Assembly of a novel supramolecular synthon of calix[4]arene presenting four carboxylic acids

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An extremely complex solid state structure described by two virtual channels and a 2-D square grid of hydrogen bonds is generated by four carboxylic acids groups of calix[4]arene tetrabutyroxycarboxylic acid.

The prediction and construction of suitable molecular building blocks for future rational design of solid-state assemblies is a keystone in crystal engineering. Rigid blocks having directed linking geometries have received wide attention; building blocks combining rigid cores with flexible linkers are also highly promising candidates in the field. Wuest and coworkers, for example, have used tetrapyridone to form diamondoid 3-D networks.[1] Molecules presenting two or more carboxylic linkers, capable of forming hydrogen bonded dimers, have also been widely used as synthons in crystal engineering.[2,3] Structures based on terephthalic and isophthalic acid[4] which present two carboxylic functions are well studied, as are those based on trimesic acid which present three carboxylic acids[5–8] For structures in which four carboxylic acids are present in the synthon, Dale *et al.* have studied co-crystals of pyridine with aromatic poly-acids, including pyromellitic acid.[9]

The cone conformation of calixarenes has been extensively studied in the design of nanostructures and different macrosystems have been developed, such as ionophoric cavities, synthetic receptors for biological agents,[10,11] antibody mimetics,[12] capsules and spheres.[13,14] Supramolecular assembly of calixarenes, even when based around relatively structurally invariant building blocks, such as dimeric units in the case of calix[4]arene dihydroxyphosphonic acid[15,16] or the bilayer motif of *para*-sulfonato calix[4]arene,[17] may give rise to extremely complex architectures.[18,19] A remarkable characteristic of calixarenes refers to their conformational properties, which are capable of adjusting their geometry to generate the highest degree of stability.

Among the conformations of calix[4]arenes, the 1,3-alternate conformation may be expected to generate two pairs of linking units pointing linearly away from the aromatic core. However, if the two pairs of linking units joined to the calix[4]arene skeleton possess high flexibility, truly novel solid-state arrangements may be expected. Recently, Wang *et al.* thus described the fibriform one-dimensional hydrogen-bonded network of 1,2-*alt* calix[4]arene tetraacetic acid.[20]

In this paper we discuss the architecture generated by a calixarene derivative in the 1,3-alternate conformation, namely calix[4]arene tetrabutyroxycarboxylic acid, emphasising the elements responsible for the structural organisation.

A two step reaction starting from the H-calix[4]arene yields calix[4]arene tetrabutyroxycarboxylic acid (**1**; Fig. 1). First, tetra(butyroxycarbonylmethoxy)calix-[4]arene was obtained by alkylation of H-calix[4]arene in acetonitrile, in the presence of K_2CO_3, following the procedure described by Iwamoto and Shinkai, for similar derivatives[21] having shorter, less flexible, alkyl chains. The intermediate compound was then saponified by KOH in ethanol–water, leading to calix[4]arene tetrabutyroxycarboxylic acid (**1**), as confirmed by COSY ^{1}H NMR.

Crystals of **1** were grown from methanol–H_2O, by slow evaporation at room temperature.

As illustrated in Fig. 2, the molecule can be described as two similar subunits (blue and grey). The lateral chains are oriented in pairs, one pointing along the base of the molecular axis and the second pointing perpendicular to this axis.

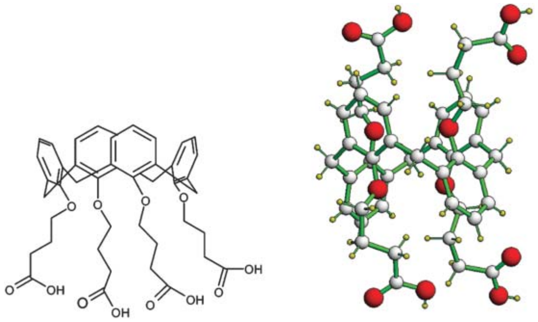

Fig. 1 Molecular formula and structure of **1**.

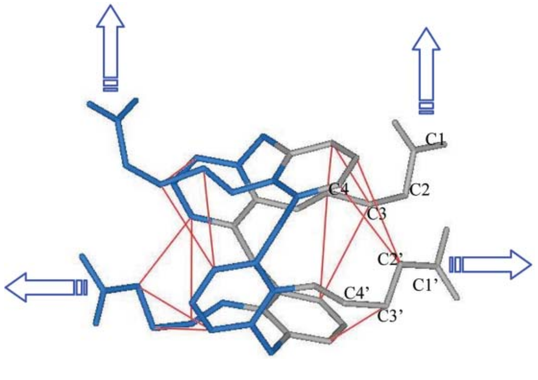

Fig. 2 Intramolecular hydrophobic short distances, less than 3.8 Å, present in **1** with the color differentiation of the sub-units of **1**.

