COMMUNICATION

ChemComm www.rsc.org/chemcomm

Pseudopolymorphism in the *p-tert*-butylcalix[4]arene—n-butylamine system: directing the structural motifs

Konstantin A. Udachin, Gary D. Enright, Philip O. Brown and John A. Ripmeester*

Steacie Institute for Molecular Sciences, National Research Council Canada, Ottawa, ON K1A 0R6, Canada. E-mail: John.Ripmeester@nrc.ca; Fax: +(613) 998-7833; Tel: +(613) 993-2011

Received (in Columbia, MO, USA) 21st March 2002, Accepted 12th August 2002

First published as an Advance Article on the web 27th August 2002

***p-tert*-Butylcalix[4]arene forms three compounds with n-butylamine, two weakly interacting guest–host compounds of 1 : 1 and 1 : 2 stoichiometry, as well as a hydrogen-bonded 3 : 1 compound containing some n-butylamine molecules not coordinated to the host.**

In previous work we have identified several new structural motifs for the simple *p-tert*-butylcalix[4]arene (**1**) compounds[1–3] in addition to those known from early crystallographic studies,[4] and we have shown that **1** also is a remarkably versatile host.[5] Some complexity was indicated in the case of amine guests, as for some amines an interaction of the amino groups with the calixarene hydroxys was inferred from solid-state ^{13}C NMR and this was confirmed by examining the crystal structure.[3] As many other amines gave the standard 1 : 1 guest–host compounds it was clear that there was no simple correlation of structural motif with the pK_a of the base, indicating that other factors must also play important roles in directing the structure.[3] In studies involving modified calixarenes it has also been noted that amines may interact with the calixarene hydroxy in either *endo* or *exo* positions.[6] Since directional H-bonding and non-specific short-range interactions can be expected to compete as the structure-directing mechanisms, it became of some interest to see under which conditions one set of interactions might prevail over the other. In the course of an investigation of compound formation between **1** and n-butylamine, it became apparent that in fact a number of compounds existed in this system, the first example of pseudopolymorphism in simple compounds of **1**.

Crystalline material that resulted upon evaporating **1** from n-butylamine, when subjected to thermogravimetric analysis (TGA), showed two clear regions of guest loss, one at 70 °C, the other at 150 °C. Solid-state ^{13}C NMR spectra showed the complexity that can be associated with the H-bonded structural motif[3] for the as-prepared material. This transformed to the much simpler spectral pattern of the simple guest–host material after heating. Large crystals of the product were easily obtained upon slow evaporation, and diffraction data were collected and solved as outlined. The compound proved to be a 3 : 1 amine–calix[4]arene compound (**2**) with a monoclinic ($P2_1/c$) structure and three molecules of n-butylamine in the asymmetric unit.† One molecule acts as a guest and is deep inside the cavity of calix[4]arene with the amino group pointed outside the cavity (Fig. 1). Two other molecules of n-butylamine are outside the cavity and are connected by hydrogen bonds to the n-butylamine molecule inside the cage forming a ‘T’ shaped fragment of three molecules. (N···N distances are 2.95 3.08 Å). All three n-butylamine molecules are in the all-*trans* conformation and are disordered over two crystallographically independent positions with site occupancies of 0.68–0.32 for the molecule inside the cavity, and 0.80–0.20 for molecules outside the cavity. One of the *tert*-butyl groups of the calixarene molecule is disordered over three positions with site occupancies 0.37, 0.37 and 0.26. Three of four atoms in each calix[4]arene molecule participate in hydrogen bonding with amine molecules, thus forming a fragment of two hydroxy to hydroxy oriented calix molecules with two ‘T’-shaped fragments of three n-butylamine molecules between them (Fig. 1) (O···N distances are 2.85–3.09 Å). Only three fully occupied hydrogen positions were found for the the calixarene hydroxys. Additional electron density was found around one of the amino groups, so, the conclusion can be made that one of the hydroxy protons has been transferred to the amino group.[7]

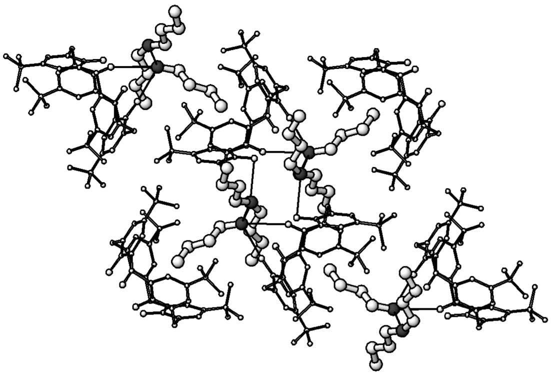

Fig. 1 Structure of *p-tert*-butylcalix[4]arene*3n-butylamine. View along *a* axis. Thin dark lines represent O···N and N···N hydrogen bonds.

