Lanthanide-induced helical arrays of [{Co(III) sepulchrate} ∩ {p-sulfonatocalix[4]arene}] supermolecules†

**Christopher B. Smith,*[a] Leonard J. Barbour,[b] Mohamed Makha,*[a] Colin L. Raston*[a] and Alexandre N. Sobolev[a]**

In the presence of lanthanide ions, a Co(III) sepulchrate cation [Co(diHOsar)]$^{3+}$ and sodium p-sulfonatocalix[4]arene form a 1 : 1 host–guest complex which is self-assembled into a zeolite-like lattice network comprised of parallel, single stranded helices.

Water soluble sulfonated calix[*n*]arenes (*n* = 4–8) are attracting considerable attention as host molecules for binding organic[1] and inorganic species.[2] The molecular recognition properties of these amphiphiles are of interest in nanochemistry where they have potential applications in building up new synthetic materials,[3] and in medicinal applications which include drug delivery, and sensing.[4] *p*-Sulfonatocalix[4]arene, **1**, has been the most widely studied of these receptors, mainly due to its ability to retain a cone conformation in both solution and the solid state and its ease of synthesis. The hydrophobic nature of its cavity encourages the formation of host–guest or inclusion complexes, with early examples being for small, simple organic molecules,[1] and more recently, biologically relevant molecules such as amino acids.[5]

Calixarene **1** often crystallises in an up–down 'bi-layer' arrangement, in which the host molecules interact through phenyl π-interactions to form clay-like structures.[1,6] However, many recent reports have detailed the formation of 'Russian doll' inclusion complexes in which a guest molecule, mainly a crown ether or aza macrocycle, is sandwiched between two calixarenes.[6,7] These complexes are mainly formed at low pH (< 4) in the presence of lanthanide(III) ions, which act to close the molecular capsules by coordinating with the sulfonate groups. At pH > 4, deprotonation of one of the lower-rim phenolic units of **1** occurs, which can result in the tethering of the molecular capsules through additional metal-ion or guest coordination external to the binding cavity of the host. This has resulted in the formation of remarkably dramatic nanometre scale superstructures, in particular two 'giant spheroidal' arrays from inclusion of [18-crown-6],[8] or pyridine *N*-oxide[9] within the cavity of **1** in the presence of aquated lanthanide(III) ions. With pyridine *N*-oxide, a helical tubular array based on binary 1 : 1 inclusion complex motifs also results when the ratios of the starting components are varied.[9]

[a]*School of Biomedical, Biomolecular and Chemical Sciences, University of Western Australia, Crawley, W.A. 6009, Australia.*
E-mail: cbsmith@cyllene.uwa.edu.au; Fax: +61 86488 1005;
Tel: +61 86488 4422
[b]*Department of Chemistry, University of Stellenbosch, 7602, Matieland, South Africa*

