Encapsulation of $Et_3N^+–H\cdots OH_2$ in a hydrogen-bonded resorcarene capsule

Alexander Shivanyuk,* Kari Rissanen* and Erkki Kolehmainen

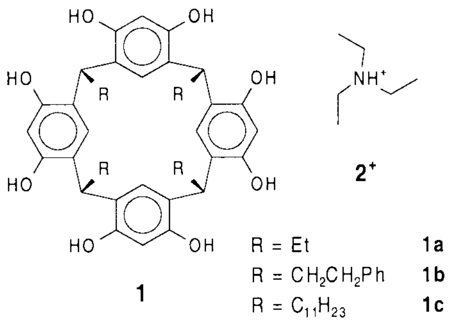
Department of Chemistry, University of Jyväskylä, PO Box 35, Jyväskylä, FIN-40351, Finland. E-mail: shivan@jyu.fi and kari.rissanen@jyu.fi

Received (in Cambridge, UK) 16th March 2000, Accepted 15th May 2000
Published on the Web 8th June 2000

In the crystalline state a resorcarene dimer linked by ten hydrogen-bonding water molecules encapsulates the hydrogen-bonded complex $Et_3N^+–H\cdots OH_2$ while bromide anions are positioned outside the cavity.

Supramolecular encapsulation is a topic of considerable current interest.[1] Designed self-complementary molecules form dimeric[2] or tetrameric[3] hydrogen-bonded capsules including charged and neutral guest species. Resorcarenes **1** linked by smaller hydrogen-bonding molecules assemble into dimeric[4] and hexameric[5] hollow structures in the solid state**.** Molecular encapsulation of dimeric hydrogen-bonded complexes has been discovered recently in apolar solutions[6] however much less is known about such complexation in the crystalline state.[7]

Herein we describe the first single crystal X-ray structure of a hydrogen-bonded molecular capsule encapsulating the hydrogen-bonded heterocomplex $Et_3N^+–H\cdots OH_2$.



Co-crystallization of **1a** with a ten-fold excess of Et_3NHBr from aqueous EtOH results in cubic crystals which, although unstable without solvent, were suitable for single crystal X-ray analysis.† The resorcarene molecules adopt a perfect cone conformation stabilized by four intramolecular hydrogen bonds between neighboring hydroxy groups. Two molecules of **1a**, sitting on a two fold crystallographic rotation axis, form a dimer held together by ten hydrogen-bonded water molecules disordered over 16 sites (Fig. 1). One $\mathbf{2}^+$ and one hydrogen-bonded water molecule [N1A···O12a 2.735(7) Å] are encapsulated in such a dimeric cavity.[8] Two opposite orientations occur for the encapsulated $Et_3N^+–H\cdots OH_2$ with occupancy factors of 0.7 and 0.3. Furthermore, in each orientation the ethyl groups are strongly disordered owing to the fact that the three-fold axis of $\mathbf{2}^+$ coincides with the two-fold axis of the capsule. Encapsulated $\mathbf{2}^+$ is shifted by 0.28 Å from the center of the cavity[9] towards resorcarene molecule B. Several close non-bonded contacts (3.49–3.67 Å) were found between carbon atoms of $Et_3N^+–H$ and resorcinol rings of **1a** which manifest C–H··π attractions. The encapsulated water molecule (O12a) is located deep in the resorcarene socket of molecule A forming four close non-bonded contacts to the aromatic C–H atoms of the resorcinol rings with O–C distances of 3.327(4) and 3.335(4) Å.[10] Such an arrangement allows O–H··π interactions between the encapsulated water molecule and the resorcinol rings. The hydrogen bonding in $Et_3N^+–H\cdots OH_2$ should theoretically increase the positive charge on the hydrogen atoms of the water molecule and thus facilitate O–H··π attractions.

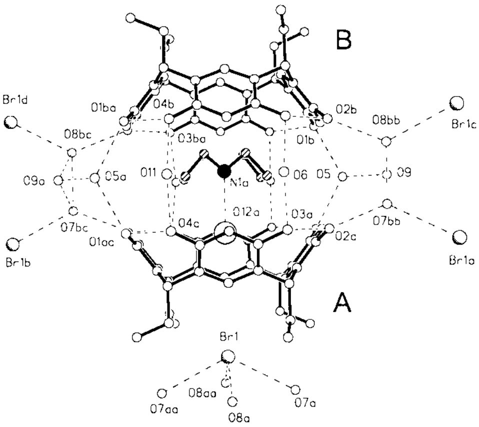


Fig. 1 Single-crystal X-ray structure of $[(\mathbf{1a}_2\cdot 10H_2O)@(\mathbf{2}^+\cdot H_2O)]Br^-\cdot 4.8H_2O$. All hydrogen atoms are omitted for clarity. Hydrogen bonds are indicated by dotted lines. The most populated orientation of the disordered cation and water molecule is indicated. The nitrogen atom of $\mathbf{2}^+$ and oxygen atom of encapsulated water molecule are shown with arbitrary radii. Distances between hydrogen-bonding oxygen atoms are between 2.606(3) and 2.791(5) Å. Distances between the hydrogen-bonded Br anion and water molecules are between 3.323(6) and 3.348(5) Å.