As mentioned above, TGA shows that two of the three amine molecules are lost rather easily, and the NMR suggests that the compound formed is the 1 : 1 guest–host material. Therefore an attempt was made to grow crystals at higher temperature. One such attempt involved recrystallizing **1** from n-butylamine at 70 °C and simply constricting the opening of the crystallization vessel so that the solvent would not evaporate too quickly. The attempt was successful, and again crystals suitable for crystallographic analysis resulted.† The structure was indeed found to be the standard 1 : 1 guest–host material (**3**) where there is no interaction between guest and host other than non-specific short-range interactions. In this case the guest lies along the calixarene symmetry axis, and is disordered over four sites, consistent with the symmetry of the host. However, there is a clear indication that the amine functional group is excluded from the cavity, the methyl group being deeply included. This has been seen before for halogenated alkanes, where Cl and Br groups were excluded in favour of methyl or methylene inclusion in the deep cavity.[8]

A second attempt involved the treatment of a suspension of **1** in a dilute solution of n-butylamine in tetradecane in a sealed vial at 70 °C. Again, crystals suitable for crystallographic analysis were obtained,† and, interestingly, this time the product proved to be the 1 : 2 guest–host compound (**4**). Here the guest is encapsulated between two molecules of **1**, a motif observed for longer aliphatic and aromatic hydrocarbon guests as well as substituted hydrocarbon derivatives of similar size. Again, for the 1 : 1 compound, this system displays an ‘aminophobic’ tendency, as the amino groups are not situated as deep in the cavity as the methyl groups (Fig. 2).

From these results it is clear that temperature plays an important role in switching from a H-bonded motif to a weakly interacting guest–host compound. Either the 1 : 1 or the 1 : 2 compounds result at higher temperature, depending on the guest concentration. For linear hydrocarbons the switch from the 1 : 1

DOI: 10.1039/b204313k

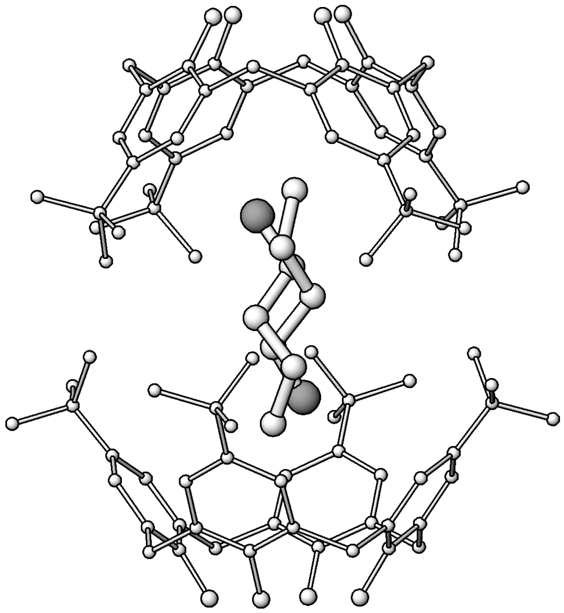

Fig. 2 Structure of *p-tert*-butylcalix[4]arene–*n*-butylamine (2:1 compound). View along *a* axis. Dark balls represent NH_2 groups of n-butylamine. Only two of eight possible positions of the guest molecule are shown.

to 2:1 structural motif occurs on going from n-pentane to n-hexane for materials recrystallized from pure guest solvent at ~70 °C. For n-butylamine at this temperature it appears that guest concentration plays a determining role in directing the structure to one or the other. It remains for us to rationalize the structure obtained at room temperature. Since H-bonding interactions are usually an order of magnitude stronger than the weak short-range interactions prevalent in simple guest–host compounds, it would appear that other factors must make this motif less attractive since one form transforms to the other easily under mild conditions. A clue comes from the complex structure of the H-bonded material. The presence of a strong directional interaction, with the transfer of a proton from one of the calixarene hydroxys to the amine, destroys the high symmetry of the host molecule, clearly causing packing problems so that extra solvent molecules are required to give a more efficiently packed structure. Of course, proper thermodynamic measurements would allow the usual arguments to be made as to how the structures are directed by enthalpic *versus* entropic factors. We may expect there to be an enthalpy gain and an entropy loss for the H-bonded structure with respect to the weakly interacting guest–host materials.

