

Helical aquatubes of calix[4]arene di-methoxycarboxylic acid

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Two trimeric units of calix[4]arene di-methoxycarboxylic acid form a six-pointed star architecture that, in turn, generates triple helical aquatubes which intermesh between themselves by aromatic–aromatic interdigitation of the macrocycle.

The facility of selective chemical modification of calixarenes¹ has led to a panoply of molecules readily available for solid-state studies.^{2,3} The structural diversity of certain calixarene derivatives functionalised at the upper rim, such as *para*-sulfonatocalix[4]-arene, is truly remarkable, ranging from the classical organic clay bilayer systems,⁴ through interpenetrated bilayers in the complex with lysine⁵ and complex arrangements with arginine,⁶ to capsules,⁷ spheres⁸ and other geometrical solids.⁹ Other calixarene derivatives, carrying one or more pendant acidic arms on the lower rim, give rise to architectures such as inclusion polymers¹⁰ or nanotubes.¹¹ More constant in self-organisation is the calix[4]arene dihydroxyphosphonic acid characterized by the dimeric motif omnipresent in all solid-state structures reported up to now. This dimeric unit¹² is the building brick of the highly divergent topologies developed in the systems of calix[4]arene dihydroxyphosphonic acid with aliphatic or heterocyclic amines: aquachannels in the complex with propandiamine,¹³ cages in the case of phenanthroline¹⁴ or 1-D ladder structures as in the complex with pyridinium ligands.¹⁵ Such dimeric motifs are also present in the structures of dicyanomethoxy calix[4]arene¹⁶ or dipropylether calix[4]arene.¹⁷

In this paper, we have turned our attention to a calix[4]arene di-methoxycarboxylic acid (**1**). Here, in turn, a totally novel helical tube structure having interdigitated gear faces is observed.

Calix[4]arene di-methoxycarboxylic acid **1**, Fig. 1, is synthesised by treatment of calix[4]arene with ethylbromo-acetate in acetonitrile, in the presence of K₂CO₃, following the procedure described by Iwamoto and Shinkai.¹⁸ The intermediate compound was

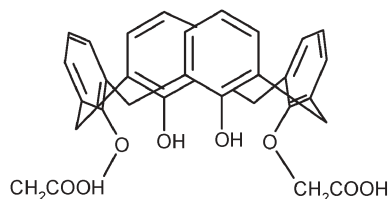


Fig. 1 Molecular structure of **1**.

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obtained as mono- and di- esters. The mixture was separated by column chromatography, with an eluant solution of chloroform–hexane 3 : 1; the yield of the first step synthesis is 70%. The di-methoxycarbonylmethoxy calix[4]arene was then saponified by KOH in ethanol–water, leading to **1**, in quantitative yield.

Crystals of **1** were grown in a water–methanol solution, by slow evaporation at room temperature.†

The unit cell is formed of two molecules of **1**, both in the flattened cone conformation, along with five water molecules. One pendant arm of one of the molecules is highly disordered and was modelled in only one position with an occupation factor of 0.5 due to the difficulty of finding other clear possibilities. The non-disordered and the disordered molecules are denoted **1A** and **1B** respectively. The torsion angles of the pendant arms of the two molecules are very similar (176.2° and 179.6° in the case of **1A** and 177.7° and 179.6° in the case of **1B**), Fig. 2.

Intramolecular hydrogen bonds are formed between the phenolic oxygen atoms and the oxygen atoms coupled to the carboxylic acid arms with shorter distances in the case of **1A**: 2.681 Å and 2.632 Å, as compared to **1B**: 2.871 Å and 2.845 Å. These differences in the intramolecular hydrogen bond distances induce a slight variation in the cone angles of the aromatic core. Thus the cone angles formed by opposite aromatic cycles of the calixarene molecules are 105.6° and 40.5° for **1A** and 104.6° and 35.7° for **1B**.

The flattened cone conformation adopted by the calixarene molecules favours interdigitation of aromatic crowns, yielding the classical dimeric motif observed in many other disubstituted calix[4]arene derivatives.^{12,16,17}

The angle between the *para*-carbon atoms describing the interdigitation is 162.4° as compared to that found for calix[4]arene dihydroxyphosphonic acid of 158.2°¹² or for dipropylether calix[4]arene that is 162.3°.¹⁷

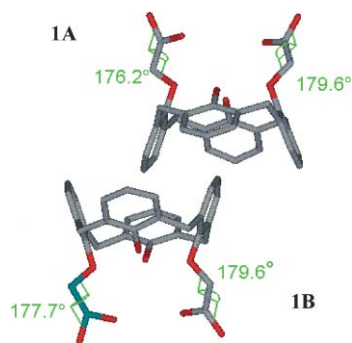


Fig. 2 Dimers of **1** illustrating the torsion angles of the pendant arms; the non-disordered molecule is denoted **1A** and the one containing a disordered pendant arm (that is colored green) is denoted **1B**.