The bromide anion is positioned outside the cavity and lies within the shallow pocket formed by four pendant CH_2 groups of molecule A[11] and is solvated by four disordered hydrogen-bonded water molecules (Fig. 1). The shortest N···Br distance [8.212(6) Å] is *ca.* 2.5 times longer than in $\mathbf{2}^+$ Br^-.[12] The distance of the bromide anion to the carbon atom of the CH_2 group is 4.004(4) Å reflecting weak $C–H\cdots Br^-$ interactions. The hydrogen-bonded array of the resorcarene dimer is not saturated and therefore four symmetry related bromide anions are hydrogen bonded to the bridging water molecules (Fig. 1).

^1H NMR spectroscopy shows that no complex is formed between **1** and $\mathbf{2}^+$ in polar solvents such as methanol-d_4 or DMSO-d_6. However, in $CDCl_3$ saturated with H_2O, lipophilic resorcarenes **1b,c** strongly interact with $\mathbf{2}^+$ X^- (X^- = Cl^-, Br^-, ClO_4^-). At $[\mathbf{2}^+ X^-]/[\mathbf{1b,c}] \geqslant 0.5$, ^1H NMR spectra show sharp signals of methyl and methylene protons of the complexed cation which are both shifted upfield by *ca.* 1.3 ppm (Fig. 2). The exchange of complexed and free $\mathbf{2}^+$ is slow on the NMR timescale at 303 K (500 MHz) and the integration shows that two resorcarene molecules complex one cation $\mathbf{2}^+$. The signal of the water protons (5–6 H per **1c**) is shifted downfield ($\Delta\delta$ = 1.9 ppm) and the multiplet of resorcinol OH groups is centered at δ 9.5 owing to strong hydrogen-bonding. These results suggest that hydrogen-bonded water molecules participate in the formation of the 2:1 capsule also in $CDCl_3$.[13] These results are also in agreement with the fact that in dry $CDCl_3$ the systems **1b,c** + *n* $\mathbf{2}^+X^-$ exhibit broad ^1H NMR spectra, most probably owing to the formation of ill defined hydrogen-bonded aggregates. Detailed NMR investigations of these complex systems in apolar solvents are currently in progress and will be reported in due course.

In conclusion, the solid-state encapsulation of ammonium cations by a water linked dimer of **1a** is strongly dependent on

DOI: 10.1039/b002144j

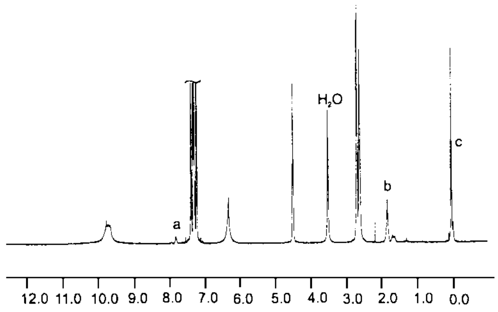


Fig. 2 ^{1}H NMR spectrum of 2 **1b** + **2**$^+$Cl$^-$ {[**1b**] = 3×10^{-2} M, 500 MHz, 303 K, CDCl$_3$}. The signals of the complexed cation are: a, NH; b, CH$_2$; c, CH$_3$.

the structure of the guest. For the previously studied complex with Et$_4$N$^+$[14] no anion is found while the negative charge was distributed over all oxygen atoms of the capsule. The smaller volume of Et$_3$NH$^+$ and the presence of the hydrogen bonding N–H group seem to be crucial for the encapsulation of Et$_3$N$^+$–H··OH$_2$ in the cavity of the resorcarene dimer. The incomplete saturation of the hydrogen-bonded array within the hydrogen bonded shell determines the strong hydrogen-bonding interaction of the capsule with external bromide anions. This feature is being currently explored for the rational design of externally tuned supramolecular containers.