Changing the included molecule from planar pyridine *N*-oxide to torus shaped [18-crown-6] results in a dramatically different spheroidal array of twelve calixarenes either in the form of an icosahedron or a cuboctahedron.[8] The encapsulation of globular-like macrobicyclic compounds such as [2,2,2]cryptand in the presence of a large excess of lanthanide metal cations results in a 2-D bi-layer coordination polymer.[7] Herein we report our findings on the inclusion of a polar globular-like Co(III) sepulchrate complex [Co(diHOsar)]$^{3+}$, **2**,[10] in the cavity of *p*-sulfonatocalix[4]-arene to ascertain whether the sepulchrate is an effective internal core unit for the formation of giant spheroidal, or tubular arrays. The latter is indeed the case, at least in the presence of Ln^{3+} ions. We also noted that the presence of two terminal hydroxyl groups on each end of the sepulchrate complex is likely to aid the formation of host–guest molecules *via* hydrogen bonds with the sulfonate groups of the calixarene.
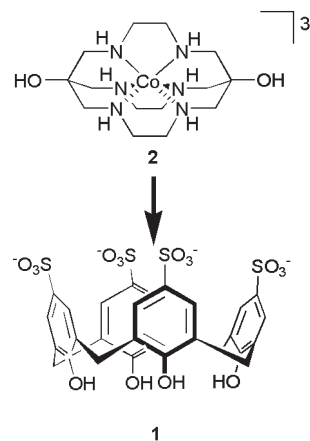
Under conditions analogous to those used for the formation of the *p*-sulfonatocalix[4]arene : [18-crown-6] spheroidal cuboctahe-dron,[8] the reaction of a 1 : 3 ratio of host **1** as its sodium salt to guest **2** in aqueous solution (pH = 4–5) in the presence of excess Pr(O$_3$SCF$_3$)$_3$ afforded orange crystals which were characterised using single crystal X-ray diffraction methods,‡ and shown to be a hydrated complex, **I**, based on the supermolecule [{Co(diHOsar)} ∩ {p-sulfonatocalix[4]arene}], Fig. 1. Praseodymium ions are included within the structure, and although they have a low distribution level (0.17 per asymmetric unit) their presence in solution is essential in controlling the assembly process leading to **I**. This unusual templating phenomenon involving lanthanide ions has been noted for the interplay of the same calixarene with the tetraphenylphosphonium cation.[3] The discrepancy in charge
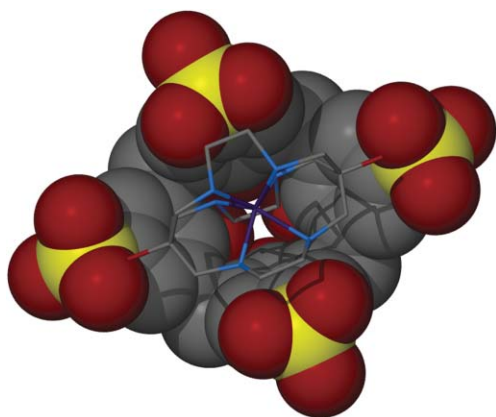
Fig. 1 Structure of the binary inclusion complex [{Co(diHOsar)} ∩ {*p*-sulfonatocalix[4]arene}] in **I**; only one enantiomer of the sepulchrate is shown for clarity with the Co(III) centre shown in purple and N atoms in blue.

balance may be addressed through possible protonation of the sulfonate groups or through the presence of oxonium ions, as reported in other *p*-sulfonatocalixarene supramolecular arrays.[6,7]

The supermolecule in **I** has the guest 'perched' with respect to the cavity of the calixarene which adopts a 'pinched cone' conformation. The cavity is too small to enable complete guest lateral encapsulation of **2** which is orientated with an ethylene group directed into the cavity. In addition, the hydroxyl groups at each end of the guest molecule point directly towards two opposite sulfonate groups of the calixarene, held by hydrogen bonding with O···O contacts of 2.76 and 2.95 Å respectively. The cation **2** is disordered corresponding to a 50 : 50 ratio of each enantiomer (Δ or Λ). Each calixarene interacts through phenyl ring π stacking to three neighbouring calixarenes, with two of these having centroid….centroid distances of 3.60 Å, and one longer contact at 3.87 Å. The other phenyl ring is slightly disordered over two positions and does not show π-stacking interactions to other neighbouring calixarenes.

