Extending the chemistry of *p-tert*-butylcalix[4]arene with H-bonding and secondary coordination

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Through hydrogen bonding and secondary coordination, aliphatic amines, together with water and metals, form novel compounds with *p-tert*-butylcalix[4]arene containing complex clusters and layers.

While *p-tert*-butylcalix[4]arene (C4A) has been a favoured synthetic precursor for the synthesis of a wide variety of receptor molecules,[1–3] the parent compound's low solubility in common organic solvents have caused it to be viewed as unsuitable for the design of self-assembled materials with functional applications. As a model compound for investigating the forces guiding self-assembly, however, C4A has been demonstrated to be an extremely versatile host, with a variety of inclusion motifs observed, ranging from self-included and intercalated structures to 1 : 1 and 1 : 2 compounds with motifs dictated largely by guest size.[4–7] A prominent exception to these motifs was first observed in a compound with a diamine as guest: the first example where both directional H-bonding and non-specific interactions were in competition in the formation of an inclusion compound of C4A.[8]

We were intrigued by the possibility of using amines to elaborate the supramolecular chemistry of C4A, as besides being good solvents, the possibilities of using van der Waals forces in conjunction with the H-bonding and coordinating ability of the amine nitrogen gives excellent prospects for new structural motifs as determined by the relative importance of the various competing interactions. The introduction of other non-covalent bonding intermediaries, such as water or metal centres, should allow for fine tuning of the resulting structures. Introducing metal centres into simple calixarenes *via* secondary coordination is particularly attractive, as they may display novel chemical activity by virtue of their isolation.

Our previous studies have demonstrated that C4A recrystallized from n-butylamine (nBA) yields a hydrogen-bonded 3 : 1 amine–calixarene inclusion compound which converts to the more conventional 1 : 1 inclusion compound after heating to 70 °C.[9] Recrystallization of C4A from an aqueous solution of nBA by slow evaporation yields crystals of an inclusion compound (**1**) with a 3 : 1 amine–calixarene packing motif similar to that previously reported, but with the addition of included water molecules that further extend the observed hydrogen bonding network[9]†. The observed stoichiometric ratio of nBA : C4A :water is 3 : 1 : 2.

As seen in our previous study, one of the three crystallographically independent nBA molecules is included within the C4A's bowl-shaped cavity (*endo*), while two are situated outside the cavity (*exo*). The disordered *exo* amines show increased electron density surrounding them, which, in conjunction with a single elongated O···O distance in the C4A molecule, indirectly indicate proton transfer from the C4A to the amine, resulting in an anionic C4A balanced by a cationic amine.

In this case, the terminal carbon of the aliphatic tail of the *endo* amine is directed outwards with the 2′ carbon adjacent to the amino group most deeply inserted (Fig. 1). With this conformation, the *endo* nBA is hindered from hydrogen bonding directly to the *exo* amines. Instead, a water molecule forms a hydrogen-bonded bridge (N···O distances of 2.72, 2.73, 3.15 Å) between the *endo* nBA and each of the two independent *exo* nBA molecules. The water molecule and the two *exo* nBA molecules also form hydrogen bonds with hydroxyl groups of two adjacent C4A molecules. Additional water molecules form H-bonded bridges cross-linking the *exo* nBA molecules of adjacent asymmetric units. The result is a large H-bonded cluster consisting of six nBA and four water molecules all situated within a large cavity bounded by four C4A molecules.

The suggestion of proton transfer in these and previous studies, led us to consider including cationic metal centres into a framework containing anionic C4A molecules. Secondary coordination, or intermolecular interactions with a portion of the primary coordination sphere of a metal complex, has been

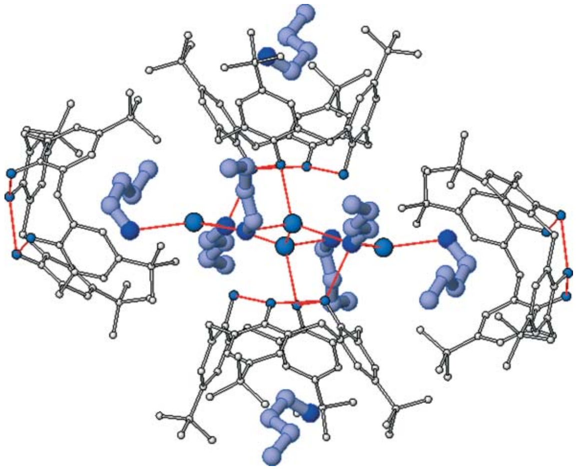

Fig. 1 View along the *a* axis of the packing scheme of nBA in the extended cavity of **1**. nBA guests, water and phenolic hydroxyls are highlighted in blue, and H-bonds indicated in red.

