Cation–Calixarene Interactions: Tetraalkylammonium Cation Binding by Calixarene Anions

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Syntheses of a number of tetraalkylammonium derivatives of various calix[*n*]arenes (*n* = 4, 6, 8) have been conducted by reacting the tetraalkylammonium hydroxides with the parent calixarenes. ^{1}H NMR studies in acetone and dimethylsulfoxide (DMSO) solvents have shown that cation inclusion by the anionic calixarenes occurs in some cases for only the tetramethyl- and tetraethylammonium cations, indicating that different forms of ion association must occur in solution. The nature of cation–anion interactions in the solid tetraethylammonium salts of the monoanions of p-*tert*-butylcalix[4]arene (L2) and its dihomooxa analogue (L3) has been explored by room temperature single-crystal X-ray studies of the two salts and the parent ligand L3, all recrystallised variously solvated from acetonitrile. In both solid salts, columnar arrays of alternating cations and anions are found: in the dihomooxa ligand (L3) salt, the cations are captured within the ligand cup, forming contact ion pairs, the column comprising stacks of these. By contrast, the columnar array found in the parent ligand (L2) salt consists of discrete moieties, with the anion cavity occupied by acetonitrile. The free (neutral) ligand L3, as its acetonitrile monosolvate, contains the acetonitrile within the ligand cavity also. The structure determination of the unsubstituted calix[4]arene ligand, L1, is recorded as its $\frac{1}{3}$ acetonitrile solvate, with location of all phenolic hydrogen atoms bridging their associated oxygen atoms; the acetonitrile in this case simply occupies a lattice void, as in the isomorphous acetone solvate.

The interactions that occur between a charged atom or molecule and its environment of both charged and uncharged species are fundamental determinants of the properties of an extremely diverse range of materials.[1] In some instances, such as the formation of coordination complexes of transition metals, for example, these interactions are considered to be well understood but in many others this is not so.[2,3] In particular, the solvation and association of ions which may be formally 'non-coordinating' or which contain highly delocalised charges are properties which are difficult to characterise and are consequently in need of more thorough documentation.[4–6] In attempting to factorise thermodynamic quantities concerning solvent transfer processes into cation and anion contributions, for example, it is a common procedure to adopt the 'extra-thermodynamic assumption' that salts such as $[(C_6H_5)_4As]^+$-$[B(C_6H_5)_4]^-$ involve fully dissociated ions which interact equivalently with any given solvent, even though the evidence to support this assumption is largely based on circular arguments.[7] Perhaps more importantly, it has long been recognised that many biological phenomena, such as the tetramerisation of haemoglobin through 'salt bridges',[8] depend on ion association, and recently there has been intense general interest in ion binding to biopolymers[9] as structural information, for example, the crystal structure of acetylcholine esterase,[10] has begun to more rapidly accumulate. The field of 'inclusion chemistry'[11] also involves a major focus on ion binding, and the great variety of synthetic receptors available allows systematic study of particular binding mechanisms to be developed. One group of receptors which readily form anionic derivatives when associated with various types of cations is that of the 'calixarenes',[12] and the present work is concerned with the properties of some calixarene salts formed with tetraalkylammonium ions. The results are considered not only to define the possible inclusion mechanisms for calixarenes but also to be of some direct relevance to understanding of the characteristics of closely related 'resorcinarene' systems, for which considerably more extensive solution thermodynamic measurements concerning their ability to bind cations are available.[5,13]

From consideration of the structures of numerous inclusion complexes formed between the calixarenes and neutral molecules, attractive interaction between the methyl groups of guest and the π-clouds of the phenyl groups of the calixarenes has been identified as a major factor giving rise to inclusion.[12,13] For substituted calixarenes, such as the commonly encountered *p-tert*-butylcalixarenes, it has been recognised that reciprocal interactions between the calixarene alkyl groups and aromatic moieties within the guest play a significant rôle as well. Indeed, in the particular instance where comparison is drawn between calix[4]arene and *p-tert*-butylcalix[4]arene, it is apparent that the much more extensive inclusion chemistry of the latter must be attributed to attractive interactions between the guests and the *tert*-butyl substituents.[14] For cationic guests within the calixarene cavity, the situation is less clear, and for tetraalkylammonium ions, for example, we have observed structures[15] which may be interpreted as indicative of significant alkyl/*tert*-butyl attractions, while for Cs^+ there seems little doubt that its inclusion is due to cation coordination by the aromatic π system.[16] In an effort to further characterise the nature of cation interactions with calixarenes, we have extended some of our earlier studies of metal ion complexation by *p-tert*-butylcalixarenes[15–21] to those of alkylammonium ion binding, and report herein syntheses and spectroscopic studies of a variety of alkylammonium 'salts' of calixarenes of several ring sizes as well as detailed structural characterisation of, in particular, the tetraethylammonium derivatives of the monoanions of *p-tert*-butylcalix[4]arene and dihomooxa-*p-tert*-butylcalix[4]arene. For the purpose of useful comparison, we include also descriptions of the structural characterisation of the acetonitrile adducts of both calix[4]arene and dihomooxa-*p-tert*-butylcalix[4]arene.

Table 1 $[Me_4N]_x[Ln - xH]$

L	Yield (%)	x	C (%)[a]	H (%)[a]	N (%)[a]
L1	80	1	77.4 (77.2)	6.9 (7.09)	2.8 (2.81)
L2	78	1	79.8 (79.8)	9.6 (9.35)	1.9 (1.94)
L3	60	1	78.4 (78.2)	9.1 (9.25)	1.8 (1.86)
L4	59	1	76.2 (76.3)	6.2 (6.54)	2.6 (1.94)
L5	54	2	79.5 (79.4)	9.5 (9.54)	2.6 (2.50)
L6	50	2	76.3 (77.3)	7.0 (7.00)	2.8 (2.82)
L7	46	2	79.5 (79.9)	8.7 (9.29)	1.1 (1.94)

[a] Calc. figures in parentheses.

Table 2 $[Et_4N]_x[Ln - xH]$

L	Yield (%)	x	C (%)[a]	H (%)[a]	N (%)[a]
L1	34	1	78.0 (78.0)	7.6 (7.83)	2.3 (2.53)
L2	40	1	80.4 (80.3)	9.6 (9.71)	1.8 (1.80)
L3	40	1	77.0 (77.8)	9.5 (9.49)	2.9 (3.30)[b]
L4	70	2	77.8 (77.8)	6.8 (6.64)	3.2 (3.13)
L5	68	2	79.8 (80.0)	9.7 (9.98)	2.4 (2.27)
L6	44	3	77.7 (77.7)	8.6 (8.56)	3.5 (3.40)
L7	70	3	78.6 (79.8)	9.9 (10.1)	2.4 (2.49)

[a] Calc. figures in parentheses. [b] Calc. figures for $[Et_4N][L3 - H]\cdot CH_3CN$.