The packing of this system is highly complex and is entirely based on interactions between the calixarene molecules, either by hydrogen bonds or by hydrophobic interactions.

The carboxylic groups of three molecules of **1A** are situated in the same plane and generate an equilateral-trigonal geometry. The edge, calculated between the upper crown limits of the calixarene molecules is approximately 17 Å (see molecules colored in blue in Fig. 3). Similarly, an equilateral triangle is formed by three molecules of **1B**, rotated with respect to the former one by 60° (see molecules colored in red in Fig. 3). A “six pointed star” architecture is thus generated (Fig. 3).

A three fold axis dominates the packing of the system.

This topology generates aquatubes of an inner diameter of approximately 8.5 Å. These tubes are smaller than the aquachannels generated in the complex of calix[4]dihydroxyphosphonic acid with propanediamine.¹⁴ The latter structure presents an “hour glass” form generated by the alternation of hexameric units of calixarene diphosphonate dimers with hydrophobic zones of alkyl chains, the inner diameter varying in the range 8–14 Å. In the two cases the aquatubes are filled exclusively with water molecules. In the present system all the water molecules present are contained in the tube. The positional disorder of these molecules is related to the disorder of the carboxylic acid chain of **1B**.

The hexagonal aquatubes assemble into a discrete close-packed honey comb structure, Fig. 4, similar to those observed by Atwood *et al.*⁷ and Hosseini *et al.*¹⁹ Interactions between neighbouring tubes are formed by intermeshing gear type contacts generated by the interdigitation of the aromatic rings, Fig. 5 (distances between the two *para*-carbon atoms of one calixarene and the *para*-carbon atom of the interpenetrating ring of the second calixarene are 3.5 Å and 3.62 Å). It is of interest to notice that similar intermeshed gear structures are one of the Holy Grails of nanotube chemistry.

The interior surface of the tube is hydrophilic and is characterised by symmetric hydrogen bonds between the carboxylic acid groups. The hydrogen bond distances in the trigonal motif generated by **1A** are formed directly between the carboxylic acid groups and are 2.87 Å and 2.68 Å. In the case of the **1B** trigonal motif, a water molecule is involved in hydrogen bonds with the carboxylic acid groups forming a bridge between the two pendant arms with distances of 2.57 Å and 2.41 Å.

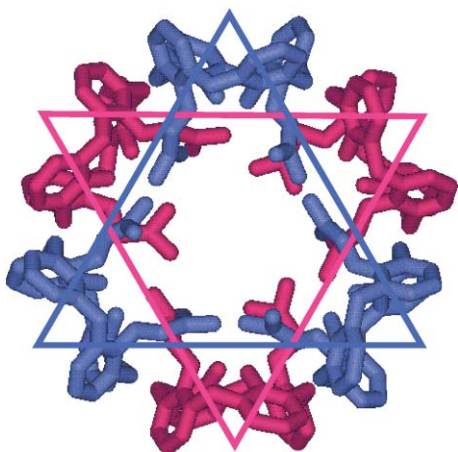


Fig. 3 Six pointed star architecture generated by calixarene molecules found, three by three, in the same plane.

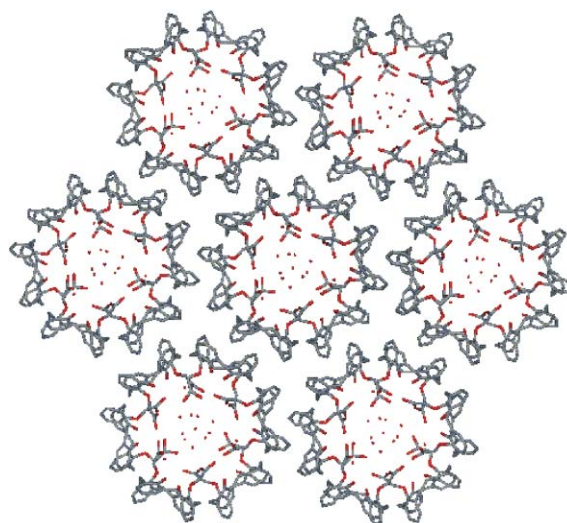


Fig. 4 Packing along *abc* plane illustrating the dense network of aquachannels.