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investigated in a variety of host–guest systems.[10] In particular, studies have focused on well-known macrocyclic systems, ranging from crown ethers,[11–13] to cyclodextrins[14,15] and substituted calixarenes.[16–19] Traditionally, studies of such systems involve relatively small complexes,[20–22] with only a limited selection of studies examining larger, multifunctional primary and secondary ligands, capable of forming extended structures.[23–25] The hydrophobic cavity and phenolic OH groups of C4A provide ideal sites for secondary coordination, thereby further favouring the introduction of metal centres into a calixarene framework through self-assembly.

In one attempt, $ZnCl_2$ was dissolved in a mixture of nBA and water, and the structure of the resulting compound (**2**) determined by single crystal X-ray diffraction.† The C4A molecules are arranged in layers of self-included dimers, while two distinct clusters occupy the space between the C4A layers (Fig. 2). Each of these clusters contains a tetrahedrally co-ordinated Zn centre. One of the clusters consists of a Zn centre surrounded by three nBA molecules plus a Cl^- ion, resulting in an ionic cluster $[Zn(nBA)_3Cl]^+$. The second cluster is highly disordered, consisting for the most part (occupancy of 0.68) of Zn surrounded by four nBA molecules, resulting in $[Zn(nBA)_4]^{+2}$, while in the remainder (occupancy of 0.32) one of the nBA molecules is replaced by a Cl^- ion weakly interacting with a protonated nBA molecule resulting in $[Zn(nBA)_3(Cl^-{\cdot}nBA^+)]^{2+}$. In all of the clusters, one nBA molecule is observed to have adopted a partial *cis* conformation, presumably to accommodate a more energetically favourable packing scheme. In addition to the two cationic clusters, and a deprotonated C4A molecule the asymmetric unit contains additional anions, one Cl^- and one hydroxyl, thus attaining charge balance.

We also investigated the inclusion of metal centres with amines smaller than nBA. Slow evaporation of C4A and $AgNO_3$ from isopropylamine (iPA) yielded large crystals which were also suitable for single crystal X-ray diffraction. The resulting amine/silver-C4A compound (**3**) has an asymmetric unit consisting of two silver cations co-ordinated by three molecules of isopropylamine each, with two C4A molecules, each serving as a host to a single isopropylamine from one cluster.† The observed packing (Fig. 3) is similar to that observed for **1**. The singly-charged silver cations are balanced by the deprotonated C4A molecules. There is no evidence of proton transfer to the amines.

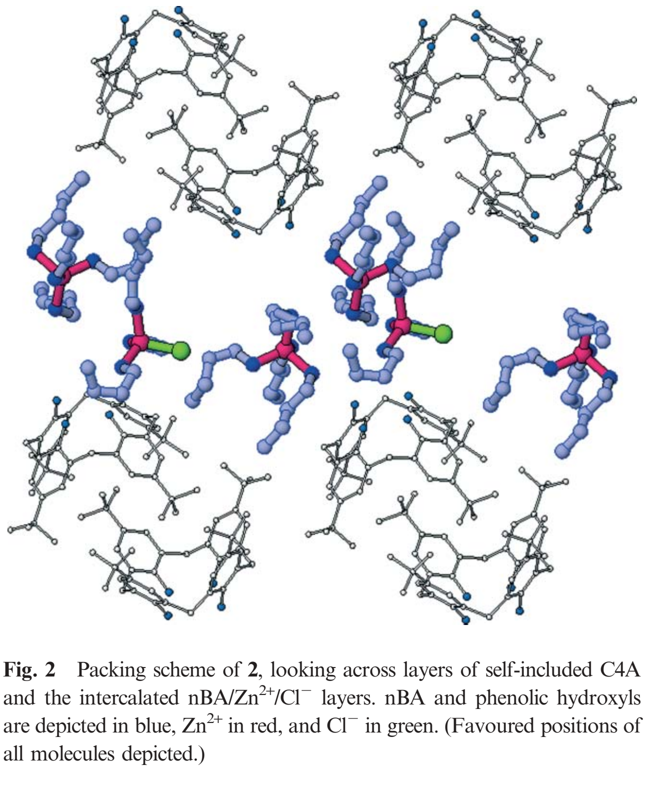

Fig. 2 Packing scheme of **2**, looking across layers of self-included C4A and the intercalated nBA/Zn^{2+}/Cl^- layers. nBA and phenolic hydroxyls are depicted in blue, Zn^{2+} in red, and Cl^- in green. (Favoured positions of all molecules depicted.)