Experimental

Analysis and Instrumentation.—Elemental analyses were performed by MHW Laboratories Ltd (Arizona, USA). Solution ^1H NMR spectra were recorded on Bruker WP80 and AM300 instruments.

Syntheses.—Calix[4]arene (L1),[22] *p-tert*-butylcalix[4]arene (L2),[23] dihomooxa-*p-tert*-butylcalix[4]arene (L3),[15,24] calix[6]arene (L4),[25] *p-tert*-butylcalix[6]arene (L5),[26] calix[8]arene (L6)[25] and *p-tert*-butylcalix[8]arene (L7)[27] were prepared by methods given in the literature. L1 and L3 were recrystallised from acetonitrile to provide the solvates. Tetraethylammonium hydroxide was used as a 25% aqueous solution (BDH). Methanolic solutions of other tetraalkylammonium hydroxides (R_4NOH, R = CH_3, C_3H_7, C_4H_9) were prepared as follows: a solution of R_4NBr (0.05 mol) in methanol (50 cm^3) was added to an aqueous slurry of Ag_2O (~ 10 g in 10 cm^3); the mixture was stirred for 1 h, the solution tested (acidic $AgNO_3$) to ensure no Br^- remained and then filtered to provide ~ 1 mol dm^{-3} R_4NOH.

*Tetramethylammonium salts: (calixarenes L*1, *L*2 *and L*7). Methanolic Me_4NOH (5 cm^3) was added to a warm (60 °C) slurry of the calixarene (0.5 g) in acetonitrile (10 cm^3). The mixture was stirred vigorously for 15 min as the solid transformed without dissolution. The white product was collected by filtration and recrystallised from hot dimethylsulfoxide (DMSO). The colourless crystals were dried by vacuum desiccation over silica gel.

(*Calixarenes L*3–*L*6). Methanolic Me_4NOH was added to a warm (60 °C) slurry of the calixarene (0.5 g) in acetonitrile (10 cm^3) until all the calixarene had dissolved. The solution was filtered and allowed to cool to room temp. Colourless crystals of the derivatives of L3–L5 precipitated over a period of several hours but the L6 derivative did not precipitate until the solution had been cooled at 0 °C for 24 h. All materials were then recrystallised from acetonitrile and air dried. Yields and analytical data for $[Me_4N]_x[Ln - xH]$ are summarised in Table 1.

*Tetraethylammonium salts: (calixarenes L*1–*L*7). Excess aq. Et_4NOH (~ 3 cm^3) was added to a warm (60 °C) slurry of the calixarene (0.5 g) in acetonitrile (10 cm^3). Heating was continued until all the calixarene dissolved, then the solution was filtered and allowed to cool to room temp. With the exception of the L6 solution, each deposited colourless crystals over a period of several hours, and these products were then recrystallised from acetonitrile. The L6 derivative was precipitated by addition of ether (10 cm^3) to the reaction mixture. Yields and analytical data for $[Et_4N]_x[Ln - xH]$ are summarised in Table 2.

*Tetrapropylammonium salts: (calixarenes L*1–*L*7, *except L*3). Methanolic Pr_4NOH was added dropwise to a warm (60 °C) slurry of the calixarene (0.5 g) in acetonitrile (10 cm^3) until the calixarene had dissolved. The solution was filtered and allowed to cool to room temp. In the cases of L1 and L2, colourless crystals deposited over a period of a few hours but for the remaining compounds crystallisation only occurred on cooling at 0 °C for 24 h. All materials were recrystallised from acetonitrile and dried in air. Yields and analytical data for $[Pr_4N]_x[Ln - xH]$ are summarised in Table 3.

*Tetrabutylammonium salts: (calixarenes L*4, *L*5 *and L*7). Methanolic Bu_4NOH was added dropwise to a warm (60 °C) slurry of the calixarene (0.5 g) in acetonitrile (10 cm^3) until the calixarene had dissolved. The solution was filtered and cooled at 0 °C for 24 h to cause deposition of colourless crystals. All materials were recrystallised from acetonitrile and dried in air. Yields and analytical data for $[Bu_4N]_x[Ln - xH]$ are summarised in Table 4.

Structure Determinations.—Unique data sets were measured at ~295 K within the specified $2\theta_{max}$ limits on capillary-mounted specimens using a CAD-4 diffractometer ($2\theta/\theta$ scan mode; monochromatic Mo*K*α radiation, $\lambda = 0.7107_3$ Å). *N* Independent reflections were obtained, N_0 with $I > 3\sigma(I)$ being considered 'observed' and used in the full-matrix least squares refinements without absorption correction after solution of the structures by direct methods. Anisotropic thermal parameters were refined for C, N, O; $(x, y, z, U_{iso})_H$ were included constrained at estimated values, phenolic hydrogens (when not located) excepted. Residuals on $|F|$ at convergence, R, R_w, are quoted, statistical weights derivative of $\sigma^2(I) = \sigma^2(I_{diff}) + 0.0004\,\sigma^4(I_{diff})$ being used. Neutral atom complex scattering factors were employed, computation using the XTAL 3.0 program system[28] implemented by S. R. Hall. Pertinent results are given in the Figures and Tables. Individual variations in procedure, *etc.* are noted below. Material deposited comprises structure factor amplitudes, atom coordinates and thermal parameters, and full non-hydrogen geometries.*

Crystal/refinement data. (**1**) $[NEt_4][L2 - H]\cdot 1.24CH_3CN\cdot 0.48H_2O \equiv C_{52}H_{75}NO_4\cdot 1.24CH_3CN\cdot 0.48H_2O$, $M = 837.7$. Monoclinic, space group $C2/c$ (C_{2h}^6, No. 15), $a = 46.25(5)$, $b = 16.46(2)$, $c = 24.00(2)$ Å, $\beta = 119.54(10)°$, $V = 15896$ Å^3. D_c ($Z = 12$) = 1.05 g cm^{-3}; $F(000) = 5497$. $\mu_{Mo} = 0.9$ cm^{-1}; specimen: cuboid, ~0.4 mm^3. $2\theta_{max} = 40°$; $N = 7386$, $N_o = 3293$; $R = 0.083$, $R_w = 0.064$.

