank Mr Reijo Kauppinen for his help in NMR experiments and Prof. C. A. Schalley for his helpful comments.

References

1 (*a*) M. M. Conn and J. Rebek, Jr, *Chem. Rev.*, 1997, **97**, 1647; (*b*) J. Rebek, Jr, *Acc. Chem. Res.*, 1999, **32**, 278; (*c*) C. A. Schalley, *Adv. Mater.*, 1999, **11**, 1535.
2 (*a*) H. Mansikkamäki, M. Nissinen and K. Rissanen, *Chem. Commun.*, 2002, 1902; (*b*) H. Mansikkamäki, M. Nissinen, C. A. Schalley and K. Rissanen, *New J. Chem.*, 2003, **27**, 88; (*c*) H. Mansikkamäki, M. Nissinen and K. Rissanen, *CrystEngComm*, 2005, **7**, 519; (*d*) H. Mansikkamäki, C. A. Schalley, M. Nissinen and K. Rissanen, *New J. Chem.*, 2005, **29**, 116.
3 M. Luostarinen, A. Åhman, M. Nissinen and K. Rissanen, *Supramol. Chem.*, 2004, **16**, 505.
4 E. A. Meyer, R. K. Castellano and F. Diederich, *Angew. Chem., Int. Ed.*, 2003, **42**, 1210.
5 J. M. Rivera, T. Martín and J. Rebek, Jr, *Science*, 1998, **279**, 1021.
6 J. Kang and J. Rebek, Jr, *Nature*, 1997, **385**, 50.
7 (*a*) L. M. Tunstad, J. A. Tucker, E. Dalcanale, J. Weiser, J. A. Bryant, J. C. Sherman, R. C. Helgeson, C. B. Knobler and D. J. Cram, *J. Org. Chem.*, 1989, **54**, 1305; (*b*) T. Gerkensmeier, C. Agena, W. Iwanek, R. Frölich, S. Kotila, C. Näther and J. Mattay, *Z. Naturforsch., B: Chem. Sci.*, 2001, **56**, 1063.
8 (*a*) K. Murayama and K. Aoki, *Chem. Commun.*, 1998, 607; (*b*) A. Shivanyuk, K. Rissanen and E. Kolehmainen, *Chem. Commun.*, 2000, 1107.

---

§ CCDC reference numbers 611014–611017†.

9 (*a*) A. Shivanyuk and J. Rebek, Jr, *Chem. Commun.*, 2001, 2374; (*b*) A. Shivanyuk, J. C. Friese, S. Döring and J. Rebek, Jr, *J. Org. Chem.*, 2003, **68**, 6489.

10 (*a*) L. R. MacGillivray and J. L. Atwood, *Nature*, 1997, **389**, 469; (*b*) T. Gerkensmeier, W. Iwanek, C. Agena, R. Fröhlich, S. Kotila, C. Näther and J. Mattay, *Eur. J. Org. Chem.*, 1999, 2257; (*c*) J. L. Atwood, L. J. Barbour and A. Jerga, *Chem. Commun.*, 2001, 2376; (*d*) L. Avram and Y. Cohen, *Org. Lett.*, 2003, **5**, 3329.

11 (*a*) A. Shivanyuk and J. Rebek, Jr, *Chem. Commun.*, 2001, 2424; (*b*) A. Shivanuyk and J. Rebek, Jr, *Proc. Natl. Acad. Sci. U. S. A.*, 2001, **98**, 7662; (*c*) L. Avram and Y. Cohen, *J. Am. Chem. Soc.*, 2003, **125**, 16180.

12 (*a*) H. Mansikkamäki, M. Nissinen and K. Rissanen, *Angew. Chem., Int. Ed.*, 2004, **43**, 1243; (*b*) H. Mansikkamäki, S. Busi, M. Nissinen, A. Åhman and K. Rissanen, *Chem.–Eur. J.*, 2006, **12**, 4289.

13 S. J. Dalgarno, G. W. V. Cave and J. L. Atwood, *Angew. Chem., Int. Ed.*, 2006, **45**, 570.

14 X-ray structure data of **2b**$^+$Cl$^-$: a = 16.4671(7), c = 19.2680(6) Å, space group $I4/m$, R_1 = 14.94%.

15 (*a*) M. Munakata, L. P. Wu, T. Kuroda-Sowa, M. Maekawa, Y. Suenaga, K. Sugimoto and I. Ino, *J. Chem. Soc., Dalton Trans.*, 1999, 373; (*b*) M. Nissinen, E. Wegelius, D. Falábu and K. Rissanen, *CrystEngComm*, 2000, **28**, 151; (*c*) A. Åhman and M. Nissinen, *Chem. Commun.*, 2006, 1209.

16 M. Mäkinen, P. Vainiotalo, M. Nissinen and K. Rissanen, *J. Am. Soc. Mass Spectrom.*, 2003, **14**, 143.

17 Z. Otwinowski, W. Minor, Processing of X-ray Diffraction Data Collected in Oscillation Mode, in *Methods in Enzymology, Macromolecular Crystallography Part A*, ed. C. W. Carter, Jr and R. M. Sweet, Academic Press, New York, 1997, vol. 276, p. 307.

18 G. M. Sheldrick, *Acta Crystallogr., Sect. A: Found. Crystallogr.*, 1990, **46**, 467.

19 G. M. Sheldrick, *SHELXL-97, Program for refinement of crystal structures*, University of Göttingen, Germany, 1997.