

Deprotonation of Large Calixarenes – Cation Binding and Conformations

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Dedication. Vale the inimitable Bos. We miss his cheerful and memorable hypercynical and irreverent aphorisms, e.g. “*In the land of the one-eyed, the two-faced man is king*”.

Abstract Single crystal X-ray studies of p-t-butylcalix[10]arene·2dmsO·7H₂O (**1**) and [NMe₄][p-t-butylcalix[9]arene-H]·2dmsO·H₂O (**2**), provide new data on these large macrocycles and their conformations, that of **2** being the first where an encapsulated [NMe₄]⁺ cation is present, while **1** contains the neutral ligand. Both were obtained as crystalline products of the reactions of the calixarenes with tetramethylammonium hydroxide after long standing. The structure of [NEt₄][calix[4]arene-H], in which the cation approaches inclusion in the shallow cone of the anion, is also defined and compared with various other alkylammonium derivatives of calixarenes as well as that of p-t-butylcalix[9]arene.

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Introduction

While investigations of the chemistry of the larger calixarenes have been relatively limited compared to those of calix[4]arene and its derivatives,^[1] there is particular interest in the larger species because of their capacity to act as di- or poly-topic receptors and thus provide frameworks suited to the development of, for example, multimetallic catalysts.^[2] The conformational lability of the larger calixarenes^[1,3] means, however, that it is difficult to predict how they may function as receptors so that structural studies of these calixarenes in both their free and complexed forms are fundamental to developing an understanding of their behaviour. It has been long known, for example, that unsolvated p-t-butylcalix[8]arene adopts a nearly flat, 'pleated loop' conformation^[4] which is not suggestive of any exceptional inclusion properties. This conformation is essentially unchanged in inclusion complexes of the calixarene with neutral solvents,^[5,6] but slightly modified in its inclusion complexes with organic bases^[7] and in some mononuclear metal complexes.^[8] However extensive deprotonation and binding to two lanthanide cations^[9] results in a completely different conformation resembling a fusion of two conical calix[4]arene units twisted into a chiral form, a result at variance with the complex formed with a pair of uranyl ions.^[10] The present report is the result of work which was begun with the intent of studying the effect of deprotonation and inclusion of a small organic cation (tetramethylammonium) on the conformations of p-t-butylcalix[9]arene and p-t-butylcalix[10]arene; this particular cation, on the basis of the nature of its complexes with calix[4]arene monoanion^[11] and p-t-butylcalix[6]arene dianion^[12] may be expected to be compatible with the formation of cone-like components for inclusion within the macrocycles. As for all crystallographic studies, this work was dependent upon our ability to obtain suitable crystals, which were obtained in a desired salt form for p-t-butylcalix[9]arene, leading to a useful comparison of the structure of $[\text{N}(\text{Me})_4][\text{p-t-butylcalix[9]arene-H}]$ with that of unsolvated $[\text{NEt}_4][\text{calix[4]arene-H}]$. With p-

t-butylcalix[10]arene, despite efforts to react it with $[\text{NMe}_4]\text{OH}$ and thus obtain the analogue of the p-t-butylcalix[9]arene derivative, crystals were obtained only as the free ligand in a new (dmsO/H₂O) solvate form.

Experimental

Experiments in which dimethylsulfoxide (dmsO) solutions of p-t-butylcalix[9]arene and p-t-butylcalix[10]arene were treated with various molar amounts (in excess of 1:1) of ethanolic $[\text{NMe}_4]\text{OH}$ provided, after warming the initial mixtures and then allowing them to cool, extremely thin, lath-like crystals in both cases. These were completely unsuitable for X-ray diffraction studies with the then-available instrumentation but after leaving stand the mixtures for an extended period (ten years), both proved to contain some useful specimens which, with more modern technology, diffracted acceptably. The structure solutions thereby obtained modelled the materials persuasively as p-t-butylcalix[10]arene·2dmsO·7H₂O (**1**) and $[\text{NMe}_4][\text{p-t-butylcalix[9]arene-H}] \cdot 2\text{dmsO} \cdot \text{H}_2\text{O}$ (**2**). $[\text{NEt}_4][\text{calix[4]arene-H}]$ (**3**) was obtained by treating a slurry of calix[4]arene in acetonitrile with excess methanolic $[\text{NEt}_4]\text{OH}$, followed by heating and addition of dichloromethane until all solids dissolved. The solution was allowed to evaporate, under ambient conditions, providing crystals of **3**.

Structure determinations

Full spheres of area-detector CCD diffractometer data were measured for **1**, **2** (ω -scans, monochromatic Cu K α radiation, $\lambda = 1.54178 \text{ \AA}$), processed together with an older unique single counter instrument set for **3** ($2\theta/\theta$ scans, Mo K α radiation, $\lambda = 0.71073 \text{ \AA}$), yielding $N_{\text{(total)}}$ reflections, these merging to N unique (R_{int} cited) after 'empirical'/multiscan 'absorption

correction', N_o with $I > 2\sigma(I)$ being considered 'observed' and used in the full matrix least squares refinements on F^2 , reflection weights being $(\sigma^2(F_o^2) + (aP)^2 + (bP))^{-1}$ ($P = (F_o^2 + 2F_c^2)/3$). Computation used the SHELXL2014 program.^[13] Results are presented below and in the Figures and Tables; full *.cif* depositions (excluding structure factor amplitudes) are deposited with the Cambridge Crystallographic Data Centre, CCDC 973920 (1), 973919 (2), 973918 (3).

Crystal/refinement details

1. p-t-butylcalix[10]arene·2dmsO·7H₂O: C₁₁₀H₁₄₀O₁₀·2dmsO·7H₂O, $M_r = 1904.6$. Orthorhombic, space group *Fmm2* (C_{2v}^{18} , No. 42), $a = 32.0088(4)$, $b = 32.1639(2)$, $c = 12.1181(1)$ Å, $V = 12475.9(2)$ Å³ ($T = 100(2)$ K). D_c ($Z = 4$) = 1.014 g cm⁻³. $\mu_{Cu} = 0.84$ mm⁻¹; specimen: 0.44 x 0.25 x 0.05 mm; $T'_{\min/\max} = 0.71$. $2\theta_{\max} = 135^\circ$; $N_t = 30997$, $N = 5113$ ($R_{\text{int}} = 0.029$), $N_o = 5065$; $R_1 = 0.099$, $wR_2 = 0.27$; $S = 1.04$. $x_{\text{abs}} = 0.05(8)$. $|\Delta\rho|_{\max} = 1.4(1)$ e Å⁻³.

Variata. The 'plane' of the macrocycle lies normal to the two-fold axis of the *mm2* array, one independent t-butyl only being ordered. The dmsO molecules lie on or close to one of the mirror planes and disordered about it, both modelled as superimposed with a water molecule with appropriate fractional occupancy with other fractionally occupied components further afield, one on a mirror plane. Full details are available in the *.cif* file.