Abnormal features/variations in procedure. Wide linewidths precluded a precise cell determination; note that $Z = 12$, $\beta \sim 120°$ and $a \sim 2c$. The ethyl groups of the cations are disordered over two sets of sites, modelled with equal population (after initial refinement of site occupancies) and with geometries constrained at idealised values. The cations have no intimate association with the anions in spite of their disposition in stacks (see below). The anion cavities are occupied by acetonitrile molecules which have uncertain N-atom assignment and very high thermal motion. Phenolic hydrogen atoms were

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* For details of the CCDC deposition scheme, see 'Instructions for Authors', *J. Chem. Soc., Perkin Trans. 2*, 1993, issue 1.

Table 3 $[Pr_4N]_x[Ln - xH]$

L	Yield (%)	x	C (%)[a]	H (%)[a]	N (%)[a]
L1	35	1	78.9 (78.8)	8.2 (8.43)	2.3 (2.30)
L2	30	1	80.8 (79.6)	9.8 (9.90)	3.2 (3.20[b]
L4	42	2	77.9 (78.7)	8.8 (9.00)	2.7 (2.78)
L5	40	1	81.0 (80.8)	9.6 (9.66)	1.3 (1.21)
L6	35	3	77.1 (78.6)	8.8 (9.26)	2.6 (2.99)
L7	45	3	80.1 (80.3)	10.6 (10.5)	2.3 (2.27)

[a] Calc. figures in parentheses. [b] Calc. figures for $[Pr_4N][L2 - H]\cdot CH_3CN$.

Table 4 $(Bu_4N]_x[Ln - xH]$

L	Yield (%)	x	C (%)[a]	H (%)[a]	N (%)[a]
L4	26	1	79.1 (78.3)	8.0 (8.15)	1.3 (1.59)
L5	28	1	80.9 (81.1)	9.6 (9.87)	1.1 (1.15)
L7	60	2	80.5 (80.9)	10.0 (10.3)	1.7 (1.57)

[a] Calc. figures in parentheses.

Table 5 Calyx dihedral angles (°); the dihedral angles between the C_6 phenyl ring skeleton planes and the O_4 plane of the apex are given

Ring	**1**[a]	**2**	**3**	**4**
1/1a	61.0 (3)	45.8 (4)	66.8 (2)	68.8 (2)
2/2a	57.9 (3)	25.9 (5)	42.2 (1)	36.8 (2)
3/1b	56.3 (3)	68.3 (4)	62.5 (2)	69.5 (2)
4/2b	59.5 (3)	40.9 (4)	—	32.7 (5)

[a] Values for cation **a**; for cation **b** (rings 1, 2), values are 59.4(3), 62.0(3)°.

not located in difference maps. There are two distinct anions, one with all atoms crystallographically dependent, the other disposed about a two-fold crystallographic axis; the acetonitrile associated with the latter lies on that axis. The third acetonitrile has no anion affiliation but occupies what would otherwise be a void in the lattice; after refinement, its population was constrained at 0.35. A final difference map residue was modelled as oxygen, presumably of a water molecule, with a population refining to 0.73; no associated hydrogen atoms were located.

(**2**) $[NEt_4][L3 - H]\cdot CH_3CN \equiv C_{55}H_{80}N_2O_5$, M = 849.3. Monoclinic, space group $P2_1/c$ (C_{2h}^5, No. 14), a = 17.383(3), b = 17.123(3), c = 23.117(2) Å, β = 130.52(1)°, V = 5231 Å^3. $D_c(Z = 4) = 1.08$ g cm^{-3}; $F(000) = 1856$. $\mu_{Mo} = 0.7$ cm^{-1}; specimen: cuboid, 0.4 mm^3. $2\theta_{max} = 46°$; $N = 7257$, $N_o = 2369$; $R = 0.067$, $R_w = 0.062$.

Abnormal features/variations in procedure. Two of the *tert*-butyl groups were disordered over two sets of sites, with major and minor components in each case; isotropic thermal parameters were refined for the minor components in each case, component populations being determined by refinement as (0.74_3, 1–0.74_3), (0.84_3, 0.15_7). The solvent population when refined did not differ significantly from unity and was constrained at that value; N atom assignment is insecure.

(**3**) $L1\cdot\frac{1}{3}CH_3CN \equiv C_{28.67}H_{25}N_{0.33}O_4$, M = 438.2. Hexagonal, space group $P6_3/m$ (C_{6h}^2, No. 176), a 14.358(3), c = 18.498(6) Å, V = 3301(2) Å^3. D_c (Z = 6) = 1.32 g cm^{-3}; $F(000) = 1388$. $\mu_{Mo} = 0.9$ cm^{-1}; specimen 0.23 × 0.48 × 0.14 mm. $2\theta_{max} = 47.5°$; $N = 1740$, $N_o = 798$; $R = 0.044$, $R_w = 0.038$.

Abnormal features/variations in procedure. The setting is based on that of its acetone solvate analogue but with a connected set within the half-molecule comprising the asymmetric unit for the ligand. Phenolic hydrogen atoms were located and refined with all other hydrogen atoms, apart from those of the solvent molecule, which is disordered.

(**4**) $L3\cdot CH_3CN \equiv C_{47}H_{61}NO_5$, M = 720.0. Triclinic, space group $P\bar{1}$ (C_i^1, No. 2), a = 17.565(2), b = 15.402(8), c = 9.363(4) Å, α = 73.24(4), β = 76.31(2), γ = 73.78(3)°, V = 2295 Å^3. $D_c(Z = 2) = 1.02$ g cm^{-3}; $F(000) = 780$. $\mu_{Mo} = 1.0$ cm^{-1}; specimen: cuboid, 0.3 mm^3. $2\theta_{max} = 50°$; $N = 8069$, $N_o = 3773$; $R = 0.085$, $R_w = 0.094$.

Abnormal features/variations in procedure. Three of the four *tert*-butyl groups are disordered; populations of major and minor components were established by refinement, as was that of the acetonitrile (with dubious N assignment).

Results

Syntheses.—Although it would appear that in all cases presently examined a solution of the calixarene deprotonated to some degree by the quaternary base could be obtained, several of these 'salts' (especially those containing the tetrabutylammonium cation) proved to be so soluble that either they could not be precipitated or residual undeprotonated calixarene precipitated preferentially. Physical measurements are only reported for those materials which could be crystallised and therefore purified as solids.