Notes and references

† *X-Ray crystal structure analysis*: Data were recorded with a Kappa CCD difractometer using graphite monochromatised Mo-Kα radiation [λ(Mo-Kα) = 0.71073 Å]. The data was processed with Denzo-SMN v0.93.0 [Z. Otwinowski and W. Minor, *Processing of X-ray Diffraction Data Collected in Oscillation Mode, Methods in Enzymology*, vol. 276: *Macromolecular Crystallography*, 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 placed in calculated idealized positions with isotropic temperature factors (1.2 times the C temperature factor) and refined as riding atoms. The hydrogen atoms of water molecules and disordered cation were not located. The atoms of the cation in the less populated orientation as well as two strongly disordered water molecules were treated isotropically.

Crystal data: $[(\mathbf{1a}_2\cdot 10H_2O)@(\mathbf{2}^+\cdot H_2O)]Br^-\cdot 4.8H_2O$: crystal size $0.4 \times 0.3 \times 0.25$ mm, tetragonal, space group $I4_1/a$, a = 20.2620(5), c = 43.1040(7), V = 17696.3(7) Å^3, Z = 8, D_c = 1.214 g cm^{-3}, μ = 0.542 mm^{-1}, $2\theta_{max}$ = 49.44°, F(000) = 6824, $R1$ = 0.0539, $wR2$ = 0.15875 [for 5042 reflections with $I > 2\sigma(I)$], R_{int} = 0.0525, $R1$ = 0.0792, $wR2$ = 0.1800 (for all 7537 reflections), 590 parameters, S = 1.106.

CCDC 182/1639. See http://www.rsc.org/suppdata/cc/b0/b002144j/ for crystallographic files in .cif format.

1 M. M. Conn and J. Rebek, Jr., *Chem. Rev.*, 1997, **97**, 1647.
2 B. C. Hamman, K. D. Shimizu and J. Rebek, Jr., *Angew. Chem., Int. Ed.*, 1999, **35**, 1326; O. Mogck, E. F. Paulus, V. Böhmer, I. Thondorf and W. Vogt, *Chem. Commun.*, 1996, 2533; R. G. Chapman, G. Olovsson, J. Trotter and J. C. Sherman, *J. Am. Chem. Soc.*, 1998, **120**, 6252.
3 C. Nuckolls, F. Hof, T. Martín and J. Rebek, Jr., *J. Am. Chem. Soc.*, 1999, **121**, 10281.
4 K. N. Rose, L. J. Barbour, G. W. Orr and J. L. Atwood, *Chem. Commun.*, 1998, 407; L. R. MacGillivray, P. R. Diamente, J. L. Reid and J. A. Ripmeester, *Chem. Commun.*, 2000, 359.
5 L. R. MacGillivray and J. L. Atwood, *Nature*, 1997, **389**, 469.
6 T. Heinz, D. M. Rudkevich and J. Rebek, Jr., *Angew. Chem., Int. Ed.*, 1999, **38**, 1136.
7 For encapsulation of a hydrogen bonded dimer of sulfuric acid in a dimeric calixarene capsule, see: M. J. Hardie, M. Makha and C. L. Raston, *Chem. Commun.*, 1999, 2409.
8 The 2:1 ratio between **1a** and Et$_3$NH$^+$ was additionally established by ^{1}H NMR spectroscopy. Crystals were removed from the mother liquor, cleaned with filter paper, and dissolved in DMSO-d$_6$.
9 The center of the cavity is determined as the gravity center of the bridging methine atoms of the resorcarene molecules forming the dimer.
10 For inclusion of water molecules in the cavity of calixarenes, see: J. L. Atwood, F. Hamada, K. D. Robinson, G. W. Orr and R. L. Vincent, *Nature (London)*, 1991, **349**, 683; A. Drjaca, M. Hardie and C. L. Raston, *J. Chem. Soc., Dalton. Trans.*, 1999, 3639.
11 Compare with: A. Shivanyuk, E. F. Paulus and V. Böhmer, *Angew. Chem., Int. Ed.*, 1999, **38**, 2906.
12 M. A. James, T. S. Cameron, O. Knop, M. Neuman and M. Falk, *Can. J. Chem.*, 1985, **63**, 1750.
13 The encapsulation of β-methyl glucoside by a resorcarene dimer in CDCl$_3$ has been described, however, the detailed structure of the complex could not be established: Y. Kikuchi, Y. Tanaka, S. Sutarto, K. Kobayashi, H. Toi and Y. Aoyama, *J. Am. Chem. Soc.*, 1992, **114**, 10 302.
14 K. Murayama and K. Aoki, *Chem. Commun.*, 1998, 607.