2. [NMe₄][p-t-butylcalix[9]arene-H]·2dmsO·H₂O: C₁₀₃H₁₃₇NO₉·2dmsO·H₂O, $M_r = 1699.3$. Monoclinic, space group *P2₁/m* (C_{2h}^2 , No. 11), $a = 11.7820(2)$, $b = 30.4081(5)$, $c = 15.9367(3)$ Å, $\beta = 107.816(2)^\circ$, $V = 5435.8(2)$ Å³ ($T = 100(2)$ K). D_c ($Z = 2$) = 1.038 g cm⁻³. $\mu_{Cu} = 0.86$

mm^{-1} ; specimen: 0.38 x 0.18 x 0.03 mm; $T'_{\text{min/max}} = 0.81$. $2\theta_{\text{max}} = 135^\circ$; $N_t = 56566$, $N = 9867$ ($R_{\text{int}} = 0.057$), $N_o = 7509$; $R_1 = 0.104$, $wR_2 = 0.23$; $S = 1.00$. $|\Delta\rho|_{\text{max}} = 1.15(8) \text{ e } \text{\AA}^{-3}$.

Variata. The 'plane' of the macrocycle lies normal to the crystallographic mirror plane, with the cation and dmsO 1,3, H₂O 1,3 components lying in or close to the plane and disordered about it, the dmsO and H₂O components superimposed and fractionally occupied. dmsO 2 was modelled with its sulfur atom disordered over two sites, the whole being superimposed also with a fractionally occupied water molecule. Full details are available in the .cif file.

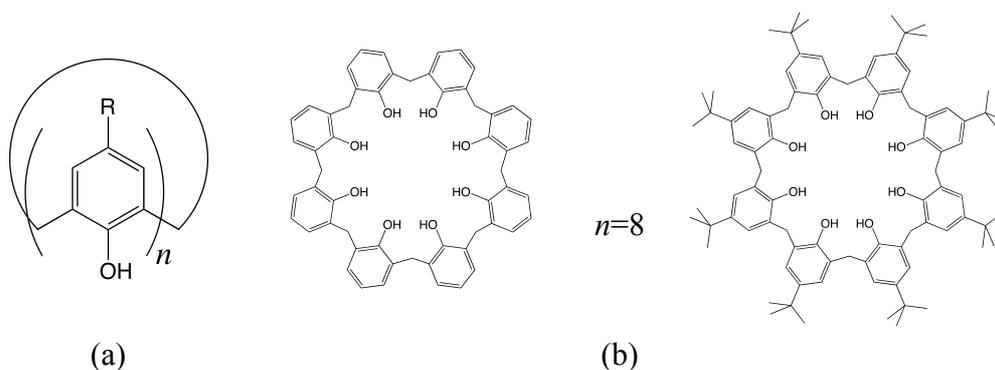
3. [NEt₄][calix[4]arene-H]: C₃₆H₄₃NO₄, $M_r = 553.7$. Orthorhombic, space group *Fdd2* (C_{2v}^{19} , No. 43), $a = 22.153(4)$, $b = 22.383(4)$, $c = 23.948(5) \text{ \AA}$, $V = 11875(4) \text{ \AA}^3$. ($T \text{ ca } 150 \text{ K}$). D_c ($Z = 16$) = 1.239 g cm⁻³. $\mu_{\text{Mo}} = 0.080 \text{ mm}^{-1}$; specimen: 0.25 x 0.12 x 0.08 mm; $T'_{\text{min/max}} = 0.99$. $2\theta_{\text{max}} = 45^\circ$; $N_t = N = 2005$, $N_o = 1437$; $R_1 = 0.16$, $wR_2 = 0.39$; $S = 1.21$. x_{abs} indeterminate. $|\Delta\rho|_{\text{max}} = 0.56(9) \text{ e } \text{\AA}^{-3}$.

Variata. Each cation is disordered about the same crystallographic 2-axis, their relative dispositions being quasi-orthogonal, the disordered components being refined with isotropic displacement parameters. Within the ligand, phenolic hydrogen atoms were modelled over two crystallographically independent sites, one fully occupied and one half-occupied. Three of the four independent ethyl groups in the cation are rotationally disordered about their pendent bonds, site occupancies 0.5.

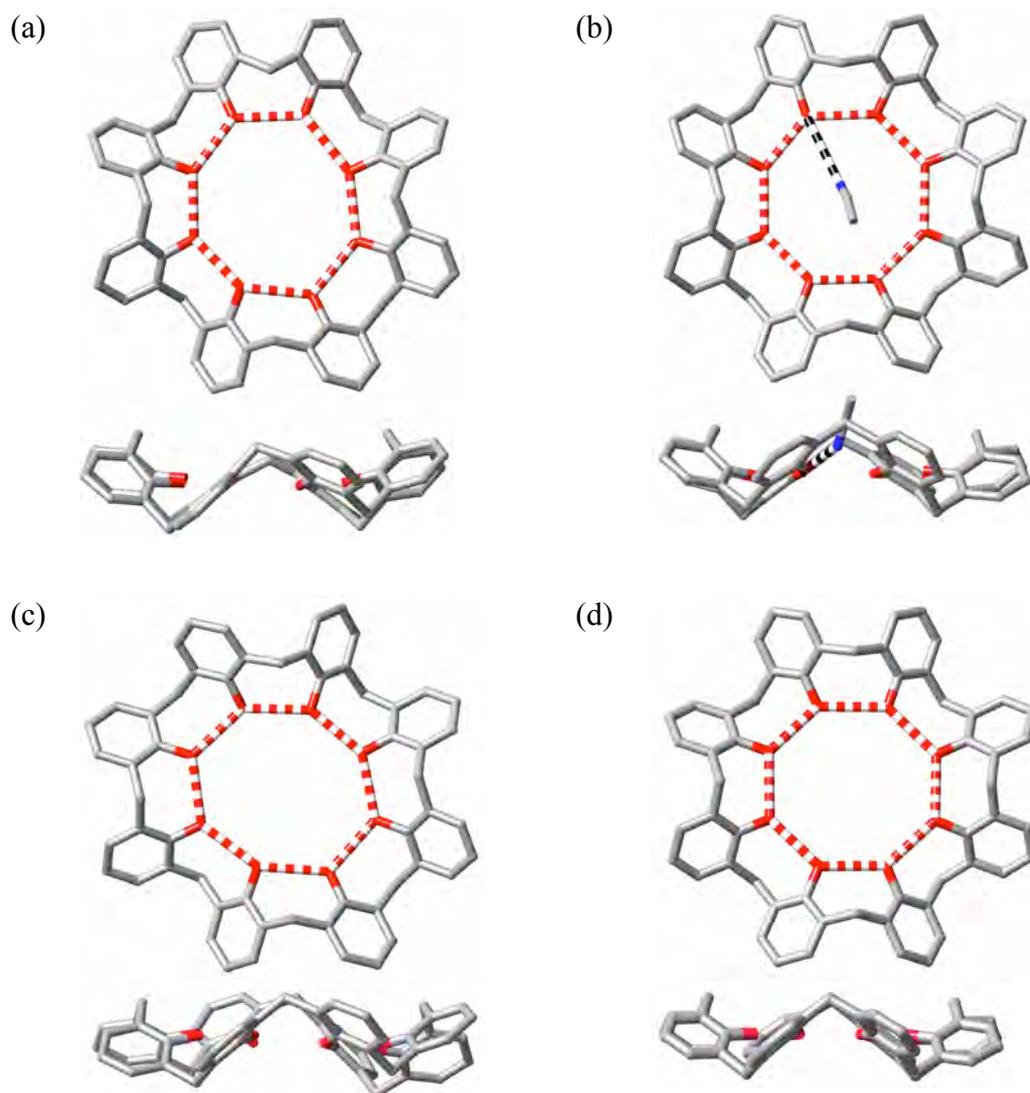
Results and discussion

The development of efficient syntheses, coupled to full characterisation, of the three p-t-butylcalix[n]arenes with $n = 4, 6$ and 8 by Gutsche and co-workers more than 40 years ago was the foundation of the remarkable subsequent development of the field of calixarene chemistry.^[1] The larger two do not share the ready introduction of conformational restrictions