The supermolecules pack together in the crystal lattice to form infinite single stranded regular helical chains, which run along the *c* axis, Fig. 2. Each helix completes a full turn every 41.51 Å, which corresponds to the *c* dimension of the unit cell (*cf.* 34 Å in B-DNA).[11] The interplay between helices in **I** is governed by calixarene…calixarene π-stacking interactions (centroid…centroid distance 3.60 Å), such that a parallel network of helices is obtained throughout the crystal lattice, Fig. 3. No hydrogen bonding interactions between adjacent guest molecules are evident (O…O distance 3.55 Å). Both helical enantiomers (*P* and *M*) are present within the structure and are arranged such that adjacent helical pairs are of opposite chirality, with the overall structure being
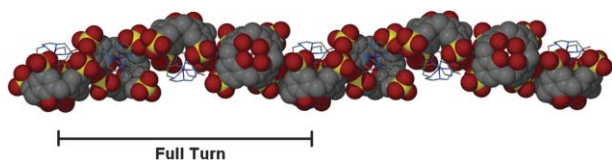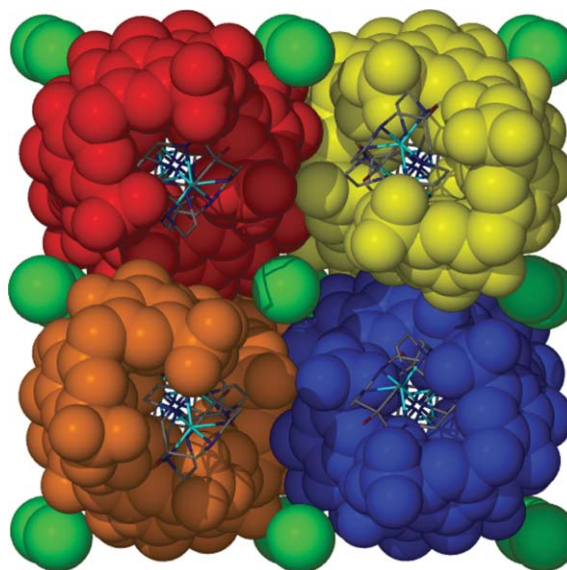

Fig. 3 The packing of adjacent helices in **I** viewed down the *c* axis; Pr^{3+} and associated disordered water molecules are shown in green and occupy the channels. Adjacent helices (*e.g.* red and yellow, brown and blue) have opposite chirality.

achiral. The crystal lattice contains loosely-defined channel regions at the centre of each group of four helical chains and running parallel to the helical axes. The diameter of these varies along their length (minimum 4.80 Å, maximum ∼ 10 Å), which corresponds to the convergence, and divergence of the four helical strands from each other. At the widest point there is considerable distance between two adjacent helical strands (∼ 6.5 Å), resulting in the formation of channels down the *a* and *b* axes within the structure, Fig. 4. Water molecules and aquated Pr^{3+} ions, each of which occupy two crystallographic positions, reside within the channel regions. These channels are not heavily filled and considerable voids are present within the molecular solid, creating a 3D network of interconnected cavities reminiscent of that present in zeolitic structures.[12]

It is interesting to contrast the structure of **I** with the aforementioned example resulting from pyridine *N*-oxide inclusion within *p*-sulfonatocalix[4]arene.[9] In this case there is a regular, single stranded helical tube with a significantly larger hydrophilic channel (diameter ∼ 15 Å), arising from extensive coordination of the lower rim of the calixarene to a network of aquated Ln^{3+} and Na^+ ions. The structure of **I** differs by having a less well-defined, smaller channel for which the surface is defined by four chiral, helical strands.

The supramolecular array in **I** can also be formed under different conditions and with different lanthanides. At a host–guest
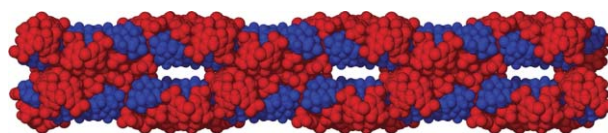

Fig. 2 A view of one helical strand in **I** (viewed down the *a* direction) highlighting one turn of the helix.

Fig. 4 A representation of two helices (viewed down the *a* direction); guests are shown in blue and calixarenes in red. The open spaces where the helices diverge are occupied by Pr^{3+} ions and water molecules.

ratio of 2 : 1 and lower pH (= 1), and in the presence of aquated Yb^{3+}, the components self-assemble to give complex $\mathbf{I}$.[13]

The structure above contrasts with that obtained in the absence of Ln^{3+} ions. Prismatic orange crystals resulted from exposure of host $\mathbf{1}$ as its sodium salt to guest $\mathbf{2}$ at pH = 1 in aqueous solution. A preliminary X-ray structure of this material shows that it is composed entirely of the binary supermolecules as in $\mathbf{I}$. Although the structure presents some disorder, the helical orientation of host–guest complexes which features in $\mathbf{I}$ is absent.