Structure Determinations.—Those of compounds containing *tert*-butyl substituted calixarene derivatives, particularly at room temperature as with the present studies, are typically of low precision with limited accessible data in consequence of high thermal motion, and with rotational disorder or high thermal motion possibly encompassing unresolved disorder frequently found in the *tert*-butyl groups.[14,15–21,29] In these circumstances, assignment of the extent and nature of protonation is not feasible. Such problems are compounded by the presence of included acetonitrile, also with very high thermal motion, so much so that location of the methyl hydrogen atoms and assignment of the nitrogen atom is also often not normally feasible. Bond lengths and angles are generally as expected, and the structures are discussed in terms of their chief features of interest and the rationale of the study—interspecies interactions and anion conformations.

Compound **1**, $[NEt_4][L2 - H]\cdot 1.24CH_3CN\cdot 0.48H_2O$. The asymmetric unit of the structure comprises one discrete, complete anion (with included acetonitrile), **a**, and cation and one half of the same, **b**. Anions and associated cations comprise alternating stacks, that up the crystallographic two-fold axis involving anion **b** being depicted. Projections, normal to the O_4 'plane' of the anions with their included axial acetonitrile molecules are shown in Fig. 1(*a*); the columnar array along the two-fold axis is shown, projected normal to the axis, in Fig. 1(*b*), the central atom of the acetonitrile lying ~ 5.2 Å from the O_4 plane (both calices), so that the acetonitrile is disposed at the level of the *tert*-butyl groups. Dihedral angles between the C_6 phenyl ring skeletons and the associated O_4 planes (Table 5) lie in the range 59 ± 3°; the degree of tilt does not alternate around the macrocyclic ring as is often the case in other examples of structures of derivatives of L2.

Compound **2**, $[NEt_4][L3 - H]\cdot CH_3CN$. The asymmetric unit of this compound comprises one each of the anion, cation and acetonitrile solvent. Unlike as in **1**, the acetonitrile molecule, although present in the lattice, is not included in the anion. Rather, the cation has now become included instead [Fig. 2(*a*)], again at the level of the *tert*-butyl groups, with the central nitrogen atom ~ 4.7 Å out of the basal O_4 plane, and with the anion/cation pairs then arrayed in an alternating stack, perpetuated by the crystallographic 2_1 screw axis [Fig. 2(*b*)]. Fig. 2(*a*) shows the cation is displaced well off-centre in the anion cup, so much so as to suggest that the anion from L2 might well be able to include the tetraethylammonium cation in the absence of competition with a solvent such as acetonitrile, which seemingly has a high affinity for the calixarene cup.

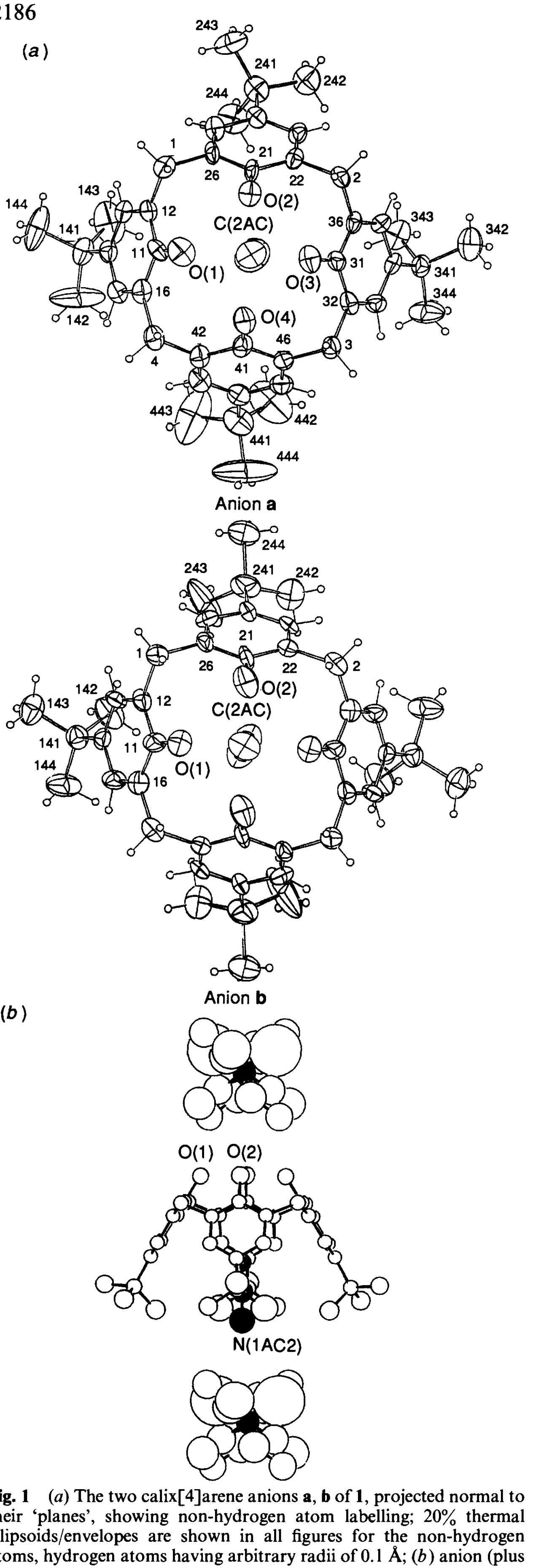

Fig. 1 (*a*) The two calix[4]arene anions **a**, **b** of **1**, projected normal to their 'planes', showing non-hydrogen atom labelling; 20% thermal ellipsoids/envelopes are shown in all figures for the non-hydrogen atoms, hydrogen atoms having arbitrary radii of 0.1 Å; (*b*) anion (plus solvent)/cation stack of the entities located on the two-fold axis of the cell, atoms are shown as equivalent isotropic envelopes (the cation is disordered; the acetonitrile and cation nitrogen atoms are shown as solids)