which has made *p*-*t*-butylcalix[4]arene and its derivatives the basis of a prolific family with an extraordinary range of applications. The largest, *p*-*t*-butylcalix[8]arene, and its dealkylated derivative (Scheme 1) have, nonetheless, provided a substantial amount of valuable reference data for the present study.



Scheme 1. (a) General structure of *para*-substituted calix[*n*]arene, and (b) structures of calix[8]arene, and *p*-*t*-butylcalix[8]arene.



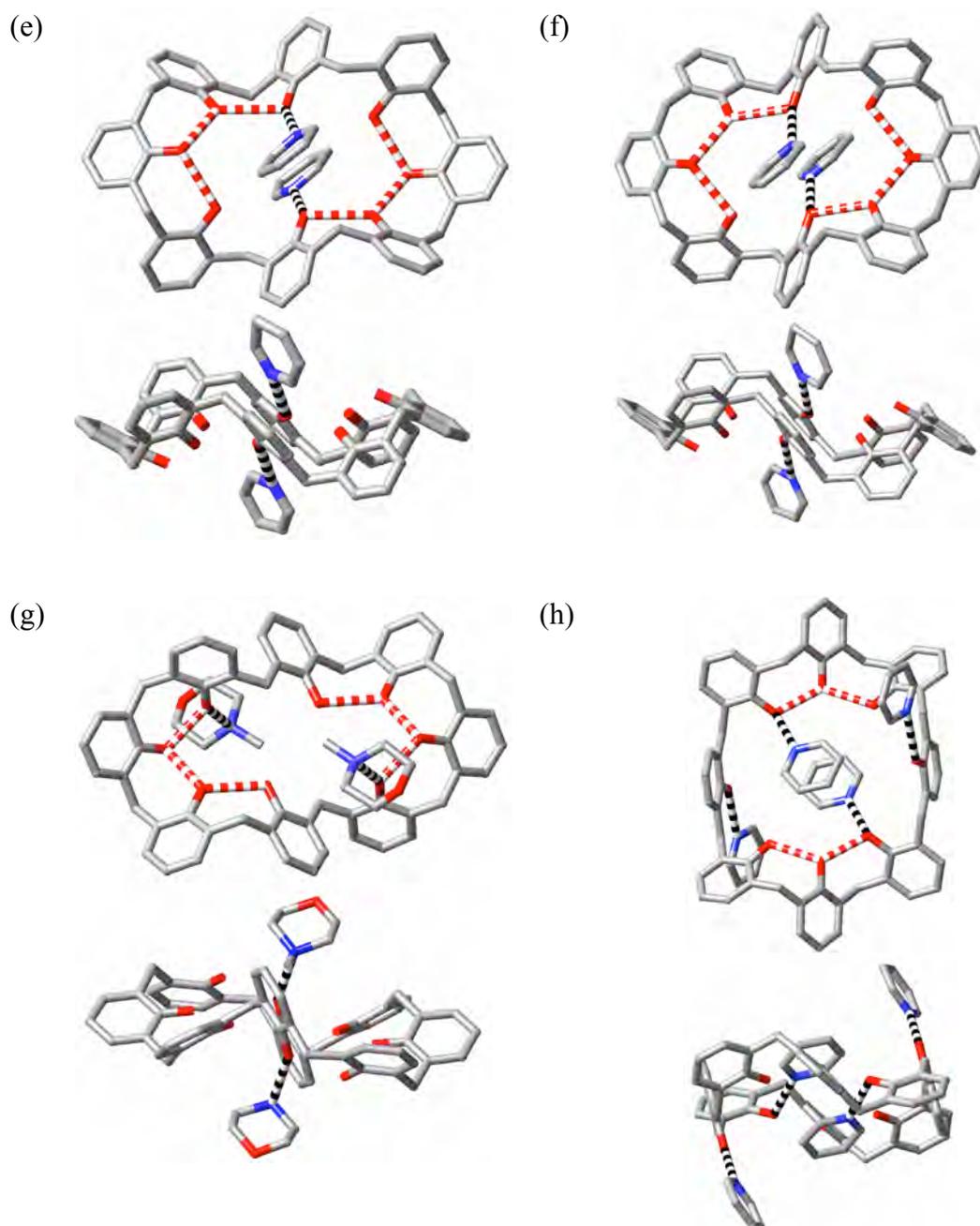


Fig. 1. Orthogonal views of the inner macrocycle conformation in various known solvates of calix[8]arene. Shown are p-t-butylcalix[8]arene in the "pleated loop" (a) unsolvated,^[4] (b) tetrakis(acetonitrile) solvate,^[6] (c) bis(acetonitrile) solvate,^[6] (d) chloroform solvate^[5]; and in the "stretched chair" form (e) (octakis) pyridine solvate,^[7(a)] (f) (tetrakis) pyridine solvate,^[7(b)] and (g) morpholine solvate.^[7(c)] Calix[8]arene (as the hexakis(pyridine) solvate) in the "stretched chair" form is shown in (h).^[14] Here, and in subsequent Figures, H-atoms and (sometimes disordered) t-butyl groups are not shown; dashed red-and-white lines indicate phenolic H-bonding interactions and dashed black-and-white lines phenolic-OH...N interactions. In stick representations the colour code, where employed, is, C = grey, N = blue, O = red.