As a result, two contrasting structural motifs, either as amine inclusions in an extended cavity produced by C4A, or layers of amines alternating with layers of self-included C4A, are observed to emerge, depending on the size of the amine, amine–water or amine–metal moieties. In particular, the inclusion motifs of compounds **2** and **3** suggest that the addition of a metal centre results in the formation of coordination compounds whose geometry and size subsequently dictate whether an extended cavity or self-included C4A structure is energetically favourable. This follows from the fact that the coordinate bonds thus formed are more thermodynamically favourable than the simple non-specific forces governing the inclusion of the hydrophobic tail of the amine, or the hydrogen bonds formed with adjacent calixarenes.

Given this, it would still be expected that for compound **3**, the four molecules of iPA not included within a specific C4A cavity in each asymmetric unit would be quite labile. Thermogravimetric analysis of dried crystals of (**3**) showed three regions of guest loss: two relatively broad transitions at 73 °C and 115 °C, and a sharper transition at 250 °C, with the weight percentage lost corresponding to the loss of 2.3, 2.0 and 1.8 molecules of iPA. This indicates that as the first pair of exo amines are stripped away, the silver centres bind the remainder more tightly, such that the *endo* amines are only released just before the C4A sublimes. Given our previous work indicating the importance of temperature on the structural

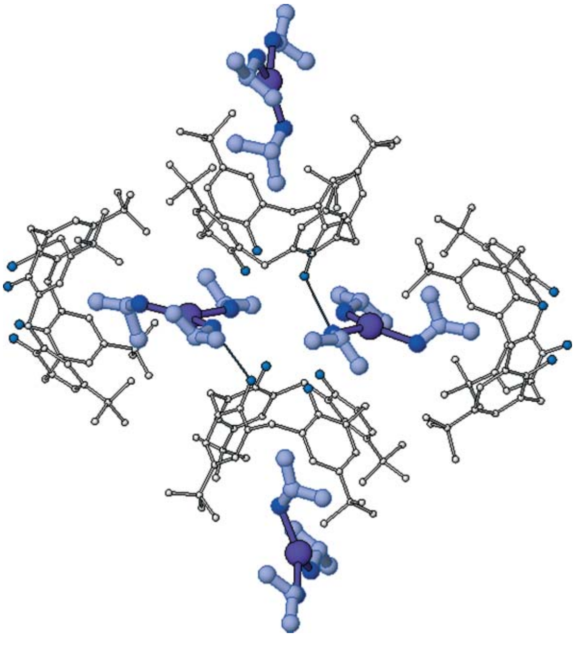

Fig. 3 View of the extended cavity formed by **3** in the *ab* plane. The iPA, Ag^+ and phenolic hydroxyls are depicted in blue.

motif observed for amine inclusion in C4A,[9] the resulting structures of these deaminated materials remain under investigation as a possible route to inclusion of metals in simple calixarenes.

It is evident that aliphatic amines present a novel opportunity to further investigate the versatile host properties of C4A with an eye towards the synthesis of functional materials. With a variety of forces involved in governing the motif observed in all cases, it is apparent that while a capped structure is favoured at room temperature in many cases, such a motif can be easily disrupted by appropriate choice of the amine or metal centre. Further studies should help to further elucidate which forces direct the structural motif observed depending on the conditions of synthesis.

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Notes and references

† *Crystal data*. In all cases, measurements were made on a Bruker SMART diffractometer (Mo–Kα λ = 0.71073 Å; graphite monochromator; T = 173 K) using an area CCD Detector. An empirical absorption correction was applied using the SADABS program. Structures were solved using direct methods and refined using full-matrix least squares on F^2 using SHELXTL, with all hydrogen atoms placed in calculated positions, except for the hydroxyl groups of calix and water molecules, which were found from the difference electron density map.[26,27] Compound **1**, $C_{56}H_{93}N_3O_6$, M = 904.33, monoclinic, space group $P2_1/c$ (No. 14), a = 12.900(1), b = 22.217(2), c = 19.476(2) Å, β = 94.22(4)°, V = 5566.5(7) Å^3, Z = 4, ρ_{calc} = 1.079 mg m^{-3}, μ = 0.069 mm^{-1}, $2\theta_{Max}$ = 28.76°, Final R indices ($I > 2\sigma(I)$): R_1 = 0.063, wR_2 = 0.16 (65845 reflections total, 14453 unique, R_{int} = 0.0602); Compound **2**, $C_{36}H_{66.11}Cl_{1.16}N_{3.5}O_{2.5}Zn$, M = 694.53, triclinic, $P\bar{1}$ (No. 2), a = 12.585(1), b = 16.213(2), c = 20.695(2) Å, α = 77.41(1), β = 86.85(1), γ = 79.32(1)°, V = 4049.5(8) Å^3, Z = 4, ρ_{calc} = 1.139 mg/m^3, μ = 0.716 mm^{-1}, $2\theta_{Max}$ = 28.78°, Final R indices ($I > 2\sigma(I)$): R_1 = 0.074, wR_2 = 0.21(48385 reflections total, 20806 unique, R_{int} = 0.0611); Compound **3**, $C_{120}H_{149.50}Ag_2N_7O_{10}$, M = 2065.71, monoclinic, $P2_1/c$ (No. 14), a = 22.133(2), b = 20.811(2), c = 23.420(2), β = 103.438(2)°, V = 10492(2) Å^3, Z = 4, ρ_{calc} = 1.308 mg m^{-3}, μ = 0.437 mm^{-1}, $2\theta_{Max}$ = 21.15°, Final R indices ($I > 2\sigma(I)$): R_1 = 0.077, wR_2 = 0.19 (63527 reflections total, 34885 unique, R_{int} = 0.0966). CCDC 192202, 192203, and 192204. See http://dx.doi.org/10.1039/b503915k for crystallographic data in CIF or other electronic format.

