Amine guest size and hydrogen-bonding influence the structures of *p-tert*-butylcalix[4]arene inclusions†

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A novel structure involving a 2(*p-tert*-butylcalix[4]arene)·3.5(1,4-butanediamine) inclusion compound shows amine sites both *exo* and *endo* to the cavity, with the amine hydrogen-bonding to itself as well as to the host hydroxyl groups; for bulky amines with large pK_a values, steric factors are more important than basicity, and the formation of a 1:1, high-symmetry host–guest structure is preferred over a low-symmetry hydrogen-bonded structure.

The upper and lower rims of the *p-tert*-butylcalix[4]arene **1** basket-shaped cavity have been extensively derivatised in order to tailor supramolecular behaviour,[1] and almost all modifications at the lower (OH-bonded) rim have been covalent. We report the modification of the cavity's lower rim *via* H-bonding with amines, giving a non-covalent elaboration of the calixarene in the solid state. A delicate balance between amine size and basicity in forming H-bonded structures is observed. The molecular structure changes upon the induction of dynamics or guest loss for at least one of the amine guests in the 2(*p-tert*-butylcalix[4]arene)·3.5(1,4-butanediamine) compound **2**.

In general, interactions between amines and calixarenes in solution depend on the steric nature of the amine. If not too bulky the amine can abstract a proton from a calixarene hydroxyl group *via* a proton-transfer mechanism, forming an ion pair in which the guest occupies the host cavity in an *endo* arrangement.[2] Bulkier amines appear to interact with the host so that the amine is outside (*exo*) the host cavity.[3] Thermodynamic and conductance measurements of alkylamines and **1** in solution indicate H-bonding or ion-pair interactions between calixarene and amine.[4] A theoretical study of amine salts of the anion of **1** shows the preference for amine *endo* and *exo* positions to be solvent-dependent.[5] Amine interaction with the calix phenolic hydroxyl group forms the basis of sensors that change colour upon molecular recognition.[6]

Structures of several calixarene–amine complexes show that the amine interacts with the calixarene phenol in both *endo* and *exo* positions,[7] and structures of calixarenes with alkyl ammonium cations indicate cation inclusions, but no interactions between the guest and the H-bonded OH groups of the host.[8]

Solid-state ^{13}C NMR spectra of **1**·guest inclusion compounds provide a rapid means to determine symmetry elements.[9] An inclusion compound in which the host molecule has an axis of 4-fold symmetry gives a single resonance for each chemically distinct carbon of the *p-tert*-butylphenol repeat unit.[10] Lowering the symmetry element increases the multiplicity of each carbon resonance, as the four repeat units are no longer equivalent symmetrically. The ^{13}C CP-MAS NMR spectrum of **2** [Fig. 1(a)] indicates that the structure has very few, if any, symmetry elements. In particular, the δ 135–160 region shows the signals from the H1 and H4 aromatic carbons of the host. Whereas a high-symmetry structure gives only two host signals in this region, and three in the aliphatic region (δ 22–48),[9] the present spectrum shows 14 resolved lines over the region δ 135–160 and 11 lines (host and guest) in the aliphatic region. Peaks at 39.8 and 42.2 ppm arise from guest methylene carbons attached to the amine nitrogen, and are broadened due to coupling to the ^{14}N quadrupole or because of dynamic effects. The extent to which the aromatic carbon signals are spread out, the multiplicity, and the signal intensity distribution all contrast to the comparable features seen for nitrobenzene inclusion in the same host.[11] Clearly, the structure of **2** shows low symmetry, and is distinct from other low-symmetry structures such as **1**·nitrobenzene.

The existence of a significantly distorted host cavity is confirmed by the X-ray diffraction structure.‡ The asymmetric unit contains two crystallographically inequivalent host molecules, each without any element of symmetry. Each host molecule has two ordered and two disordered Bu^t groups: the *C*-host has the disordered groups positioned *cis* and the *T*-host has the disordered groups positioned *trans*. Unlike other structures of **1**, there is no clear correlation between the disorder in the host Bu^t groups and the disorder in the guest. The two Bu^t groups in the *C*-host are disordered over two positions each, while those in the *T*-host are disordered over two and four positions. There are 3.5 molecules of 1,4-butanediamine in the asymmetric unit (which contains two host molecules). Each *C*- and *T*-cavity contains one *endo* guest molecule, and that in the *T*-cavity is disordered over two positions. There are two, fully occupied *exo* guest sites outside the host cavities; one is on the inversion centre thus giving the fractional stoichiometry.