For p-t-butylcalix[8]arene, several structure determinations are available. The first,^[4] leading to the definition of the essentially fourfold-symmetric “pleated loop” conformation for the molecule (Fig. 1(a)), was of the unsolvated form, although a very similar conformation is found in two (quasi-) isomorphous acetonitrile solvates,^[6] as well as in a non-isomorphous chloroform solvate.^[5] As is very well established for calix[4]arenes,^[1] cyclic intramolecular H-bonding appears to be a major factor determining the solid state conformation, although as phenolic-H atoms were not located in any of these p-t-butylcalix[8]arene structures, the presence of H-bonds was surmised generally on the basis of O...O separations near 2.7 Å. As rather poor H-bond acceptors, chloroform and acetonitrile would not be expected to greatly perturb phenolic H-bond links (Fig. 1(b)-(d)) and it is only in the acetonitrile tetrasolvate that a weak interaction of one acetonitrile-N with a (presumably) phenolic-H is possibly the cause of a slight asymmetry of the conformation (Fig. 1(b)), although a similar asymmetry is also seen in the disolvate (Fig. 1(c)), where such an interaction is not apparent, so that crystal packing in broader terms must be considered relevant. Solvates with the much better H-bond acceptors pyridine^[7(a),(b)] and N-methyl-morpholine^[7(c)], however, do show that the stronger interactions which occur with these bases, may result in a conformation of the calix[8]arene quite different from that of the pleated loop. This conformation can be described as a base-assisted (*quasi*-centrosymmetric) “stretched chair” form (Fig. 1(e)-(g)) in that in each there are two strings of four phenolic oxygen atoms, each with a terminal N-base, directed oppositely with respect to the ring mean plane. A similar form is seen in the lattice of the hexakis(pyridine) solvate of calix[8]arene,^[14] where phenolic H-atoms could be located and refined and where the absence of t-butyl substituents appears to facilitate H-bonding to four pyridine units (Fig. 1(h)). It is worthy of note here that in p-t-butylcalix[12]arene as its decapyridine solvate,^[15] two phenolic groups are involved in H-bonding to pyridine only (and two others to pyridine and another phenol), leading to two symmetry-related groups of five

phenolic units forming independent H-bonded arrays described as partly conical, partly pleated loop, so that the whole molecule take the shape of an extended chair-like, slightly twisted ring where the 12 O-atoms are nonetheless not far from coplanar (Fig. 2(a)). This is in contrast to p-t-butylcalix[16]arene, the largest calixarene yet characterised structurally,^[16] as its acetonitrile/dichloromethane solvate, where the phenolic H-bond array is continuous about the macrocycle, which adopts a strongly convoluted, twisted tennis-ball-seam conformation (Fig. 2(b)). (Note also that for p-t-butylcalix[7]arene, crystallisation with pyridine again leads to partial disruption of the phenolic H-bond array (Fig. 2(c)), although indirectly in this case, leading to a pair of 4+1 arrays once more.^[17])

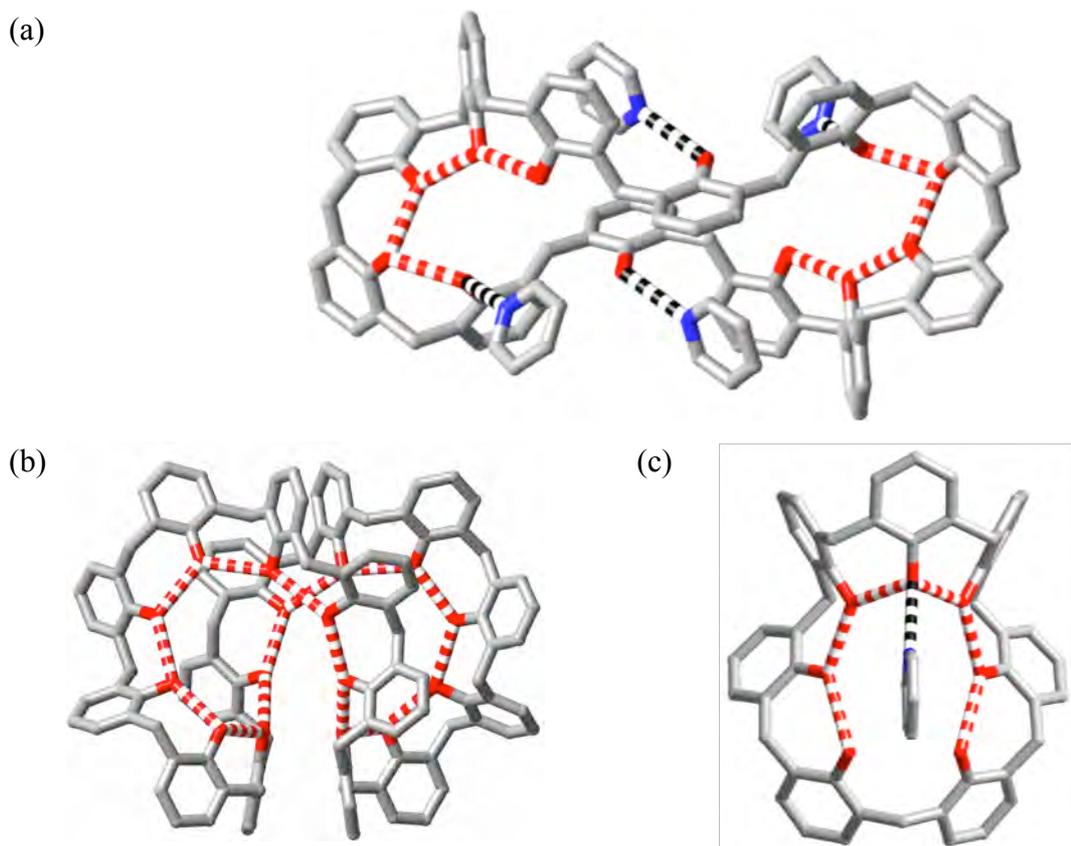


Fig. 2. Phenolic H-bonding arrays in other large calixarenes. (a) Disruption of the phenolic H-bond sequence by pyridine in p-t-butylcalix[12]arene decapyridine solvate.^[15] (b) The continuous phenolic H-bond array in p-t-butylcalix[16]arene dichloromethane/acetonitrile solvate.^[16] (c) Disruption of the phenolic H-bond array by pyridine in p-t-butylcalix[7]arene tris(pyridine) solvate.^[17]

Partial deprotonation of p-t-butylcalix[8]arene can be achieved by the use of a strong base such as hydroxide ion and the structure of the dianion as its tetrabutylammonium salt^[18] shows that this deprotonation reinforces some of the intramolecular H-bonds, resulting in a conformation which can be considered as a rather flattened chair, or "stretched loop", defining a cavity through which one arm of a tetrabutylammonium cation penetrates and is involved in CH...O interactions (Fig. 3). Use of CrystalExplorer^[19] on the ordered, included cation indicates that these interactions occur through phenolic-OH groups and not directly through the phenoxide-O atoms. Where there is direct coordination of a metal ion to the dianion (formed by the use of triethylamine as base),^[8] very little change from the pleated loop conformation is seen when the metal ion is Ca(II) and only a relatively minor change when the metal is Eu(III), indicating that every separate cation type may give rise to subtly different effects. It is also the case that (O₂)U(VI) binding to the octa-anion from p-t-butylcalix[12]arene^[15] results in relatively little change of conformation compared to that of the neutral calixarene as its pyridine solvate but, as implied in the preceding discussion, this solvate conformation could differ significantly from that of the unperturbed molecule.