1 C. D. Gutsche, 'Calixarenes', ed. J. F. Stoddart, Royal Society of Chemistry, Cambridge, UK, 1989.
2 C. D. Gutsche, 'Calixarenes Revisited', ed. J. F. Stoddart, Royal Society for Chemistry, Cambridge, UK, 1998.
3 L. Mandolini and R. Ungaro, 'Calixarenes in Action', Imperial College Press, London, UK, 2000.
4 G. D. Andreetti, R. Ungaro and A. Pochini, *J. Chem. Soc., Chem. Commun.*, 1979, 1005.
5 R. Ungaro, A. Pochini, G. D. Andreetti and P. Domiano, *J. Chem. Soc., Perkin Trans. 2*, 1985, 197.
6 E. B. Brouwer, G. D. Enright and J. A. Ripmeester, *J. Am. Chem. Soc.*, 1997, **119**, 5404.
7 E. B. Brouwer, K. A. Udachin, G. D. Enright, J. A. Ripmeester, K. J. Ooms and P. A. Halchuk, *Chem. Commun.*, 2001, 565.
8 E. B. Brouwer, K. A. Udachin, G. D. Enright, C. I. Ratcliffe and J. A. Ripmeester, *Chem. Commun.*, 2000, 1905.
9 K. A. Udachin, G. D. Enright, P. O. Brown and J. A. Ripmeester, *Chem. Commun.*, 2002, 2162.
10 F. M. Raymo and J. F. Stoddart, *Chem. Ber.*, 1996, **129**, 981.
11 J. E. Kickham and S. J. Loeb, *Inorg. Chem.*, 1994, **33**, 4351.
12 I. Batinic-Haberle, I. Spasojevic and A. L. Crumbliss, *Inorg. Chem.*, 1996, **35**, 2352.
13 S. Kannan, S. S. Raj and H. K. Fun, *Polyhedron*, 2001, **20**, 2145.
14 D. R. Alston, A. M. Z. Slawin, J. F. Stoddart and D. J. Williams, *J. Chem. Soc., Chem. Commun.*, 1985, 1602.
15 L. Caron, H. Bricout, S. Tilloy, A. Ponchel, D. Landy, S. Fourmentin and E. Monflier, *Adv. Synth. Catal.*, 2004, **346**, 1449.
16 Q. L. Guo, W. X. Zhu, S. J. Dong, S. L. Ma and X. Yan, *J. Mol. Struct.*, 2003, **650**, 159.
17 J. L. Atwood, G. W. Orr, F. Hamada, R. L. Vincent, S. G. Bott and K. D. Robinson, *J. Inclusion Phenom. Mol. Recognit. Chem.*, 1992, **14**, 37.
18 B. R. Cameron and S. J. Loeb, *Chem. Commun.*, 1996, 2003.
19 H. R. Webb, M. J. Hardie and C. L. Raston, *Chem.-Eur. J.*, 2001, **7**, 3616.
20 H. M. Colquhoun, J. F. Stoddart, D. J. Williams, J. B. Wolstenholme and R. Zarzycki, *Angew. Chem., Int. Ed. Engl.*, 1981, **20**, 1051.
21 I. Ando, D. Ishimura, K. Ujimoto and H. Kurihara, *Inorg. Chem.*, 1996, **35**, 3504.
22 R. D. Rogers and Y. Song, *J. Coord. Chem.*, 1995, **34**, 149.
23 D. A. Beauchamp and S. J. Loeb, *Chem.-Eur. J.*, 2002, **8**, 5084.
24 S. A. Dalrymple, M. Parvez and G. K. H. Shimizu, *Chem. Commun.*, 2001, 2672.
25 S. A. Dalrymple and G. K. H. Shimizu, *Supramol. Chem.*, 2003, **15**, 591.
26 G. M. Sheldrick, *Acta Crystallogr., Sect. A*, 1990, **46**, 467.
27 G. M. Sheldrick, *Acta Crystallogr., Sect. A*, 1993, **49**, C467.