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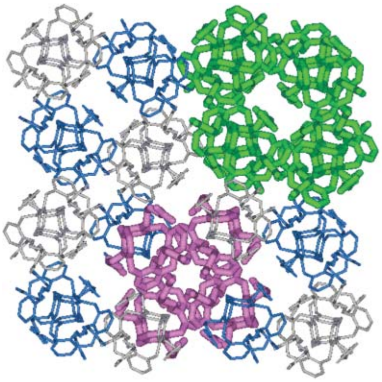

Fig. 3 General packing of **1** showing the two distinct motifs colored in magenta and green.

Pair by pair, the carboxylic chains present different torsion characteristics:

—for the perpendicularly oriented pair chains, the torsion angles C1–C2–C3–C4 are of 69.2(5) and 69.7(5)°, respectively;

—for the pair of chains aligned along the base, the torsion angles C1′–C2′–C3′–C4′ are 171.4(4) and 169.7(4)°, respectively.

It is important to note the very similar values observed for the two pairs of chains.

The folded conformation of the molecule generates short distances, around or slightly below the van der Waals contact distances between some of the methylene groups of the butyric acid chains and the aromatic rings, shown in black in Fig.2.

The packing, Fig. 3, shows a number of features: two "virtual" channels are present along with a 2-D square grid of hydrogen bonds. Both sheets and helixes are generated by the sets of hydrogen bonds.

Square virtual pores of (2.64 × 2.64 Å), shown in Fig. 4a, are formed by hydrogen bonded carboxylic acid dimers (C–OH···O 2.64 Å and 2.66 Å) of opposing units of **1**. The very small size of the pore will in all probability render it incapable of taking up even gas molecules. These hydrogen-bonded bridges form an inner envelope, oriented perpendicular to the axis of the pore. Along the axis of the pore, a double helical arrangement of four different calixarenes in the repeating unit is present (20.55 Å; Fig. 4b).

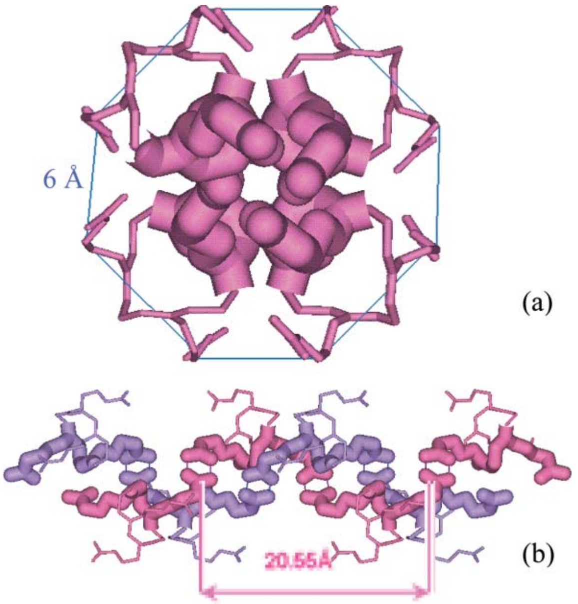

Fig. 4 (a) "Virtual" pores formed by four molecules of **1**. (b) View transverse to the pore, showing the double helix generated by carboxylic acid–carboxylic acid hydrogen bonds (aromatic rings of **1** have been omitted for better clarity).

The external envelope is octagonal with 6 Å faces. These are alternatively capped by methylene bridges of **1**. The total arrangement resembles closely the eight-fold architectural star present in decorations of many Moroccan and Muslim buildings.

Another important element in this solid-state structure, that appears as an extension of the preceding feature, concerns the connecting elements between the pores. Fig. 5a shows the double hydrogen bonds keeping together the tetrameric motifs previously described; the thus connected pores form perpendicular zig-zag sheets (colored in blue and grey in Fig. 5a).

Looking more closely at these sheets of pores, an extremely regular network of hydrogen bonds exists as the major stabilising element. Apart from the hydrogen-bond bridges crossing between pores, another class of contacts arises between the calixarene molecules of two neighbouring and intersecting pores. These correspond to a value of 2.63 Å and represent the shortest intermolecular distances of the structure (H-bonds in green in Fig. 5b). As illustrated in Fig. 5b, the dimensions of between the grids dimers of H-bonds formed by the carboxylic acid are 11.37 and 12.87 Å.

Two interdigitating molecules of **1** form one unit of the tetrameric tube (framed in lilac in Fig. 5), the second channel appearing in the solid-state structure.

The tube is formed of four such units and has a rectangular form with dimensions of 7.63 and 3.76 Å (Fig. 6a). While the internal size of this channel is such that it might be capable of taking up guest molecules, it is in fact unoccupied.

There are very short H-bonds between the carboxylic groups (2.63 Å) that generate the wall of the tube. Thus, the inner surface of the channel is formed by infinite chains of four molecules of **1**, shown in red in Fig. 6.

A schematisation of the two-dimensional and three-dimensional motifs described above is presented in Fig. 7.