Fig. 3. Orthogonal views showing the insertion of one tetrabutylammonium cation into the cavity of the dianion of p-t-butylcalix[8]arene.^[18]

Of the present studies, we consider first that of the neutral calixarene, p-t-butylcalix[10]arene. The results of the structure determination executed on crystals of this compound (Fig. 4(a),(b)), obtained from dmsO solution after standing for a number of years and perhaps contingent on the absorption of CO₂ by the initially alkaline solution in this time, are consistent with a model containing an appreciable water molecule content: p-t-butylcalix[10]arene·2dmsO·7H₂O, **1**. The orthorhombic *Fmm2* cell is very similar to that of the same calixarene crystallised as its 1:3 complex with toluene/THF, **4**:^[20] *a* 32.211(6), *b* 32.289(7), *c* 12.172(2) Å, *V* 12667(4) Å³ (*T* 223(2) K) for the latter, *a* 32.0088(6), *b* 32.1639(2), *c* 12.1181(1) Å, *V* 12475.9(2) (*T* 100(2) K) for the present, the two determinations being of similar precision. In the lattice of **1**, the crystallographic 2-axis at the intersection of the two crystallographic mirror planes passes through the centre of the ligand plane and normal to it, only one quarter of the molecule (symmetry *C*_{2v}) being associated with the asymmetric unit of the structure (Fig. 4(c)). From the viewpoint of the mirror planes, the phenolic sequence may be considered as a set of four steeply pitched neighbours to either side of the pair of rings bisected by one of the planes, *or* the same set to either side of the pairs straddling the other plane, i.e. the array may be considered as quadrupolar. While the pleated loop^[4] of calix[8]arene species can be described in terms of a U-D (up-down) alternation of methylene bridges with respect to the mean plane of the oxygen atoms, the conformation of p-t-butylcalix[10]arene in **1** could be termed U-U-D-U-D-U-U-D-U-D (and its inverse) although the phenolic-O atoms do not all lie close to one plane and the macrocyclic ring can be seen as having a near-tennis-ball-seam configuration. Remarkably, given the very different characters of the solvent molecules found in the two crystals, the conformation of p-t-butylcalix[10]arene in **1** is almost identical to that in the THF/toluene solvate **4** (Fig. 4(c)). This could be attributed to the dominant influence of the cyclic H-bonding array involving the phenolic OH groups and this is seemingly the case for **4**, where all O...O separations lie

below 3 Å and interactions of the macrocycle with the associated solvent molecules appear to be due to dispersion forces only. However, the conformation is retained in **1** despite the fact that the phenolic H-bonding array is significantly perturbed by interaction with both dmsO and water molecules, a consequence of this being that four phenolic-O separations (O(1)...O(2)) are >3.2 Å, indicative of a very weak interaction if any beyond dispersion, while six are slightly shorter than those in **4**. That the t-butyl substituents have a significant influence in maintaining the conformation in **1** and **4** is indicated by the rather different conformation found for the acetone solvate of calix[10]arene,^[20] although here the effective division of the phenolic-OH substituents into two groups of five is associated with H-bonding of one phenol in each with an acetone molecule. Description of the full H-bond array in **1** is complicated by partial occupancy of several O-atom sites but the long O(1)...O(2) separation is associated with shorter contacts, O(1)...O(4W), 2.95(1); O(2)...O(4W) 2.77(1) Å, to the fully occupied water-O(4W) site, so that the primary H-bond cycle can be regarded as passing via O(2), O(3) and O(4W), with interactions to O(1) as substituents to this ring (Fig. 4(a)). Relatively short (2.76(1) Å) contacts to O(1) involve the partially occupied dmsO-O sites, in turn involved in contacts to the partially occupied water-O sites.