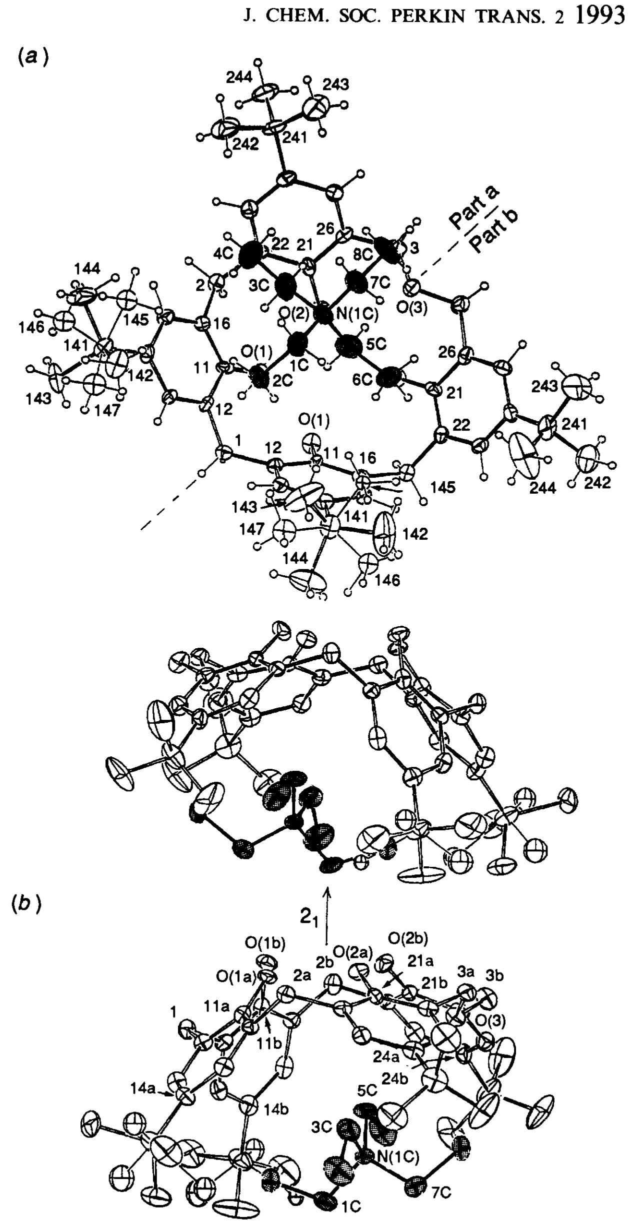

Fig. 2 (*a*) Projection of the cation/anion pair of **2** normal to the anion O_4 plane; (*b*) projection of the cation/anion stack generated by the 2_1 screw of **2** viewed down *a*.

Nevertheless, the off-centre displacement of the cation may well be consequent of factors peculiar to the L3 species, for which the phenyl rings vary considerably in their tilt, ring 2a, nearest the cation, being pitched flattest with a dihedral of 25.9(5)° relative to the O_4 plane, while ring 1b, furthest away, is steepest. Certainly an off-centre arrangement is characteristic of the relatively limited number of structures known for inclusion complexes of L3.[15,19]

Compound **3**, L1·$\frac{1}{3}$CH$_3$CN. The structure of the unsubstituted calix[4]arene as its acetonitrile solvate (Fig. 3) closely parallels that of the acetone solvate[30] of similar stoichiometry (a cell diagram is given in ref. 30). In that determination, the description of hydrogen atom location is seemingly confined to CH hydrogens, whereas the present experiment has permitted location and refinement of all calyx hydrogen atoms in (x, y, z, U_{iso}), curiously with a numerically smaller data array in the present work (N = 1740, N_o = 798 to $2\theta_{max}$ 47.5°; *c.f.* acetone solvate N = 6559, N_o = 3940? to $2\theta_{max}$ 52°), suggesting merging of data to have been appropriate for that structure in $P6_3/m$ space group. In both solvates, the polar solvent molecule lies disposed about a site of $\bar{6}$ symmetry, implying the presence of disorder in that space group.

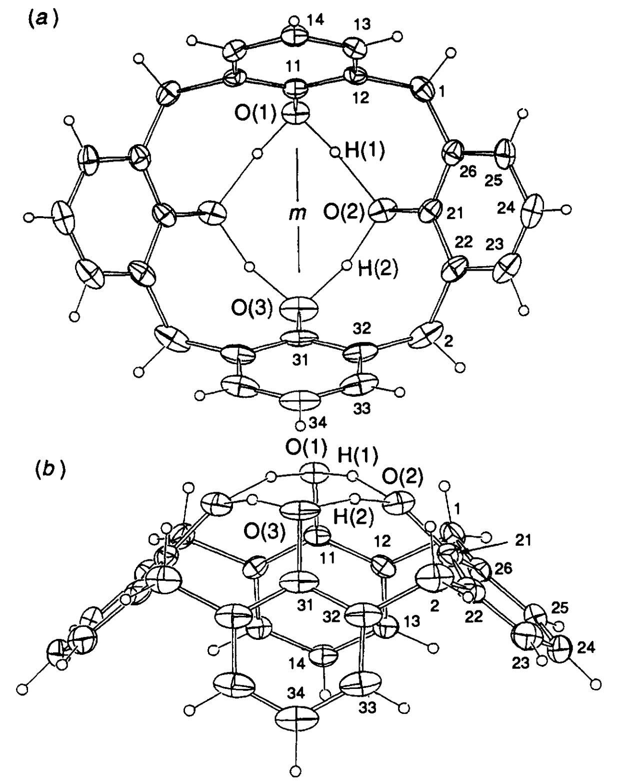

Fig. 3 (*a*) Projection of **3** normal to the O_4 plane; the crystallographic mirror plane is normal to the page; (*b*) oblique view with the crystallographic mirror plane approximately normal to the page

In both structures the calixarene molecule has *m* symmetry, one pair of phenyl rings being bisected by the mirror plane and the other pair related by them; the two ring types differ in their tilt (Table 5), rings 2 lying much 'flatter' than rings 1 and 3, which are similarly and more steeply inclined; the values are comparable to those found in the acetone solvate [66.5(1); 42.9(1); 62.7(1)°]. As refined, H(1) is unsymmetrically disposed between O(1) and O(2) [H(1) $\cdots$ O(1,2), 1.13(3), 1.58(4) Å; O–H–O, 164(5)°; H(2) $\cdots$ O(2,3), 1.39(4), 1.31(4) Å; O–H–O, 159(5)°] but definitive assertion of a difference between them should await a low-temperature neutron study. It is worth noting that the largest principal axes of the thermal ellipsoids are generally directed around the core of the system; the presence of possible disorder encompassed by these ellipsoids cannot be ruled out. Of some interest is the observation that the oxygen atoms are pulled inwards, deviating from their respective planes by 0.067(7), 0.113(6), 0.056(8) Å; the bridging/attached carbon atoms also deviate, notably about ring 2, by 0.020(7) Å (ring 1); 0.069(7), 0.084(8) Å (ring 2); 0.006(8) Å (ring 3). For the C_6 rings themselves, χ^2 (plane) are 6, 48, 0, respectively; no defining atom deviation exceeds 0.014(7) Å [C(11)] in ring 1 or 0.004(8) Å in ring 3, whereas deviations of atoms 1–6 in ring 2 are −0.023(5), 0.017(5), 0.002(6), −0.020(7), 0.009(6), 0.012(5) Å, respectively. Angles at bridging carbons 1, 2 are 113.2(4), 113.7(4)°, respectively.

