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Encapsulation of diquats by resorcinarenes: a novel staggered anion–solvent mediated hydrogen bonded capsule

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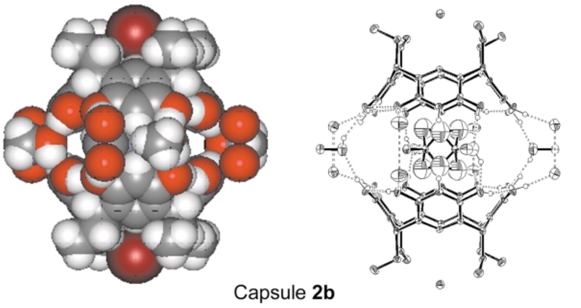
Crystallisation studies of ethyl resorcinarene with diquats 2b and 3a (1,4-dimethyl-1,4-diazoniabicyclo[2.2.2]octane dibromide and 1,4-diazoniabicyclo[2.2.2]octane dichloride, respectively) resulted in hydrogen bonded molecular capsules in which the cations are encapsulated in between the cavities of two resorcinarene molecules and anions are located in the middle of the lower rim ethyl chains.

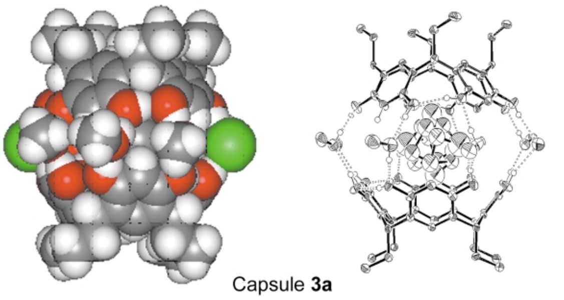
Resorcinarenes are versatile and easily available host compounds for complexation studies in the solid state as well as in solution and in the gas phase.[1,2] One of the most fascinating properties of resorcinarenes is their capability to form molecular capsules *via* hydrogen bonded networks.[3–9] In the solid state these capsules are found to be either dimeric or hexameric assemblies linked together by hydrogen bonding small polar solvent molecules.[4–10] Ammonium cations have proven to be good guest candidates for resorcinarene complexation since they have the possibility to interact *via* cation$\cdots\pi$ and $C–H\cdots\pi$ interactions as well as advantageously fill the empty space in the hollow cavity of the resorcinarene host.[2,4–8,11–13]

In our previous studies we have observed the interesting solid state feature of ethyl resorcinarene to complex tetramethylammonium cation into the cavity and simultaneously bromide anion between the lower rim ethyl chains.[2] These results inspired us to examine whether we could induce capsule formation and simultaneous anion binding if the diquats **2** and **3** were used as guests (Scheme 1). Owing to the low solubility of the ammonium salts only methanol and ethanol were used as solvents in crystallisation studies.

Cocrystallization of **1** with **2b** a in molar ratio of 2 : 1 from aqueous MeOH results in pale reddish hexagonal crystals suitable for X-ray analysis.† The formed dimeric capsule is linked by eight water and four MeOH molecules, *i.e.* altogether 20 hydrogen bonds (capsule **2b**; Fig. 1). The resorcinarene molecules adopt a perfect cone conformation (both distances between the centroids of the opposite resorcinol rings are 6.90 Å) stabilized by three intramolecular hydrogen bonds each. The fourth possible intramolecular hydrogen bond is replaced by an intermolecular H-bond to the capsule binding solvent molecule. As expected the severely disordered cation is tightly embedded inside the capsule and the Br^- anions are located in the middle of the ethyl chains *via* weak $C–H\cdots Br^-$ interactions (the average distance between $–CH_2–$ carbons and anion is *ca.* 3.97 Å). Surprisingly the NCH_3 groups of the cation adopt equatorial positions.[11,12] This alignment is stabilized by several $C–H\cdots\pi$ interactions of length 3.24–3.27 Å between the $–CH_2CH_2–$ chains of the cation and the centroids of the aromatic rings of the host.