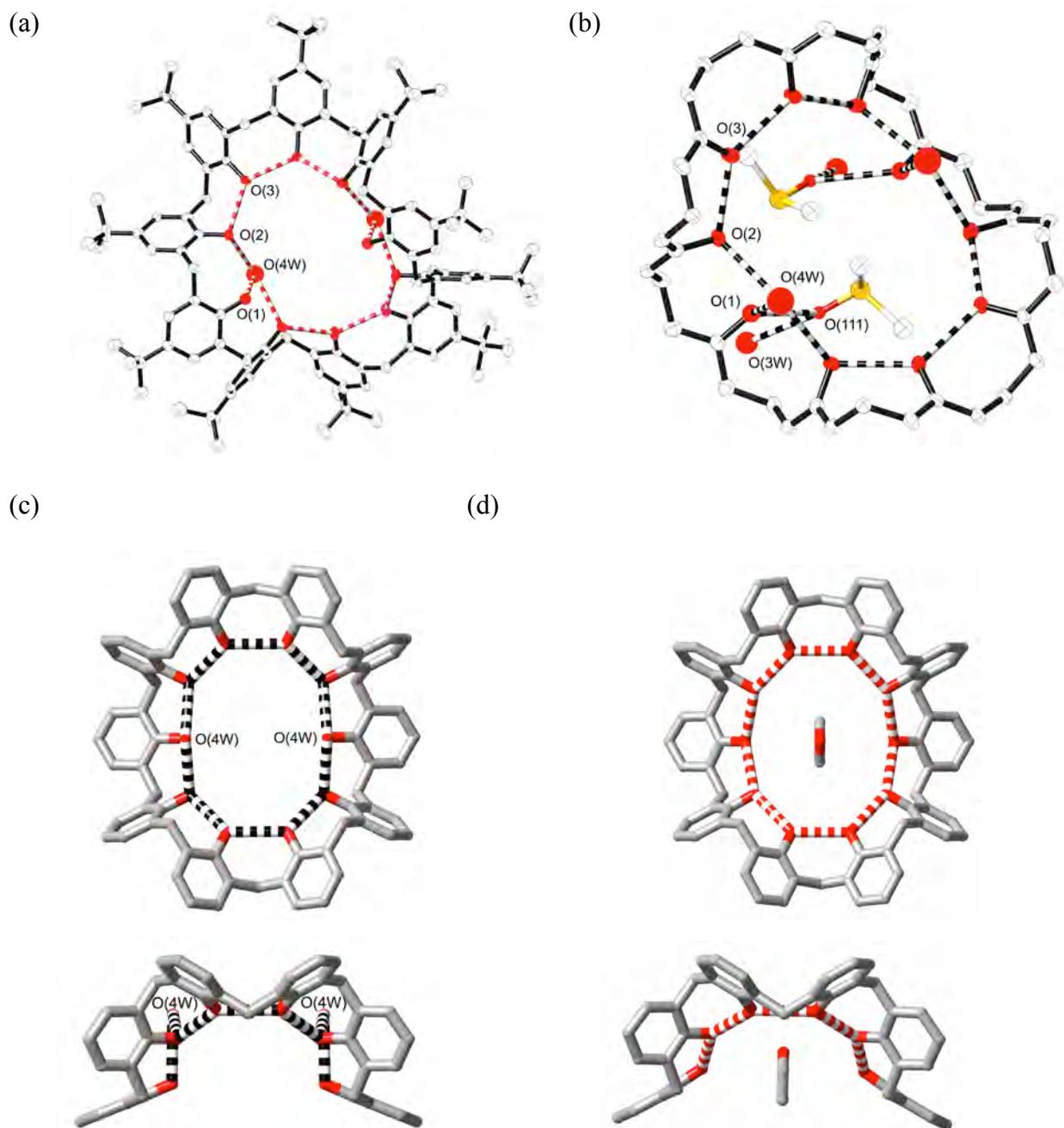


Fig. 4. (a) A perspective view of the macrocyclic molecule as found in the lattice of *p*-*t*-butylcalix[10]arene·2dmsol·7H₂O, **1**, showing the fully occupied water molecule sites associated with disruption of the cyclic phenolic H-bond array but the creation of a new cyclic array. Here, and in following figures, displacement ellipsoids shown are at the 50 % amplitude level. H-atoms are not shown and only one component of the disorder in several of the *t*-butyl groups is shown. (b) Simplified view of one component of the disordered extension of the H-bonding array to dmsol and other water molecules. (Only three carbon atoms of each phenyl ring are shown.) (c,d) Orthogonal, simplified views of the calix[10]arene units in (c) the lattice of *p*-*t*-butylcalix[10]arene·2dmsol·7H₂O and (d) in the lattice of *p*-*t*-butylcalix[10]arene·5THF·1.5C₇H₈.

A single structural study is known for the neutral *p*-*t*-butylcalix[9]arene and this concerns its adduct with *o*-carborane, cyclohexane and water.^[21] The macrocycle adopts a conformation far from planar, tracing out approximately a tennis-ball-seam form with one plane of symmetry but with all adjacent O...O separations ranging between 2.66 and 2.72 Å, consistent with a cyclic H-bond array following this seam (Fig. 5(a)). The shortest contact between phenolic-O and any of the water molecule oxygen atoms is 3.62 Å, indicating at most a very weak perturbation of the cyclic phenolic-OH array. Carborane units can be considered to lie within partial cone structures of the calixarene but there is no indication that this involves interactions with the phenolic groups. All the phenolic groups can be considered directed towards the centroid of the molecule. This is not the case for derivatives of neutral *p*-*t*-butylcalix[9]arene with large groups on the phenolic-O atoms,^[22] presumably in reflection of the steric congestion that these would provoke, and the macrocycle conformations are rather unsymmetrical (Fig. 5(b)). In the known complexes of deprotonated *p*-*t*-butylcalix[9]arene with Eu(III)^[23] and (O₂)U(VI),^[24] the macrocycle conformation is restored to having a vertical plane of symmetry (Fig. 5(c),(d)) and indeed, despite degrees of deprotonation of 3 and 6 with Eu(III) and 5 with (O₂)U(VI), with some similarities to that of the neutral molecule. Plausible putative locations of the residual phenolic protons in all these complexes are consistent with both the metal ions and these protons determining the observed conformations, although only in the case of [Eu₇(*p*-*t*-butylcalix[9]arene-6H)₂(OH)₉(OH₂)₂(dmsO)₆] can this bonding array be considered cyclic. In [Eu₂(*p*-*t*-butylcalix[9]arene-3H)(dmsO)₄], two phenolic groups form an isolated H-bonded pair, with one also being involved in an H-bond to lattice acetone, while in [HNEt₃]₃[(UO₂)₂(CO₃)(*p*-*t*-butylcalix[9]arene-5H)], two phenolic-O atoms appear to be too far apart (3.87 Å) for a significant H-bond bridge to be present, possibly because one is involved in a CH...O interaction with lattice acetonitrile.

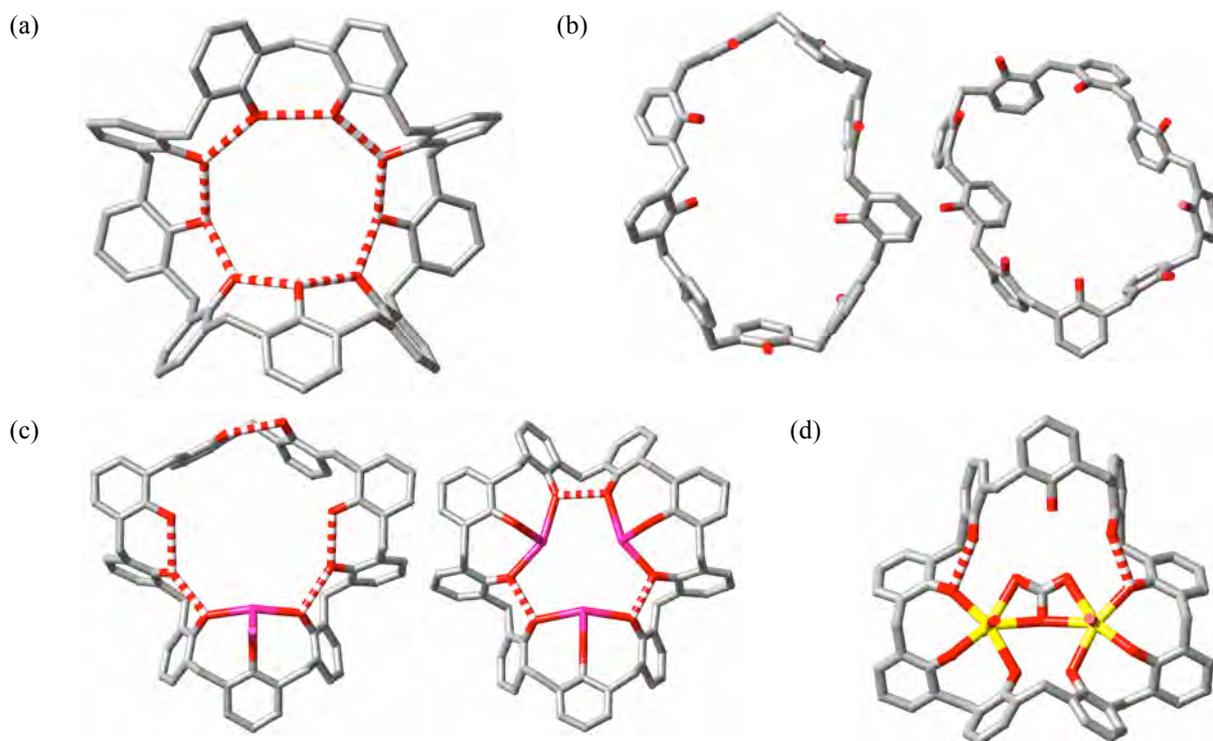


Fig. 5. Macrocyclic conformations and phenolic H-bonding links in p-t-butylcalix[9]arene derivatives in (a) p-t-butylcalix[9]arene.7(*o*-carborane).2C₆H₁₂.5H₂O.^[21] (b) (left) nona(butoxycarbonylmethyl) and (right) nona(ethoxycarbonylmethyl) ethers of p-t-butylcalix[9]arene.^[22] (c) (left) [Eu₂(p-t-butylcalix[9]arene-3H)(dmsO)₄] and (right) [Eu₇(p-t-butylcalix[9]arene-6H)₂(OH)₉(OH₂)₂(dmsO)₆].^[23] (d) [HNEt₃]₃[(UO₂)₂(CO₃)(p-t-butylcalix[9]arene-5H)].^[24]