The structure possesses two independent groupings of H-bonded guests, one a finite trimer and the other an infinite chain. The trimer involves the *endo* guest of the *C*-host cavity (Fig. 2). This fully ordered guest adopts a curled ⊂-conformation in which the guest is H-bonded to itself ($d_{N–N}$ 2.72 Å), to one hydroxyl group of a *T*-host ($d_{N–O}$ 2.80 Å), and an amine group of the *exo* guest on the inversion centre ($d_{N–N}$ 2.77 Å). The *exo* amine group also interacts weakly with a second hydroxyl group of the same *T*-host ($d_{N–O}$ 3.3 Å); this hydroxyl group is

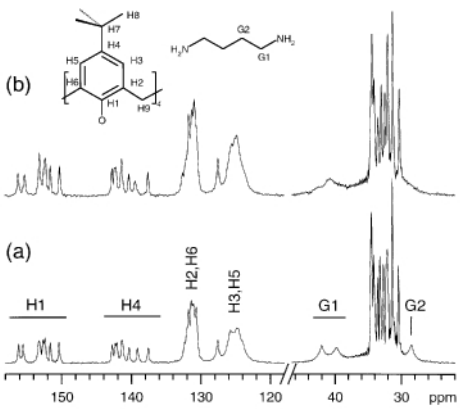

Fig. 1 Partial 75.48 MHz ^{13}C-{^{1}H} CP-MAS spectra: (a) **2**, (b) **2** after stirring in *n*-hexane. The aromatic host carbons are assigned; the aliphatic host carbons (H7, H8, H9) occur in the δ 27–36 region. Experimental details: 5.3 kHz spinning speed, 1600 transients, 3.4 μs 90° pulse, 50 kHz ^{1}H-decoupling field, 3.5 ms contact time, 1.5 s recycle delay, 40 kHz spectral width, 4 K data points collected and zero-filled to 16 K points.

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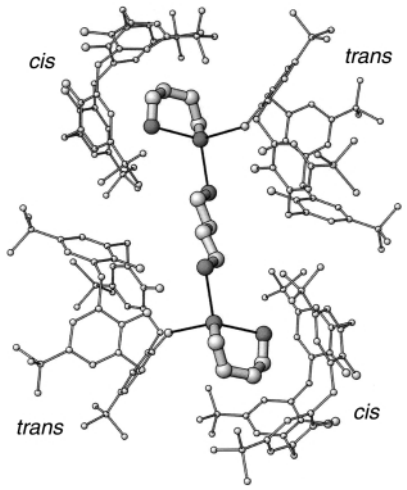

Fig. 2 Geometry of **2** indicating the finite hydrogen-bonding trimer involving the *endo* amine guest in the *C*-host cavity and the *exo* amine on the inversion centre.

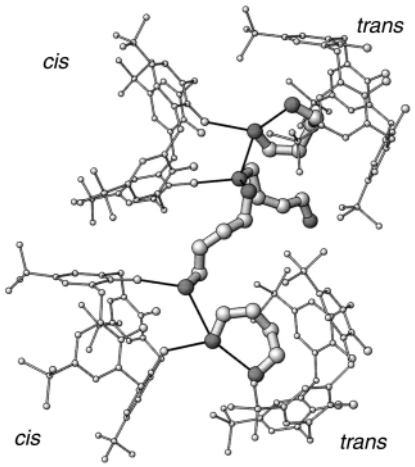

Fig. 3 Geometry of **2** indicating the infinite hydrogen-bonding chain involving the *endo* amine guest in the *T*-host cavity and the *exo* amine in the general position.

located *trans* to the first H-bonded hydroxyl group. The infinite chain involves the *endo* guest of the *T*-host cavity (Fig. 3); this guest is disordered over two positions. It is similarly curled and H-bonds to itself ($d_{N–N}$ 2.77 Å), to one hydroxyl group of a *C*-host ($d_{N–O}$ 3.01 Å), and an amine group of the second *exo* guest ($d_{N–N}$ 2.70 Å). This second *exo* guest further H-bonds with a symmetrically equivalent *exo* guest ($d_{N–N}$ 2.70 Å) and two adjacent hydroxyl groups of the *C*-host ($d_{N–O}$ 2.70 Å, $d_{N–O}$ 2.70 Å).