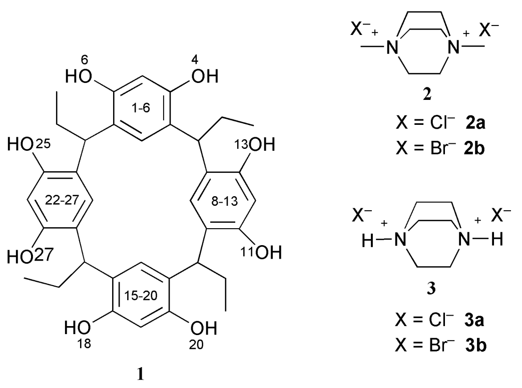


Capsule **2b**



Capsule **3a**

Fig. 1 Single crystal X-ray structures of hydrogen bonded molecular capsules based on two resorcinarenes (**1**) and included disordered cations **2b** and **3a** (capsule **2b** and **3a**, respectively). Average hydrogen bonding distances between hydroxyl groups of resorcinol and linking molecules are 2.69 Å for water molecules, 2.74 Å for MeOH in capsule **2b** and 2.66 Å for MeOH in capsule **3a** and 2.88 Å for Cl^-. Non-hydrogen bonded hydrogens are omitted from the ORTEP[14] plots for clarity.



Scheme 1 Structural formula and relevant crystallograpic numbering of ethyl resorcinarene and quats.

Complexation studies of **1** with **2a** and **3b** were not successful with methanol (aq.) and resulted in the crystallisation of resorcinarene with solvent, while the studies in ethanol (aq.) favour mainly other forms of complexation besides the capsule formation.[15]

A novel type of hydrogen bonded dimeric capsule was obtained by cocrystallisation of **1** with **3a** in molar ratio of 2 : 1 from aqueous methanol solution (capsule **3a**; Fig. 1).† Several differences distinguish capsule **3a** from capsule **2b** and from other previously published dimeric capsules.[4,5,7] The orientation of the facing resorcinarenes is not eclipsed, but the capsule halves are staggered and turned by approximately 43.6°[16] with respect to each other. Also interestingly the resorcinarenes forming the dimeric capsule are linked *via* 16 hydrogen bonds mediated by six MeOH molecules and two chloride anions instead of water (average hydrogen bond lengths are 2.66 and 2.88 Å, respectively). To our knowledge, this is the first dimeric molecular capsule of unsubstituted resorcinarene where the

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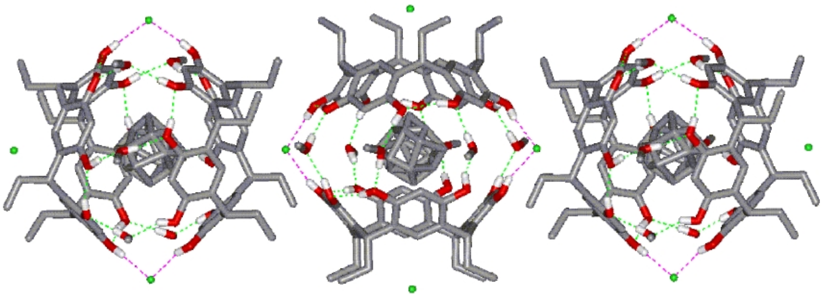

Fig. 2 Crystal packing of capsule **3a** showing how each Cl$^-$ atom is simultaneously linking together the resorcinarene capsule and placed in between the ethyl chains of the adjacent capsule. Non-hydrogen bonding hydrogens are omitted for clarity.

orientation of the aromatic groups is staggered, and in which the anions take active part in capsule formation. The staggered conformation would allow the approaching of the capsule halves, however, in this case the vertical diameter[17] of capsule **3a** is only approximately 0.07 Å shorter than the corresponding distance in capsule **2b** owing to the larger size of the mediating chloride anions compared to oxygen.

A survey of the crystal packing of capsule **3a** reveals that not only the chloride anions participate on capsule formation but they are also simultaneously located between the lower rim ethyl chains of the adjacent perpendicular capsule (Fig. 2) in this respect similarly to capsule **2b**. The Cl$^-$ anions are more tightly embedded in between the $-CH_2CH_2-$ chains than the Br$^-$ anions in capsule **2b**, since the distance between the plane defined by methine bridge carbons of the host and the anion is 3.24 Å for capsule **2b** and 2.69 Å for capsule **3a**. This could be explained by the smaller radius and more electronegative nature of Cl$^-$ compared to Br$^-$.

The conformation of the resorcinarenes in capsule **3a** is slightly distorted (the distances between the centroids of the opposite resorcinol rings are 7.01 and 6.71 Å) and stabilised by only two intramolecular hydrogen bonds in one host and four hydrogen bonds in the other capsule forming host. In spite of the incomplete intramolecular hydrogen bonding the resorcinarene molecule still remains in crown conformation owing to the intermolecular hydrogen bonding network, favourable shape of the guest, stabilising C–H$\cdots\pi$ and cation$\cdots\pi$ interactions between the hosts and the guest and C–H$\cdots$Cl$^-$ interactions at the lower rim.