Clearly, a particular conformation is determined by multiple factors and in the present structure determination of [NMe₄][p-t-butylcalix[9]arene-H]·2dmsO·H₂O, **2**, the effect of inclusion within a cavity formed by the calixarene is demonstrated (Fig. 6(a),(b)). This cavity involves three phenol units and the remaining six form an array with a conformation very close to that formed by six of the units in the neutral molecule. The triphenolic cavity is very similar to that seen in [NMe₄]₂[p-t-butylcalix[6]arene - 2H]^[12] (Fig. 6(c)) as the surroundings of one tetramethylammonium cation but this form of inclusion does not necessarily signify the operation of forces greater than those of dispersion (in particular, here, CH₃-π interactions) between the cavity and the cation. Unfortunately, disorder of three of the four methyl groups of the cation in the present case renders the present CrystalExplorer^[19]

inapplicable as a means of defining the interactions. Note, however, that the one fully occupied methyl group, which corresponds to that inserted furthest into the cavity, does not have coordinates which place it closer to the aromatic ring faces than those of disordered methyl groups and in the present case there is evidence that H-bonding may determine the positioning of the cation. Thus, considering O...O separations $< 3 \text{ \AA}$ to be indicative of proton bridging (H-bonding), it would appear in **2** that the two outer phenolic groups of the three forming the cavity are H-bonded to the central one and are also bridged by a water molecule as well as being bonded separately to dmsol molecules. The water molecule is H-bonded to a third dmsol molecule, while the water-O is 3.30 \AA from the C of the fully occupied cation methyl group, consistent with a CH...O interaction (Fig. 6(b)). If the total structure truly is an H-bonded array, it must be dynamic, since three phenolic groups and a water molecule do not provide enough protons for each link to be fully occupied. The formal negative charge on the calixarene would appear, on the basis of the short (2.43 \AA) O(5)...O(5') separation, to be localised on these O atoms and thus relatively remote from the cation, although the disordered methyl groups of the cation lie close enough to the phenolic-O atoms O(4) and O(4') for CH...O interactions to be significant, thus making them an addition to the phenolic H-bonding array involving O(3), O(4) and O(5) and their equivalents. Note that this situation is again similar to that of $[\text{NMe}_4]_2[\text{p-t-butylcalix[6]arene-2H}]$,^[12] where two of the methyl groups of the included cation which are oriented out of the cavity are also close enough to the phenolic-O atoms not involved in the cavity to be involved in CH...O interactions. In both the p-t-butylcalix[9]arene and p-t-butylcalix[6]arene derivatives, the inverted orientation of the phenolic groups not involved in the cavity can be seen as favouring this form of interaction.

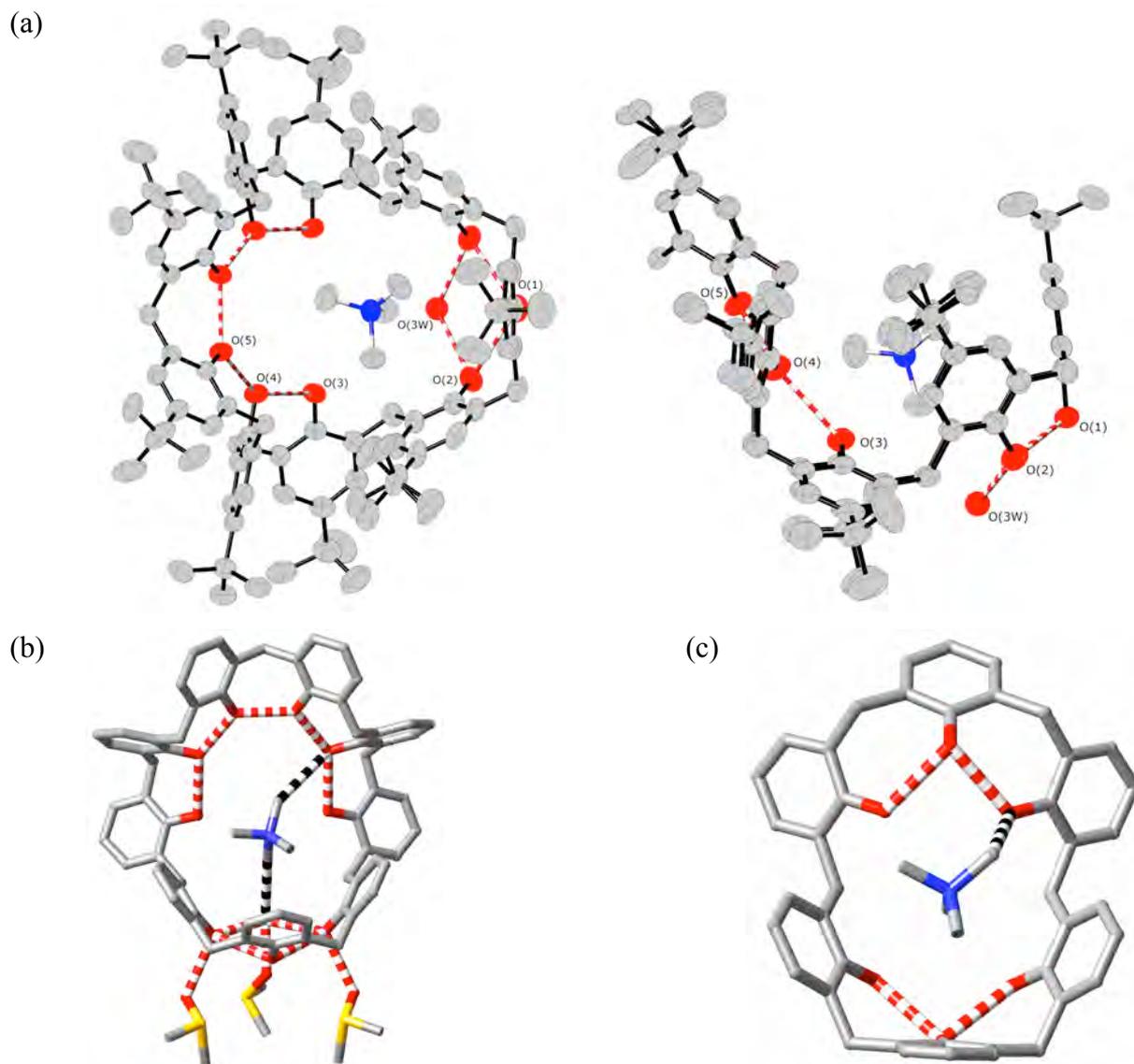


Fig. 6. (a) Orthogonal views of the calixarene anion and its included tetramethylammonium counter cation found in the lattice of $[\text{NMe}_4][\text{p-t-butylcalix[9]arene-H}] \cdot 2\text{dmsol} \cdot \text{H}_2\text{O}$, **2**. Only one component of the disorder in the tetramethyl ammonium ion and the t-butyl groups is shown. (b) A simplified view (stick representation) of the cation:anion pair with a projection of the macrocycle similar to that shown for p-t-butylcalix[9]arene in Fig. 5. Phenolic OH interactions with water and dmsol molecules on partially occupied sites are shown along with possible CH...O interactions of the cation. (c) A view of the included cation:anion pair found within the lattice of $[\text{NMe}_4]_2[\text{p-t-butylcalix[6]arene-2H}]$, again showing only one component of the cation disorder, and with a possible CH...O interaction indicated.

