Structure of encapsulated chloride anion with the preorganization of a macrotricyclic ammonium cage host

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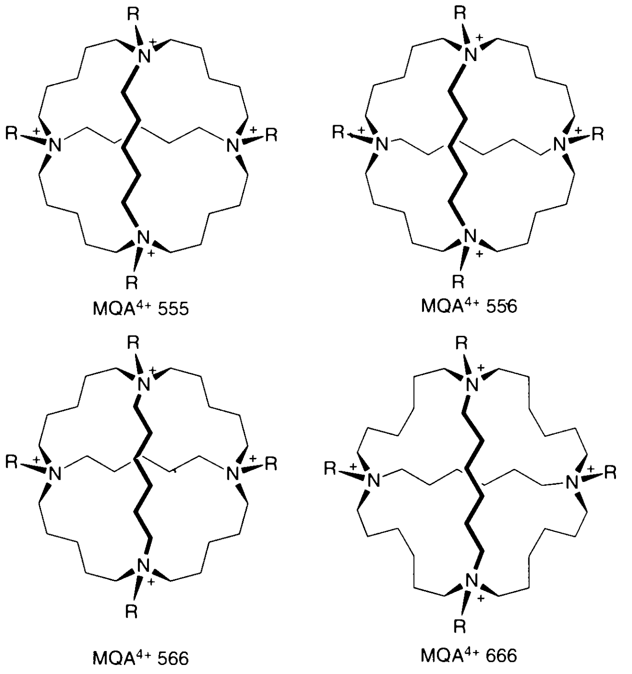
The molecular structure of $2{\cdot}4Cl^{-}{\cdot}3H_2O$, where 2 = $[(PhCH_2)_4N_4(C_5H_{10})_3(C_6H_{12})_3]^{4+}$, shows that one chloride anion is encapsulated with the preorganization of its precursor, and held in the intramolecular cavity by the electrostatic potential of four positive units located at the corners of the distorted tetrahedral structure.

Molecular recognition of anionic substrates by synthetic receptors is of intense current interest in chemical investigations because of the very significant roles played by anions in biochemical processes.[1] The design and synthesis of enzyme-mimicking host compounds is one of the most challenging and stimulating jobs in supramolecular chemistry. Although several classes of anion receptors have been designed that show complexation with anions in solution, in only a few cases, however, have their structures been determined by X-ray crystallography.[2] In most cases the ligand species feature protonated amine groups, and it is generally assumed that electrostatic and hydrogen-bonding interactions provide the binding forces for the encapsulation of anions.[3]

The preorganization is the central determinant of binding power: selective recognition of the substrates requires structural complementarity between host and guest. In the course of our study we designed four macrotricyclic cage hosts (Scheme 1), which have the characteristic feature of four positive binding sites converged to the centre, for the encapsulation and selectivity of halide ions. By systematic variation of the cyclic methylene groups, we can achieve size complementarity between the hosts and the anionic guests. The macrotricyclic quaternary ammonium ions (MQA^{4+}) are classified as MQA^{4+} 555(4), MQA^{4+} 556(2), MQA^{4+} 566(3) and MQA^{4+} 666(4) where the numbers correspond to the largest hydrocarbon cycle consisting of three chains of methylene groups which are connected by three nitrogen atoms, and the number in parentheses denotes the number of these cycles for a given MQA^{4+}. The corresponding parent amines are designated as MA using the same notation. The selectivity of halide ions can be inferred from the intracavity diameters of MA 555, MA 556, MA 566 and MA 666 which were estimated qualitatively as 3.0, 3.5, 4.0 and 4.5 Å, respectively, by CPK models as well as from crystal structures. The macrotricyclic host $[Me_4N_4(C_6H_{12})_6]^{4+}$ developed by Schmidtchen (MQA^{4+} 666) shows remarkable selectivity and complexibility toward iodide ion.[4,5] Recently, we have reported a fluoride selective host $[Me_4N_4(C_5H_{10})_6]^{4+}$ (MQA^{4+} 555) which is inaccessible to other halide ions.[6] Here, we report the crystal structures of $[(PhCH_2)N_4(C_5H_{10})_3(C_6H_{12})_3]^{4+}$ **2** into which Cl^{-} is included, as well as the corresponding macrotricyclic amine $N_4(C_5H_{10})_3(C_6H_{12})_3$, **1**.