Hydrogen-bond formation is expected to depend primarily on the acidity of the host hydroxyl group (pK_a = 19.33 in benzonitrile)[4] and the amine basicity. Several amines have been used to form inclusion compounds of **1**, and the solid-state ^{13}C NMR spectra indicate the presence or absence of H-bonded structures.§ While amines with pK_a > 9 appear to favour H-bonded structures, the *sec*- and *tert*-butylamine compounds indicate that the amine basicity does not appear to direct the symmetry of the resultant structures, which show NMR spectra of the high-symmetry 1 : 1 host–guest inclusions.[9] Inclusion and orientation of these two guests in the host cavity are dominated by steric factors. It is intriguing to consider an amine guest in which the basicity and steric factors are so closely balanced that slight changes in conditions (*P*, *T*) cause the structural motifs in the inclusion compound to switch.

Finally, we report preliminary findings on the structural modifications of compound **2** that result from stirring in *n*-hexane.¶ The ^{13}C NMR spectrum in [Fig. 1(b)] shows a single guest amine G1 carbon signal (δ 41.0) whereas in **2**, there were two signals (δ 39.8 and 42.2). This feature indicates that *n*-hexane induces dynamic changes in the guest that may result from exchange of two rigid G1 carbons and/or loss of one of the guests from the lattice. Changes in the aromatic host carbon signals, though subtle, are well enough defined as slight differences in chemical shifts and intensities. Both NMR observations indicate that the structural modifications lie primarily with the guest, and that the affected guest likely occupies an interstitial or *exo* site, due to its longer intermolecular hydrogen bonds relative to the *endo* guests.

Notes and references

‡ *Crystal data* for **2**: $2(C_{44}H_{56}O_4)\cdot3.5(C_4H_{12}N_2)$, M = 1606.38, monoclinic, space group $P2_1/c$, a = 19.8406(12), b = 39.310(2), c = 13.3090(8) Å, β = 108.1070(10)°, V = 9866.2(10) Å^3, T = 173 K, Z = 4, D_c = 1.081 g cm^{-3}, μ(Mo-Kα) = 0.068 mm^{-1}, 85570 reflections measured, 16869 unique (R_{int} = 0.0735), R = 0.0755, R_w = 0.1573 [data $I > 2\sigma(I)$]. Disordered Bu^t groups were refined anisotropically over two (and the *T*-host, four) sites with occupancy ratios ranging from 80 : 20 to 50 : 50. Disordered *endo* 1,4-butanediamine molecules were refined anisotropically over two sites with 50% occupancy. Single crystals of **2** crystallise from 1,4-butanediamine at 70 °C. The structure was solved using direct methods and refined by full-matrix least squares on F^2 using SHELXTL.[12] CCDC 182/1769. See http://www.rsc.org/suppdata/cc/b0/b001274m/ for crystallographic files in .cif format.

§ **1**·amine compounds without host–guest hydrogen bonding: aniline (pK_a = 4.63), pyridine (5.25),[13] *sec*-butylamine (10.56), *tert*-butylamine (10.68); with host–guest hydrogen bonding: ammonia (9.25), benzylamine (9.33), 2-aminoethanol (9.50), 1,4-butanediamine (10.80, 9.35), 1-cyclohexylethylamine. H-bonded structures indicated by low-symmetry ^{13}C CP-MAS NMR spectra; pK_a values taken from CRC Handbook, CRC Press, Inc., Boca Raton, FL, 79th edn., 1998–99, pp. 8–46.

¶ 100 mg of **2** was added to *n*-hexane (3 mL) and stirred overnight at room temperature. Both **1**[4] and **2** have low solubility in *n*-hexane. The ^{13}C NMR spectrum indicates that no **1**·*n*-hexane compound is formed.[9]

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