The structure of $[\text{NEt}_4][\text{calix[4]arene-H}]$ (Fig. 7) provides an interesting addition to those of tetra-alkylammonium derivatives of calixarenes in general. The compound is unsolvated, so that the only possibility for CH...O interactions of the cation would involve the phenolic-O atoms but any contacts here are very remote and deemed insignificant. Viewed

down c , it is possible to discern columns in the lattice in which the cation and anion alternate and in which the cations could be considered to be included in the shallow cone of the anion, (Fig. 7(a)) a situation analogous to that of the tetramethylammonium cation in its stoichiometrically more complicated compound with calix[4]arene mono-anion.^[11] Although disorder within the cation precludes analysis of its interactions using CrystalExplorer, in no case is the C(aliphatic)...C(aromatic) separation in the inclusion structure $< 3.5 \text{ \AA}$, whereas there are such contacts ($\sim 3.4 \text{ \AA}$) between the cation and the four proximal calix[4]arene mono-anions which surround it in the lattice (Fig. 7(b)). The simplest interpretation of the nature of the interactions determining the form of the lattice of $[\text{NEt}_4][\text{calix[4]arene-H}]$ is that they are solely dispersion forces, thus making the compound unique within the currently known family of related species. In the two structurally characterised polymorphs of $[\text{HNEt}_3][\text{calix[4]arene-H}]$,^[25] the presence of a proton on the cation clearly renders NH...O H-bonding an important force in the lattice.

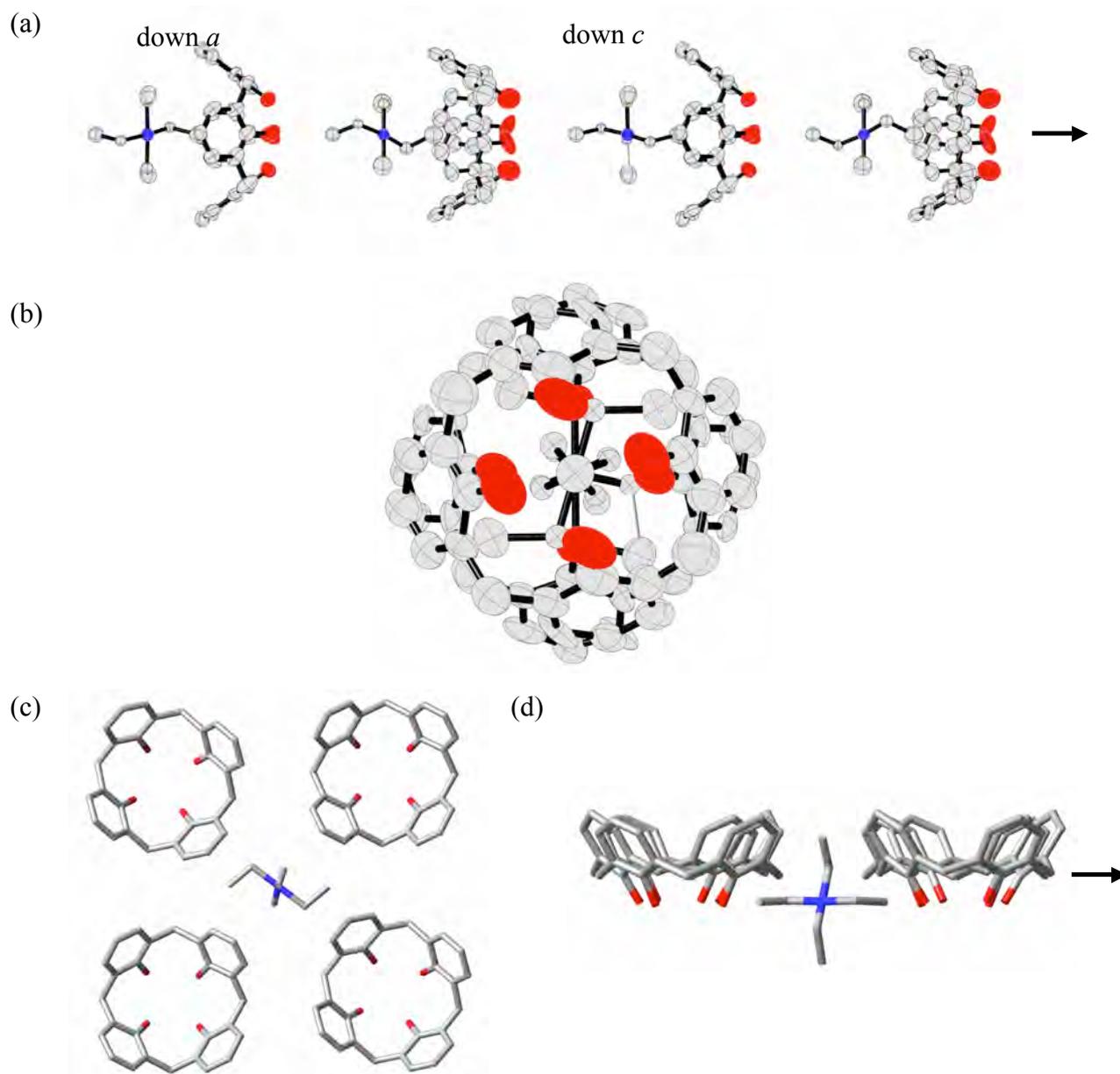


Fig. 7. Cation:anion contacts within the lattice of $[\text{NEt}_4][\text{calix}[4]\text{arene-H}]$, **3**. (a,b) Views of the cation:anion chain running parallel to the c axis in $[\text{NEt}_4][\text{calix}[4]\text{arene-H}]$. Only one component of the cation disorder is shown. (c,d) Orthogonal views of the cation and its four nearest-neighbour $\text{calix}[4]\text{arene}$ units not in the column shown in (a).

Conclusions

While the forces operative within the crystal lattices of calixarenes and their derivatives have been analysed on numerous occasions,^[26] this has usually been with the objective of understanding the inclusion behaviour of the calixarenes and of $\text{calix}[4]\text{arenes}$ in

particular.^[27,28] Thus, classical H-bonding of phenolic units has been recognised as an important factor determining the formation of cavities for inclusion^[1] but phenolic-O interactions with weak H-bond donors such as alkyl groups as discussed in the present article have, perhaps unjustifiably, been paid less attention. At least in some cases, these interactions may be more important determinants of inclusion than interactions of the included molecule with the aromatic walls of the cavity. Further, these phenolic interactions may be modified but not necessarily completely disrupted in the presence of strongly H-bonding species such as pyridine, dmsO and water, leading in some cases to quite extended structures other than the cavity itself being involved in inclusion. For large calixarenes in particular, this defines new prospects for optimisation of selectivity in inclusion.

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