The structure of **1**† shows considerable distortion from tetrahedral symmetry, as shown in Fig. 1. Only the $[N(CH_2)_5N]_3$ cycle (555 face) is near normal trigonal symmetry having N···N distances in the range 4.82–4.89 Å and the three interatomic angles of *ca.* 60°. The other three cycles (566 faces) deviate from trigonal symmetry due to the unequal number of methylene groups connecting three nitrogen ions; the largest N···N distance (7.59 Å) is observed for N(1)···N(3) and the interatomic angles [*e.g.* N(3)–N(2)–N(1)] are *ca.* 80° rather than 60°. The overall length of the cavity estimated from the crystal structure is 4.0 Å.



Scheme 1 Macrotricyclic ammonium cage hosts

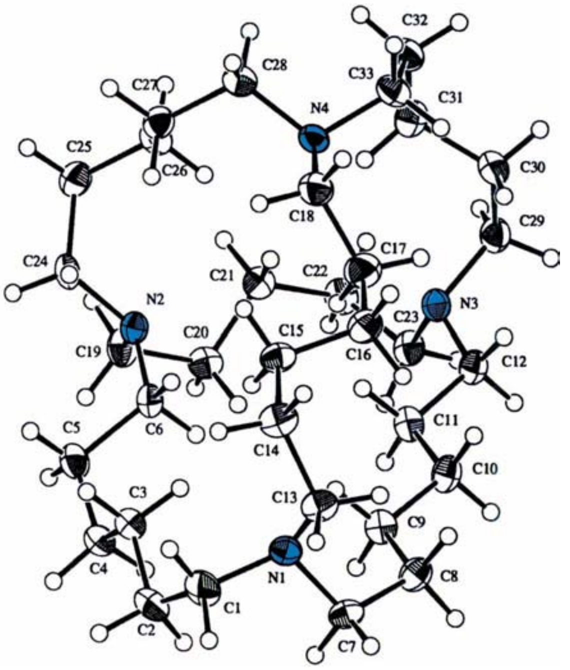


Fig. 1 ORTEP representation of the structure of **1** with thermal ellipsoids drawn at the 50% probability level

Since the electrostatic effect plays a role in the molecular recognition of anionic substrates, the quaternization of MA 566 with benzyl chloride gave rise to a novel cage host of the macrotricyclic ammonium ion $[(PhCH_2)N_4(C_5H_{10})_3(C_6H_{12})_3]^{4+}$ **2**. Inclusion of I^- with this species is not possible, however Cl^- and Br^- are expected to show complementarity with the cavity. ^1H and ^{35}Cl NMR data have shown that the host **2** discriminates the two guest species, and that chloride displaces bromide from the cavity of the host: when $[Br^-] \leqslant [Cl^-]$ no encapsulated bromide ions are observed in the cavity of **2** as ascertained by ^1H NMR spectra. Indeed, the novel host **2**, which contains anion ligating sites, provides a particularly attractive cavity for the chloride ion.