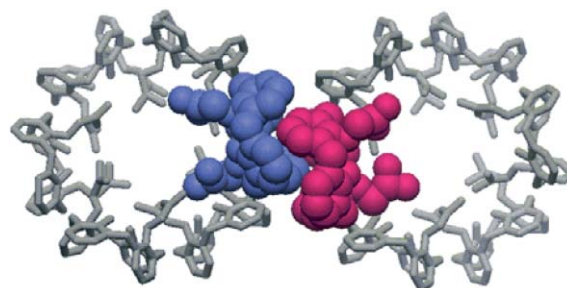


Fig. 5 Two hexameric tectons “enmeshed” by dimeric association of two calixarene molecule (molecules of **1** forming the dimeric unit colored in red and blue).

The exterior envelope is completely hydrophobic, represented by the aromatic crown of calixarene molecules.

It is obvious that only hydrophobic interactions characterise the intermolecular contacts at the exterior shell of the aquatubes. These short contacts occur between the CH₂ atoms of each carboxylic acid arm with facing aromatic cycles of neighbouring calixarene molecules. These non-covalent interactions form helical chains, a complete cycle containing six calixarene molecules with a repeat distance of 34 Å. The measured hydrophobic contacts

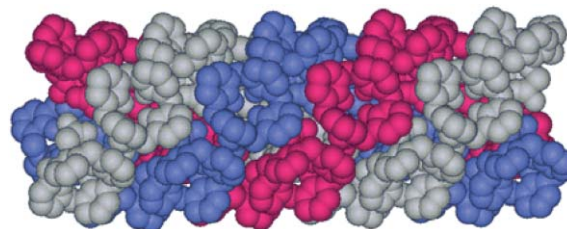


Fig. 6 Representation of the exterior envelope described by a triple helix motif. The elements of the triple helix are shown in different colors.

describing the helical loop are 3.43, 3.55, 3.68, 3.47, 3.48 and 3.27 Å.

Due to the 3-fold symmetry a triple helix arrangement is generated (see Fig. 6).

Similar helical architectures also based on hydrogen bonding have already been reported. A quintuple helical arrangement based on calixarenes bearing four pyridines that act as hydrogen bond acceptors was described by Hosseini *et al.*¹⁹ A helical arrangement is present also in the complex of *p*-sulfonatocalix[4]arene with pyridine molecules reported by Atwood *et al.*,⁷ with the diameter of the tubular assembly being 28 Å. In this latter case a polar core, a hydrophobic mid region and a hydrophilic outer shell constitute the tube where calixarene molecules alternate with pyridyl cations.

In conclusion, we have further demonstrated the structural versatility of the dimeric interdigitated building motif of di-substituted calix[4]arene derivatives; in the current case calix[4]arene di-methoxycarboxylic acid assembles *via* a hexagonal six pointed motif into discrete triple helical aquatubes.

Notes and references

† Crystallographic Data: crystals were obtained by slow evaporation of a solutions of calix[4]arene di-methoxycarboxylic acid in methanol–water, after several days.

Crystal data for (C₃₂H_{30.6}O_{11.3}), *M*_r = 595.96; colorless, 0.12 × 0.04 × 0.04 mm, rhombohedral, *a* = 20.937(2), *b* = 20.937(2), *c* = 20.937(2) Å, $\alpha = \beta = \gamma = 116.65(2)^\circ$, *V* = 4265(7) Å³, *Z* = 6, *R*3*r*, $\rho_{\text{calc}} = 1.396 \text{ g cm}^{-3}$, $2\theta_{\text{max}} = 24^\circ$, $\mu(\text{Mo-K}\alpha) = 0.11 \text{ mm}^{-1}$, 4830 independent reflections, 1071 with *I* > 2σ(*I*). Intensity data were collected at 120 K on a Nonius KappaCCD diffractometer using Mo-Kα radiation ($\lambda = 0.71073 \text{ \AA}$). Lorentz and polarisation corrections were applied and the diffraction data were not corrected for absorption. The structure was solved by direct methods and Fourier techniques (SHELXS-86²⁰) and refined, on |*F*|², using the program SHELX-97²¹. 3.3 water molecules were located on five positions. Solvent disorder is related to disorder observed on one of the independent molecule of **1**. Hydrogen atoms of **1** were placed on calculated positions. They were refined with isotropic thermal parameters based upon the corresponding bonding carbon atom [*U*(H) = 1.2 *U*_{eq}]. *R*₁ = 0.1646, *wR*₂ = 0.3802. GoodF = 1.053 for all data.

The crystal was very weakly diffracting, and the structure was only isotropically refined with 245 restraints. Residual electron density, observed close to the water positions, was between 0.899 and −0.528 eÅ^{−3}. CCDC

292896. For crystallographic data in CIF or other electronic format see DOI: 10.1039/b516963c

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