Compound **4**, L3·CH_3CN. The asymmetric unit of this structure (Fig. 4) comprises one calixarene unit with included acetonitrile; plausible phenolic hydrogen atoms were located in difference maps, in spite of the usual disorder/thermal motion problems. The included solvent is obviously only very loosely constrained; its central atom is ~4.3 Å out of the O_4 plane and it lies tilted and off-centre towards the ether oxygen, as is also the case with the dimethylformamide (DMF) adduct.[15] The ring conformation is similar to that found in the DMF solvate, also a 1 : 1 adduct, with the tilt of the phenyl rings to either side of the macrocycle ether oxygen much 'flatter' than that of the other pair (Table 4); the values differ significantly from those found in the DMF adduct [67.4(1), 31.8(1)°]. It is perhaps curious that in a family of structures where numbers of clathrates of the one calixarene are isomorphous that the present acetonitrile adduct is not isomorphous with the DMF adduct; more curiously, the present cell volume ($Z = 2$) (2295 $Å^3$) is greater than that of the DMF analogue (space group $P2_1/m$, $Z = 2$) (2236 $Å^3$) by an appreciable amount, in spite of the greater bulk of the DMF.

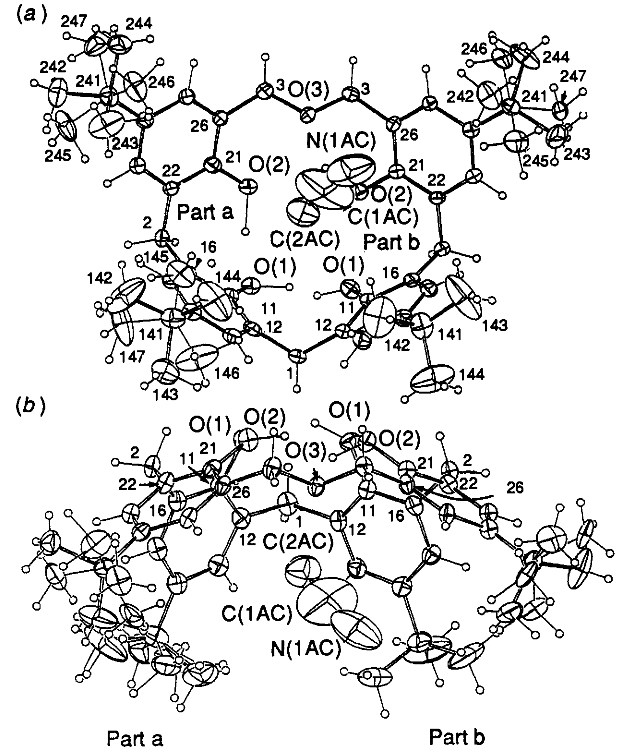

Fig. 4 Projections of the calixarene/solvent combination of **4**: (*a*) normal to the O_4 plane; and (*b*) oblique to the normal

Solution ^1H *NMR Spectroscopy*.—Spectra of the various salts were recorded for solutions in deuteriated DMSO and acetone, with solutions of the tetraalkylammonium perchlorates being used to provide chemical shift data for alkyl group resonances of the simply solvated cations. (Spectra of the neutral calixarene solvent adducts could be recorded in deuteriochloroform but this was a completely unsuitable solvent for the salts.) Only for tetramethyl- and tetraethyl-ammonium derivatives of some of the calixarenes were resonances observed to be significantly shifted from the positions of the corresponding perchlorate salt peaks, and data for these systems only are presented in Table 6. While the largest shifts observed were for acetone solvent, solubilities in acetone were generally much lower than in DMSO, and in some instances were too low for satisfactory spectra to be obtained. For all the polyammonium compounds at the temperatures attainable in DMSO (*i.e.*, above 19 °C), only single sets of alkyl group resonances were observed, indicating that exchange over any different sites must have been rapid. Where shifted peaks, indicative of cation inclusion, were observed, addition of the appropriate tetraalkylammonium perchlorate did not result in peak doubling, showing that in these systems also site exchange was rapid. At least in the case of the tetramethylammonium salt of the *p*-*tert*-butylcalix[6]arene dianion in acetone solvent, however, lowering of the temperature to −20 °C resulted in the detection of distinct cation binding sites (Fig. 5). One of the two equally intense methyl resonances occurs at a chemical shift identical to that of

Table 6 Upfield shifts (ppm) of cation methyl resonances for the alkylammonium complexes of the ligands L1–L7 in acetone and DMSO solution

	Me_4N^+	Et_4N^+	
Ligand	CH_3	CH_2	CH_3
DMSO			
L1	0.30		
L2	0.20		
L3	0.45		
L4	0.55		
L5	0.00		
L6	0.30		
L7	0.25		
Acetone			
L1	—	—	—
L2	—	0.00	0.00
L3	1.30	0.90	0.60
L4	0.05	0.50	0.40
L5	0.60	0.60	0.40
L6	0.00	0.40	0.20
L7	0.00	0.30	0.20

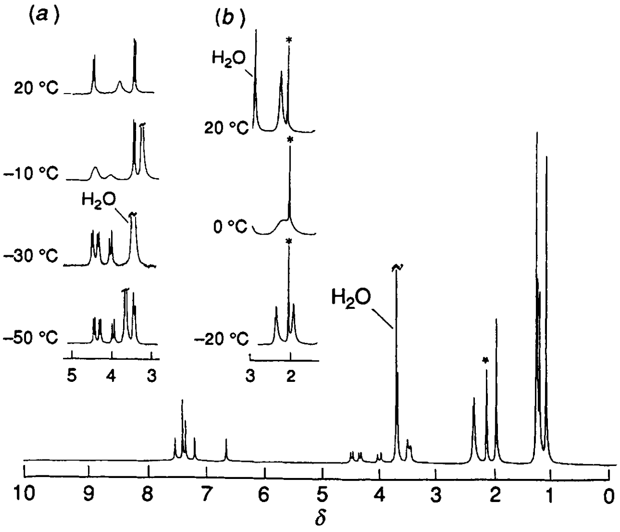

Fig. 5 Variable temperature ^1H NMR spectra for $[NMe_4]_2[$*p-tert*-butylcalix[6]arene − 2H] in $[^2H_6]$acetone. The full spectrum shows resonances observed at −50 °C; inset are (*a*) the calixarene methylene; and (*b*) cation methyl resonances at various higher temperatures. Asterisks denote the residual solvent resonances.

tetramethylammonium perchlorate in acetone at the same temperature, the other is shifted upfield, indicating that one cation is 'free' and one is included. Since four calixarene *tert*-butyl group resonances are observed, a plausible structure for the ion pair in solution is one where the calixarene adopts a 'hinged', 'three up-three down' conformation[17] with the cation enclosed by three phenyl groups, as shown in Fig. 6. Attempts were made to observe Overhauser effects expected due to the relative proximity of included alkyl group protons and aromatic protons but, at least in acetone solvent (used to give the most concentrated possible solutions), cross peaks in either NOESY or ROESY spectra significantly above the noise levels were not observed. Attempts to detect significant interactions through ^1H–^{13}C HOESY measurements were also frustrated by solubility limitations.