The structure of $\mathbf{2}{\cdot}4Cl^-{\cdot}3H_2O$‡ shows unambiguous encapsulation of one chloride ion within the cavity, as shown in Fig. 2. The encapsulated chloride ion is held in place by the electrostatic potential of four positive units located at the corners of the distorted tetrahedral structure. The four benzyl groups are arranged on the four vertices. The N···N distances in **2** are almost equal to each other (*i.e.* 6.62–7.02) upon inclusion of the chloride ion while those in its precursor **1** are in the wide range 4.83–7.59 Å. Evidently, the inclusion of chloride ion causes geometric constraints directing the size of the cavity. The Cl(1)···N(1) bond distance is 3.83 Å and the other Cl(1)···N bond distances are 4.27–4.45 Å: they are shorter than the I···N distances (4.50–4.59 Å) observed, for instance, in $\{[Me_4N_4(C_6H_{12})_6]^{4+}\ (I^-)\}$.[2d] The shortest Cl(1)···N distance, Cl(1)···N(1), indicates that the N(1) centre connected to $-(CH_2)_6-$ hydrocarbon chains is more flexible, so enabling maximization of attractive electrostatic interactions towards the central chloride. The other three Cl^- are located outside the N(3)N(2)N(4) plane: each nearest to each of the three vertices. Refinement of occupancy factors suggests that two of the outside chloride ions are disordered [Cl(4) 0.40, Cl(5) 0.60]. The space-filling model shown in Fig. 3(*a*) and (*b*), which were obtained from the structural data of $\mathbf{2}{\cdot}4Cl^-{\cdot}3H_2O$, shows that chloride can enter and leave the cavity through the three 566 faces but not through a 555 face. The distances of exterior chloride ions from their closest ammonium centres are in the range 4.02–4.75 Å, comparable with those of the encapsulated Cl^-, however the corresponding distances from the other ammonium centres are considerably higher (7.99–11.13 Å). Each of the nitrogen ions, except for N(1), is solvated by a water molecule at a distance of 4.2–5.3 Å, and is shared also by one outside chloride ion at a distance of 4.02–4.75 Å. Hydrogen-bonding distances of 2.9–3.2 Å between the outside Cl^- and O of water [*e.g.* Cl(5)···O(1) 3.160, Cl(4)···O(2) 2.904, Cl(3)···O(3) 2.914, Cl(2)···O(5) 2.996 Å, respectively] are observed.

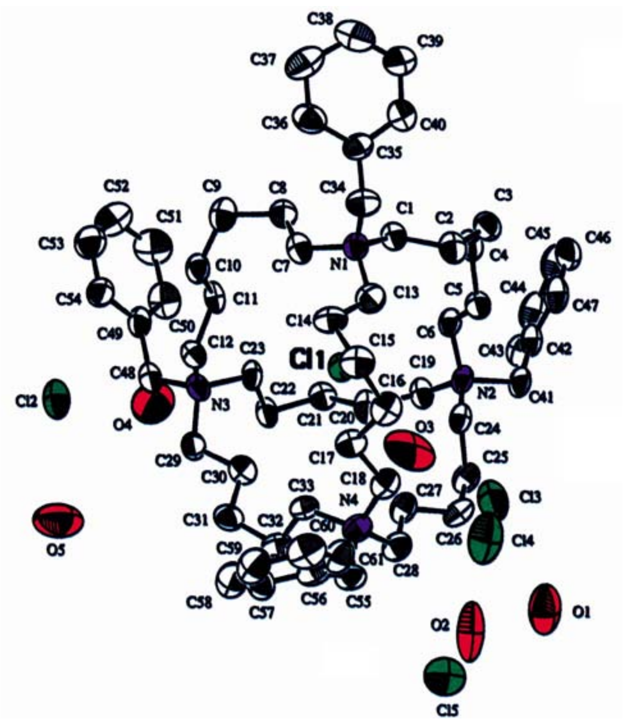


Fig. 2 ORTEP representation of the structure of $\mathbf{2}{\cdot}Cl^-{\cdot}3H_2O$ with thermal ellipsoids drawn at the 50% probability level; hydrogen atoms have been omitted for clarity

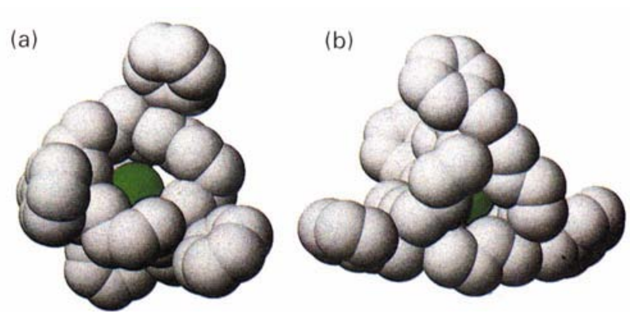


Fig. 3 Space-filling molecular structure of $\mathbf{2}{\cdot}Cl^-{\cdot}3H_2O$ viewing from (*a*) the 566 face: favourable cycle for the inclusion of Cl^-, and (*b*) 555 face: unfavourable cycle for the inclusion of the guest