The structure $\mathbf{I}$ appears to be an unprecedented hybrid of both the tubular and spherical motifs reported by Atwood and co-workers.[9] Calixarene....calixarene interactions are sufficient for helix formation to occur, but size mismatching of the guest with the calixarene through lateral inclusion is believed to be the critical factor inhibiting capsule, and therefore, spheroidal array formation in this case, and we are in the process of extending these studies to sepulchrate complexes that lack polar functionalities on their end caps.

Notes and references

1 S. Shinkai, K. Araki, T. Matsuda, N. Nishiyama, H. Ikeda, I. Takasu and M. Iwamoto, *J. Am. Chem. Soc.*, 1990, **112**, 9053; S. G. Bott, A. W. Coleman and J. L. Atwood, *J. Am. Chem. Soc.*, 1988, **110**, 610; J. W. Steed, C. P. Johnson, C. L. Barnes, R. K. Juneja, J. L. Atwood, S. Reilly, R. L. Hollis, P. H. Smith and D. L. Clark, *J. Am. Chem. Soc.*, 1995, **117**, 11426; S. Shinkai, S. Mori, H. Koreishi, T. Tsubaki and O. Manabe, *J. Am. Chem. Soc.*, 1986, **108**, 2409; P. C. Leverd, P. Berthault, M. Lance and M. Nierlich, *Eur. J. Org. Chem.*, 2000, 133; R. Zadmard, M. Junkers, T. Schrader, T. Grawe and A. Kraft, *J. Org. Chem.*, 2003, **68**, 6511; J.-M. Lehn, R. Meric, J.-P. Vigneron, M. Cesario, J. Guilhem, C. Pascard, Z. Asfari and J. Vicens, *Supramol. Chem.*, 1995, **5**, 97; S. J. Dalgarno, M. J. Hardie and C. L. Raston, *Chem. Commun.*, 2004, 2802; J. L. Atwood, S. J. Dalgarno, M. J. Hardie and C. L. Raston, *Chem. Commun.*, 2005, 337.

2 J. L. Atwood, G. W. Orr, F. Hamada, R. L. Vincent, S. G. Bott and K. D. Robinson, *J. Am. Chem. Soc.*, 1991, **113**, 2760; J. L. Atwood, G. W. Orr, N. C. Means, F. Hamada, H. Zhang, S. G. Bott and K. D. Robinson, *Inorg. Chem.*, 1992, **31**, 603; R. Fiammengo, P. Timmermann, F. de Jong and D. N. Reinhoudt, *Chem. Commun.*, 2000, 2313; A. R. Mustafina, V. V. Skripacheva, A. T. Gubaidullin, S. K. Latipov, A. V. Toropchina, V. V. Yanilkin, S. E. Solovieva, I. S. Antipin and A. I. Konovalov, *Inorg. Chem.*, 2005, **44**, 4017; S. J. Dalgarno, M. J. Hardie, J. L. Atwood and C. L. Raston, *Inorg. Chem.*, 2004, **43**, 6351.

3 M. Makha, C. L. Raston, A. N. Sobolev and A. H. White, *Chem. Commun.*, 2004, 1066; P. J. Nichols, C. L. Raston and J. W. Steed, *Chem. Commun.*, 2001, 1062.