Discussion

The structures of the acetonitrile adducts of calix[4]arene (L1) and dihomooxa-*p*-*tert*-butylcalix[4]arene (L3), compounds **3** and **4**, respectively, define inclusion modes which, at least in gross terms, have been previously recognised for both.[14,15] The stoichiometry and structure of $L1{\cdot}\frac{1}{3}CH_3CN$ (**3**) are essentially identical to those of the isomorphous $L1{\cdot}\frac{1}{3}(CH_3)_2CO$ (one of two crystalline phases known for adducts of L1 with acetone),[30] despite the different shapes of the solvent guest molecules. In these two solids, the solvent molecules form columns (resulting possibly in some favourable mutual alignment of their dipoles, though these are disordered within the $P6_3/m$ model) which fill cavities within the lattice of calixarene molecules apparently organised through the interaction of methylene group hydrogens on one calixarene with phenyl rings of others.[30] The nature of any interaction between the solvent molecule columns and the calixarene lattice is difficult to define with certainty; presumably it does not involve hydrogen bonding between the phenolic hydrogens and the nitrogen of the acetonitrile, nor inclusion of the solvent within the calixarene cavity, and possibly is best regarded as a composite of dispersion forces and dipole–dipole attractions. Whatever the exact situation, the structure provides another illustration of the fact that the type of 1 : 1 molecular inclusion seen so commonly with simple adducts of *p*-*tert*-butylcalix[4]arene must in some way depend upon the presence of the *tert*-butyl groups. The structure is also of interest because its precision is such that the expected hydrogen-bonding involving the four phenolic groups within any given calixarene molecule is well-defined and the calixarene cone is quite clearly shown to be in a 'pinched' (C_{2v}) conformation.[14,29]

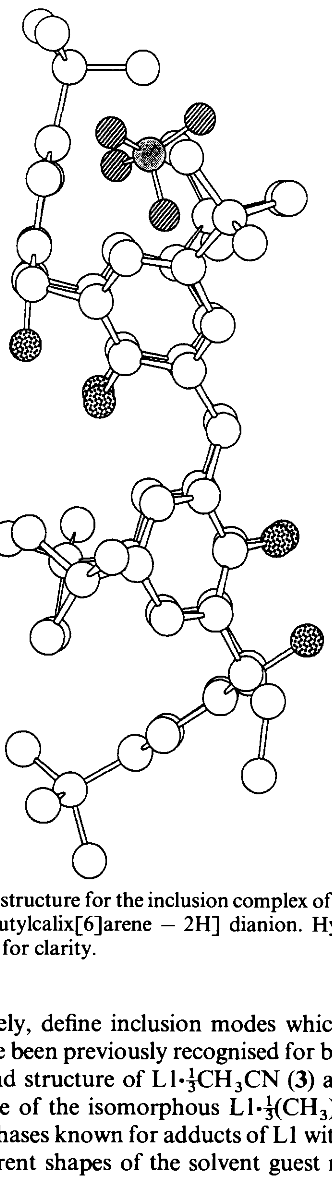

Fig. 6 A possible structure for the inclusion complex of $NMe_4{}^+$ cation with the [*p*-*tert*-butylcalix[6]arene − 2H] dianion. Hydrogen atoms have been omitted for clarity.

One of the consequences of the introduction of *p*-*tert*-butyl groups onto the calix[4]arene structure is the predominance of 1 : 1 stoichiometry in adducts formed with various solvents. The same stoichiometry is observed for adducts of dihomooxa-*p*-

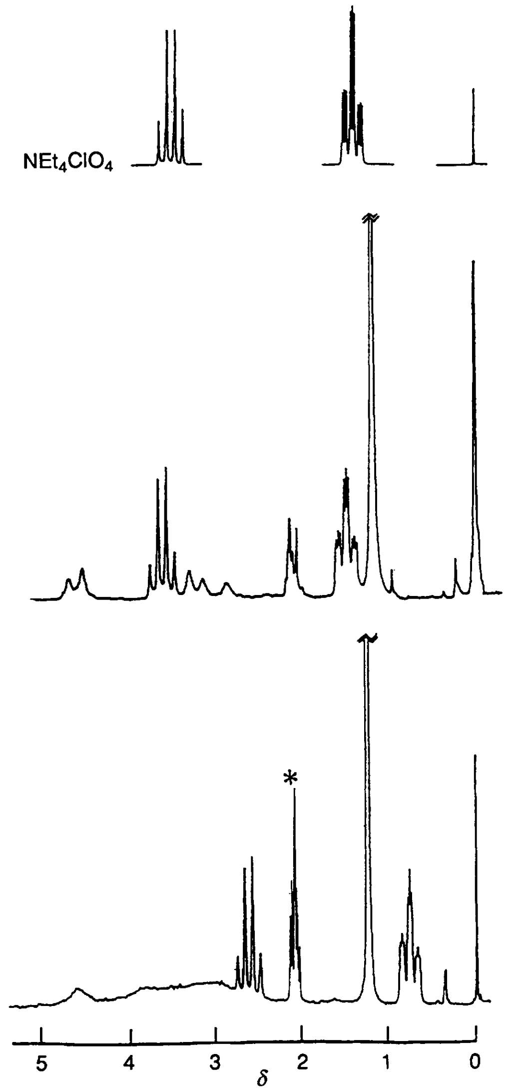

Fig. 7 ^1H NMR spectra in [$^2H_6$]acetone solution, ~295 K of: (top) [NEt_4][ClO_4]; (middle) [NEt_4][*p-tert*-butylcalix[4]arene − H] (**1**); and (bottom) [NEt_4][*p-tert*-butyldihomooxacalix[4]arene − H] (**2**). The asterisk denotes the residual solvent proton resonances.