Footnotes

† *Crystal data*: For **1**, $M = 518.91$, 0.20 × 0.20 × 0.15 mm, monoclinic, space group $P\bar{2}_1/a$, $a = 12.579(1)$, $b = 17.306(2)$, $c = 15.305(2)$ Å, $\beta = 93.27(1)°$, $U = 3326.4(7)$ Å^3, $Z = 4$, $D_c = 1.036$ g cm^{-3}, $F(000) = 1168.00$, μ(Cu-Kα) = 4.45 cm^{-1}; data were collected on a Rigaku AFC5R diffractometer, 4612 reflections, 4375 unique, 2493 observed $[I > 3\sigma(I)]$. The structure was solved by direct methods,[7] and expanded using Fourier techniques[8] to $R = 0.062$, $R_w = 0.108$, $\rho_{max,min}$ 0.38, −0.18 e Å^{-3}. All calculations were performed using the TEXSAN crystallographic software package of the Molecular Structure Corporation.[9]

‡ For $\mathbf{2}{\cdot}4Cl^-{\cdot}3H_2O$, $M = 1079.30$, 0.40 × 0.15 × 0.10 mm, monoclinic, space group $P2_1/c$, $a = 20.83(1)$, $b = 13.541(3)$, $c = 26.449(6)$ Å, $\beta = 109.35(3)°$, $U = 7039(3)$ Å^3, $Z = 4$, $D_c = 1.018$ g cm^{-3}, $F(000) = 2344.00$, μ(Mo-Kα) = 2.04 cm^{-1}; data were collected on a Rigaku RAXIS II imaging plate area detector, 8497 reflections, 3921 observed $[I > 4\sigma(I)]$, $R = 0.089$, $R_w = 0.140$, $\rho_{max,min} = 0.46$, −0.29 e Å^{-3}, respectively. Atomic coordinates, bond lengths and angles, and thermal parameters have been deposited at the Cambridge Crystallograpic Data Centre (CCDC). See Information for Authors, Issue No. 1. Any request to the CCDC for this material should quote the full literature citation and the reference number 182/144.

References

1 For recent review on recognition, see W. Xu, J. J. Vittal and R. J. Puddephatt, *J. Am. Chem. Soc.*, 1995, **117**, 8362; M. Shionoya, H. Furuta, V. Lynch, A. Harriman and J. L. Sessler, *J. Am. Chem. Soc.*, 1992, **114**, 5714; P. D. Beer, *Chem. Commun.*, 1996, 689.

2 (*a*) R. A. Bell, G. G. Christoph, F. R. Fronzeck and R. E. Marsh, *Science*, 1976, **190**, 151; (*b*) B. Metz, J. M. Rosalky and R. Weiss, *J. Chem. Soc., Chem. Commun.*, 1976, 533; (*c*) B. Dietrich, J. Guillem, J.-M. Lehn, C. Pascard and E. Sonveaux, *Helv. Chim. Acta*, 1984, **64**, 91; (*d*) F. P. Schmidtchen, *J. Chem. Soc., Chem. Commun.*, 1984, 1115; (*e*) G. Morgan, V. McKee and J. Nelson, *J. Chem. Soc., Chem. Commun.*, 1995, 1649.

3 A. Bianchi, M. Michelon and P. Pasolett, *Coord. Chem. Rev.*, 1991, **110**, 17.

4 F. P. Schmidtchen, *Angew. Chem., Int. Ed. Engl.*, 1977, **16**, 720.

5 K. Ichikawa, A. Yamamoto and M. A. Hossain, *Chem. Lett.*, 1993, 2177; K. Ichikawa, M. A. Hossain, T. Tamura and N. Kamo, *Supramol. Chem.*, 1995, **5**, 219.

6 M. A. Hossain and K. Ichikawa, *Tetrahedron Lett.*, 1994, **35**, 8393.

7 SIR 92: A. Altomare, M. C. Burla, M. Camalli, M. Cascarano, C. Giacovazzo, A. Guagliardi and G. Polidori, *J. Appl. Crystallogr.*, 1994.

8 DIRDIF 94: P. T. Beurskens, G. Admirral, G. Beurskens, W. P. Bosman, R. de Gelder, R. Israel and J. M. M. Smits, The DIRDIF-94 program system, Technical Report of the Crystallography Laboratory, University of Nijmegen, The Netherlands, 1994.

9 TEXSAN: Crystal Structure Analysis Package, Molecular Structure Corporation, revised 1992.

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