In conclusion, a dimeric ethyl resorcinarene capsule provides suitable binding sites for a spherical anion at the lower rim and for an ammonium cation in the hollow cavity. Guests with suitable size and properties facilitate capsule formation in polar solvents. Spatial staggering of the resorcinarene molecules allows the capsule halves to be drawn closer to each other, with a suitable guest possibly even at a distance close enough for direct hydrogen bonding without any intermediating solvent molecules. Our current task is to investigate the effect of the size of the guest, different solvents and the significance of the length of the alkyl chain of the resorcinarene (from C_1 to C_{11}) for the complexation of ammonium salts in the solid state as well as in solution and gas phase.

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Notes and references

† *X-Ray crystal structure analysis*: Data were recorded with a Nonius Kappa CCD diffractometer using graphite monochromatised Mo-Kα radiation [λ(Mo-Kα) = 0.71073 Å)] and at 173.0 ± 0.1 K. The data were processed with Denzo-SMN v0.95.373 (Z. Otwinowski and W. Minor, *Processing of X-ray Diffraction Data Collected in Oscillation Mode*, *Methods in Enzymology*, vol. 276: *Macromolecular Chrystallography*, Part A, ed. C. W. Carter, Jr. and R. M. Sweet, Academic Press, New York, 1997, pp. 307–326). The structures were solved by direct methods (SHELXS-97: G. M. Sheldrick, *Acta Crystallogr., Sect. A*, 1990, **46**, 467) and refinements based on F^2, were made by full-matrix least-squares techniques (SHELXL-97, G.M. Sheldrick, *A program for crystal structure refinement*, 1997, University of Göttingen, Germany). The hydrogen atoms were calculated to their idealised positions with isotropic temperature factors (1.2 or 1.5 times the C temperature factor) and refined as riding atoms. Hydrogen bonding hydrogens were located from the difference Fourier but in the final refinement refined also as riding atoms. The atoms of the severely disordered cations were treated isotropically and all atoms of the cation in capsule **3a** were treated as carbon atoms. Thus any conclusions about the orientation of the cation could not be made. The hydrogen atoms of water molecules as well as the cations were not located. Due to the severe disorder of the cations, structures could not be solved in hexagonal or tetragonal crystal systems.

Crystal data: Capsule **2b** [$\mathbf{1_2}\cdot\mathbf{2b}^{2+}\cdot 2Br^-\cdot 4MeOH\cdot 8H_2O$]: $C_{42}H_{65}O_{14}NBr_2$, M = 887.9, crystal size 0.50 × 0.40 × 0.35 mm, triclinic, space group $P1$ (no. 2), a = 14.0994(2), b = 14.0971(2), c = 14.7590(2) Å, α = 118.5304(5), β = 118.5433(6), γ = 89.9977(8)°, V = 2162.81(5) Å^3, Z = 2, D_c = 1.363 g cm^{-3}, μ = 1.017 mm^{-1}, 11802 reflections measured, 7516 independent, R_{int} = 0.0176, $R1$ = 0.0627, $wR2$ = 0.1573 for $I > 4\sigma I$, 527 parameters, S = 1.030.

Capsule **3a** [$\mathbf{1_2}\cdot\mathbf{3a}^{2+}\cdot 2Cl^-\cdot 6MeOH$]: $C_{84}H_{118}O_{22}N_2Cl_2$, M = 1578.7, crystal size 0.40 × 0.35 × 0.15 mm, monoclinic, space group $C2/c$ (no. 15), a = 48.485(1), b = 19.465(6), c = 19.462(4) Å, β = 113.660(2)°, V = 16824(6) Å^3, Z = 8, D_c = 1.247 g cm^{-3}, μ = 0.150 mm^{-1}, 29280 reflections measured, 14295 independent, R_{int} = 0.0726, $R1$ = 0.0900, $wR2$ = 0.2290 for $I > 4\sigma I$, 1024 parameters, S = 1.031.

CCDC reference numbers 186369 and 186370. See http://www.rsc.org/suppdata/cc/b2/b204937f/ for crystallographic data in CIF or other electronic format.

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16 The angle (43.6°) is measured as a torsion angle of the lower rim aromatic carbon of the upper resorcinarene (C23), centroid of the plane defined by the bridging methine atoms of the upper resorcinarene (C7, C14, C21, C28), centroid of the bridging methine atoms of the lower resorcinarene and the lower rim aromatic carbon of the lower resorcinarene (C16b). The corresponding torsion angle for capsule **2b** is 0°.

17 Diameter of a capsule means here is the distance of the planes defined by methine bridge carbons of one capsule half to the corresponding plane of the other half of the capsule.