tert-butylcalix[4]arene, though this system has been subjected to far less extensive examination and at least one instance is known of the inclusion, aided by metal ion complexation, of two solvent molecules per calixarene in the solid state.[19] In the cases where direct comparison of 1 : 1 adducts in the two systems can be made, rather marked differences in the orientations of the guests within the calixarene cavities are apparent. In the present L3·CH_3CN compound, **4** the acetonitrile molecule lies at an angle to the mean phenolic-O_4 plane which is far more acute than that, to the equivalent plane, of the acetonitrile in *p-tert*-butylcalix[4]arenetetra(ethylcarbonate)·CH_3CN.[31] {Similar remarks may be made concerning the DMF adducts of *p-tert*-butylcalix[4]arene and dihomooxa-*p-tert*-butylcalix-[4]arene, though a relevant exception to the general observation that solvent molecules in adducts of calix[4]arenes tend to align into the cone along the (pseudo)fourfold axis is provided in the recently determined structure of the ethanol adduct of 1,3-diethoxy-*p-tert*-butylcalix[4]arene.[32]} Since the cone of L3 is considerably flattened relative to that of a true calix[4]arene and this flattening is unsymmetrical, it is possible that such differences may reflect different interactions of the acetonitrile dipole with the overall dipole of the calixarene. In **4**, the methyl group and nitrogen assignments for the acetonitrile guest are insufficiently certain to enable assignment of the orientation of the acetonitrile dipole, though the structure is, nonetheless, consistent with the conventional view[14,29] that inclusion of simple methane derivatives by *p*-alkylcalix[4]-arenes results from methyl group hydrogen interactions with the aromatic π clouds, as reflected in the methyl group being inserted furthest into the cup. The assumption that this may be so underlies the atom labelling given in Fig. 4, and of course the molecular orientation where it is the nitrogen end of the acetonitrile which projects ‘out’ of the calixarene cup would be essentially that expected if the guest and calixarene moieties were to be aligned simply by their mutual dipole–dipole interaction.

In formally ionic materials, it is to be anticipated that electrostatic interactions should be the dominant contributors to association[33] and thereby determine cation/anion orientation, though it is also anticipated that this should depend upon the degree of charge delocalisation within the ions, *viz.*, the formal division of intermolecular forces into various multipole terms will obviously not be the same for all ‘ionic’ compounds, let alone all compounds. Decisions as to the most appropriate multipole distribution are, of course, equivocal but precise structural information provides one important basis, and the present structures of [NEt_4][L2 − H] (**1**) and [NEt_4][L3 − H] (**2**) both in solution and in the solid state, provide instructive illustrations of how quite subtle differences in anions can give rise to very different modes of cation association. In acetone solution, NMR spectra of **1** and **2** (Fig. 7) reveal that cation binding involves inclusion in the latter case but not the former. This is exactly mirrored in the solid state, where the X-ray diffraction studies provide detailed information on this and other differences. Thus, the crystallographic study of **1** shows the calixarene anion to have the cone conformation with very close to four-fold symmetry, with an acetonitrile molecule included in the cavity and oriented along the four-fold axis, as observed with most solvent adducts of the neutral calixarene.[14,29] The tetraethylammonium cation is found in a position which might be regarded as that expected if the anionic charge on the calixarene were to be localised on the oxygen atoms and electrostatic attractions were to be maximised, though it is also a position which allows some degree of dispersive interaction with the *tert*-butyl substituents of the next anion in the stack and possibly ion–dipole attraction for the nitrogen of the acetonitrile included in that calixarene. [Again, it is not possible to state whether it is the nitrogen or methyl end of the acetonitrile which projects from the calixarene cup but, if the former, then the nitrogen of the tetraethylammonium cation is 4.1 Å distant, a separation comparable to that of the cation nitrogen from its closest calixarene oxygens (4.0 Å). Note that in chloroform solution of **1**, the acetonitrile ^1H methyl resonance is displaced from the δ 1.98 for ‘free’ acetonitrile to δ 1.57, showing that inclusion persists with the methyl hydrogen atoms oriented towards and close to the centres of the aromatic rings, and thereby implying that if the same factors determine the relative orientations of the calixarene and the acetonitrile in both the solid and solution states, the acetonitrile in solid **1** must be oriented ‘N-out’.]

The structure of **2** is fascinating in several regards. The acetonitrile present is not included within the calixarene nor is the ammonium cation found in close proximity to the oxygen atoms where the negative charge might be considered to be significantly localised, though the stacking of units within the lattice does allow an ammonium ion to be included by one calixarene while remaining relatively close to the oxygen atoms of another. Since the positive charge is presumably significantly delocalised over the methylene group hydrogen atoms, the fact that one methylene group is oriented in such a way that one of its hydrogen atoms is nearly equidistant from and approaching (within ~3.3 Å) three oxygen atoms (one being the ether bridge atom) may be significant. The ethyl arms of the cation, though at approximately the same 'altitude' above the mean phenolic O_4 plane, appear to be directed, so far as differing symmetries allow, in between both *tert*-butyl and phenyl groups, though this does allow several methylene hydrogen atoms to approach relatively closely to *tert*-butyl group hydrogens (separations ~ 2.2–2.3 Å) and it also brings both methyl and methylene hydrogens in several cases to within 2.8 Å of phenyl carbon atoms. The interactions that occur in 'ion pairs' of the type found in **2** have been analysed recently in great detail by Schneider and co-workers,[5,6,13] who find a remarkably close to constant free energy increment (for a given solvent) is associated with cation/anion interactions regardless of the actual chemical nature of the charged centres. These data derive from solution measurements and it is, of course, possible that the solution structure of the $[NEt_4][L3 - H]$ ion pair could be quite different to that observed in the solid, so that analysis of the solid state structure in terms of binding modes may well be irrelevant to understanding of solution properties. However, the ^1H NMR spectrum of **2** in acetone solution (Fig. 7) does show marked upfield shifting of the NEt_4^+ methyl and methylene resonances which is consistent with inclusion in close proximity to the phenyl rings and thus indicative that the solid state structure is retained in this solvent. Hence, our observation that the homologue $[NBu_4][L3 - H]$ gives an NMR spectrum in acetone solvent which shows no evidence of cation inclusion (as expressed in upfield shifting of aliphatic resonances) indicates that while the greater effective size of NBu_4^+ compared to NEt_4^+ must have some degree of influence on the magnitude of 'electrostatic' interaction energies, there may be equally significant energy changes associated with differences in orientation and proximity of moieties considered to interact through multipole effects. It is interesting to note that in a relatively simple molecule containing closely similar structural features to the present salts, (1*R*,2*S*)-[3-hydroxy-3-(3-hydroxyphenyl)-2-propyl]trimethylammonium chloride,[34] the chloride anion in the solid is found quite remote (~ 4.65 Å) from the nearest quaternary ammonium centre, which is in fact in closer proximity to hydroxy phenyl moieties.

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