4 T. Jin, F. Fujii, H. Sakata, M. Tamura and M. Kinjo, *Chem. Commun.*, 2005, 4300; M. Makha, I. R. McKinnon and C. L. Raston, *J. Chem. Soc., Perkin Trans. 2*, 2002, 1801; A. W. Coleman, A. N. Lazar and E. Da Silva, *J. Drug Delivery Sci. Technol.*, 2004, **14**, 3; J. L. Atwood, R. J. Bridges, R. K. Juneja, K. Ravindra and A. K. Singh, *US Patent 748764*, 1996; K. M. Hwang, Y. M. Qi, S. Y. Liu, W. Choy and J. Chen, *US Patent 5409959*, 1995.

5 M. Selkti, A. W. Coleman, I. Nicolis, N. Douteau-Guével, F. Villain, A. Tomas and C. de Rango, *Chem. Commun.*, 2000, 161; P. J. Nichols and C. L. Raston, *Dalton Trans.*, 2003, 2923; A. Lazar, E. Da Silva, A. Navaza, C. Barbey and A. W. Coleman, *Chem. Commun.*, 2004, 2162; E. Da Silva and A. W. Coleman, *Tetrahedron*, 2003, **59**, 7357.

6 M. J. Hardie and C. L. Raston, *J. Chem. Soc., Dalton Trans.*, 2000, 2483; J. L. Atwood, L. J. Barbour, M. J. Hardie and C. L. Raston, *Coord. Chem. Rev.*, 2001, **222**, 3; S. J. Dalgarno, M. J. Hardie and C. L. Raston, *Cryst. Growth Des.*, 2004, **4**, 227; S. J. Dalgarno and C. L. Raston, *Dalton Trans.*, 2003, 287; J. L. Atwood, L. J. Barbour, S. Dalgarno, C. L. Raston and H. R. Webb, *J. Chem. Soc., Dalton Trans.*, 2002, 4351; S. J. Dalgarno, M. J. Hardie, J. E. Warren and C. L. Raston, *Dalton Trans.*, 2004, 2413.

7 S. J. Dalgarno and C. L. Raston, *Chem. Commun.*, 2002, 2216.

8 J. L. Atwood, L. J. Barbour, S. J. Dalgarno, M. J. Hardie, C. L. Raston and H. R. Webb, *J. Am. Chem. Soc.*, 2004, **126**, 13170.

9 G. W. Orr, L. J. Barbour and J. L. Atwood, *Science*, 1999, **285**, 1049.

10 R. J. Geue, T. W. Hambley, J. M. Harrowfield, A. M. Sargeson and M. R. Snow, *J. Am. Chem. Soc.*, 1984, **106**, 5478.

11 J. D. Watson and F. H. C. Crick, *Nature*, 1953, **171**, 737; R. Wing, H. Drew, T. Takano, C. Broka, S. Tanaka, K. Itakura and R. E. Dickinson, *Nature*, 1980, **287**, 755.

12 For example, see: R. Garcia-Zarracino and H. Höpfl, *J. Am. Chem. Soc.*, 2005, **127**, 3120; O. M. Yaghi, G. Li and H. Li, *Nature*, 1995, **378**, 703; H. Li, M. Eddaoudi, M. O'Keeffe and O. M. Yaghi, *Nature*, 1999, **402**, 276; S. S.-Y. Chui, S. M.-F. Lo, J. P. H. Charmant, A. G. Orpen and I. D. Williams, *Science*, 1999, **283**, 1148; J. Lu, A. Mondal, B. Moulton and M. J. Zaworotko, *Angew. Chem., Int. Ed.*, 2001, **40**, 2113; M. J. Zaworotko, *Nature*, 1997, **386**, 220; S. R. Batten and R. Robson, *Angew. Chem., Int. Ed.*, 1998, **37**, 1460.

13 C. B. Smith, M. Makha, C. L. Raston and A. N. Sobolev, unpublished results.

14 G. M. Sheldrick, *SHELX-97: Structure solution and refinement programs*, University of Göttingen, 1997.

15 L. J. Barbour, *J. Supramol. Chem.*, 2001, **1**, 189; J. L. Atwood and L. J. Barbour, *Cryst. Growth Des.*, 2003, **3**, 3.

16 http://www.povray.org.