POB and JAR thank NSERC for partial support of this work.

Notes and references

† *Crystal data*: Bruker SMART CCD, T = 173K, $\lambda = 0.71070$ Å, refinement –full matrix on F^2. For **2**: $C_{56}H_{89}$ N_3O_4, M = 868.30, space group $P2_1/c$, a = 12.940(1), b = 20.092(1), c = 20.752(1) Å, β = 91.12(1)°, V = 5394.6(4), Z = 4, D_c = 1.069, theta range 1.41–28.75°, reflections collected/unique 63839/13993, data/restraints/parameters-13993/72/735, GOF −0.948, final $R[I > 2\sigma]$ $R1$ = 0.059, $wR2$ = 0.17, residual density −0.38 and 0.42 Å^{-3}. For **3**: $C_{48}H_{67}NO_4$, M = 722.03, space group $P4/n$, a = 12.982(1), b = 12.982(1), c = 12.646(1) Å, V = 2131.1(1) Å^3, Z = 2, D_c = 1.125, theta range −1.61–28.69°, reflections collected/unique 24412/2722, data/restraints/parameters 2722/9/205, GOF 1.064, final $R[I > 2\sigma]$ $R1$ = 0.048, $wR2$ = 0.13, residual density −0.16 to 0.50. For **4**: $C_{92}H_{123}NO_8$, M = 1370.91, space group $P4/nnc$, a = 12.884(1), b = 12.884(1), c = 25.102(2) Å, V = 4166.7(4) Å^3, Z = 2, D_c = 1.093, theta range −2.76–28.73°, reflections collected/unique 45158/2700, data/restraints/parameters 2700/39/154, GOF −1.046, Final $R[I > 2\sigma]$ $R1$ = 0.051, $wR2$ = 0.15, residual density, −0.24 to 0.36. CCDC 181105 (for **2**), CCDC 181107 (for **3**), and CCDC 181106 (for **4**). See http://www.rsc.org/suppdata/b2/b204313k/ for crystallographic files in .cif or other electronic format.

1 E. B. Brouwer, G. D. Enright and J. A. Ripmeester, *J. Am. Chem. Soc.*, 1997, **119**, 5404–12.

2 E. B. Brouwer, K. A. Udachin, G. D. Enright, J. A. Ripmeester, K. J . Ooms and P. A. Halchuck, *Chem. Commun.*, 2001, 565–6.

3 E. B. Brouwer, K. A. Udachin, G. D. Enright, C. I. Ratcliffe and J. A. Ripmeester, *Chem. Commun.*, 2000, 1905–6.

4 G. D. Andreetti, R. Ungaro and A. Pochini, *J. Chem. Soc., Chem. Commun.*, 1979, 1005; R. Ungaro, A. Pochini, G. D. Andreetti and P. Domiano, *J. Chem. Soc., Perkin Trans. 2*, 1985, 197–201.

5 E. B. Brouwer, J. A. Ripmeester and G. D. Enright, *J. Inclusion Phenom. Mol. Recognit. Chem.*, 1996, **24**, 1–17; E. B. Brouwer and J. A. Ripmeester, *Adv. Supramol. Chem.*, 1999, **5**, 122–151; K. A. Udachin, , E. B. Brouwer, , G. D. Enright, , C. I. Ratcliffe and and J. A. Ripmeesterin *Calix 2001*, ed. Z. Asfari, V. Bohmer, J. Harrowfield and J. Vicens, Kluwer, Dordrecht 2001, pp. 296–311.

6 G. D. Andreetti, F. Ugozolli, Y. Nakamoto and S.-I Ishida, *J. Inclusion Phenom. Mol. Recognit. Chem.*, 1991, **10**, 241; M. Czugler, S. Tisza and G. Speier, *J. Inclusion Phenom. Mol. Recognit. Chem.*, 1991, **11**, 323; C. Bavoux and M. Perrin, *J. Inclusion Phenom. Mol. Recognit. Chem.*, 1992, **14**, 247.

7 Some other examples of anionic calixarenes: J. M. Harrowfield, M. I. Ogden, W. R. Richmond, B. W. Skelton and A. H. White, *J. Chem. Soc., Perkin. Trans. 2*, 1993, 2183; J. M Harrowfield, W. R. Richmond, A. N. Sobolev and A. H. White, *J. Chem. Soc., Perkin Trans. 2*, 1994, 5.

8 E. B. Brouwer, K. A. Udachin, G. D. Enright, C. I. Ratcliffe and J. A. Ripmeester, *Chem Commun.*, 1998, 587.