Pseudo T-shaped aromatic interactions are present in the rectangular channel between neighbouring calixarenes, the

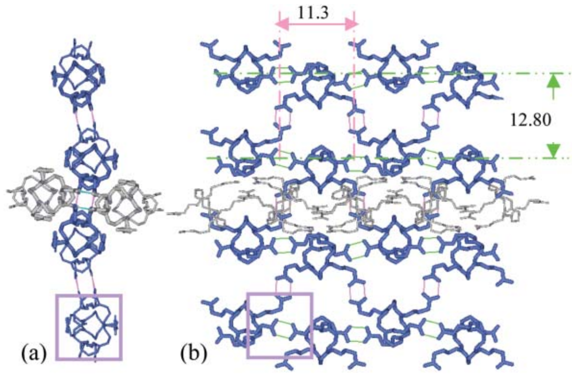

Fig. 5 (a) Perpendicular sheets generated by the tetrameric pores. (b) Perpendicular view to those sheets, showing the carboxylic acid–carboxylic acid hydrogen bonds, and the grid dimers ions (aromatic rings of **1** have been omitted for better clarity).

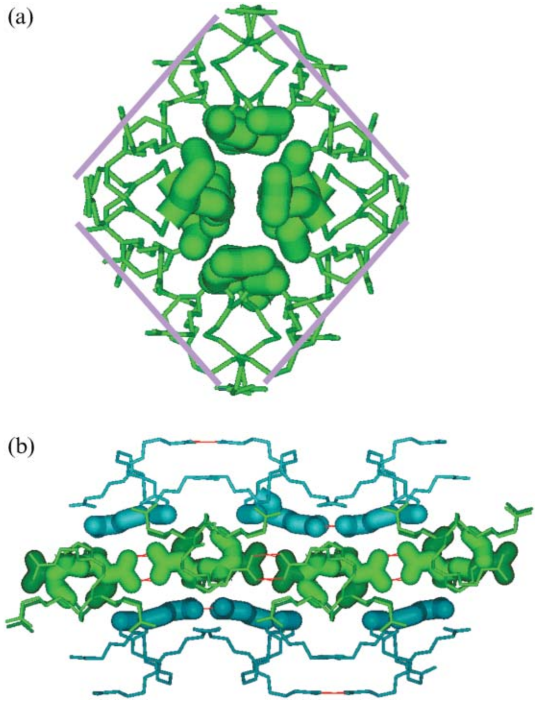

Fig. 6 (a) The second channel in the structure of **1**. (b) Perpendicular view of the tubes; visualisation of the four polymeric chains of **1** formed by hydrogen bonds—these chains are colored in different green styles for better visualisation.

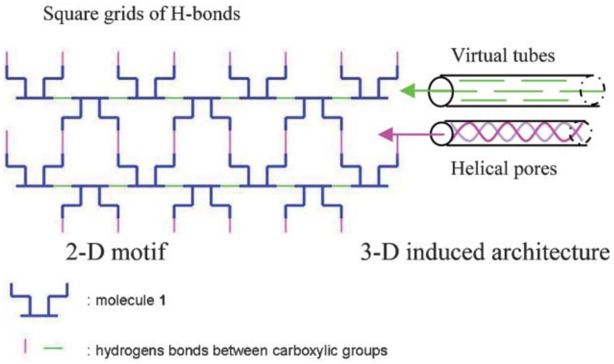

Fig. 7 On the left, the two-dimensional grid of hydrogen bonds (in green and magenta); on the right, the 3-D motif that they induce (tubes in green and pores in magenta).

measured distances being 3.69 and 3.72 Å. Other relatively short range intermolecular contacts maybe noted, for example: CH_2–CH(aromatic) of 3.65 and 3.73 Å, as well as CH_2–aromatic ring of 3.70 and 3.72 Å, and CH_2–CH_2 contacts of 3.73 Å.

In conclusion, the solid state of calix[4]arene tetrabutyroxycarboxylic acid presents a highly complex architecture based on two divergent sets of carboxylic acid dimers. The assembly yields two distinct forms of pores, one effectively virtual and the second, in spite of a size capable of accommodating guests molecules, unoccupied.†

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Notes and references

† *Crystal data*. Crystals were obtained by slow evaporation of calix[4]arene tetrabutyroxycarboxylic acid from methanol–water solution. $C_{44}H_{48}O_{12}$, $M_r = 768.82$, colorless, 0.32 × 0.27 × 0.20 mm, tetragonal, $P4_12_12$, $a = 18.712(4)$, $c = 22.740(4)$ Å, $V = 7962.2(3)$ Å^3, $Z = 8$, $\rho_{calc} = 1.283$ Mg m^{-3}, $\theta_{max} = 20.81°$, $\mu(MoK\alpha) = 0.093$ mm^{-1}, 4157 independent reflections, 3324 $[I > 2\sigma(I)]$. $R = 0.044$, $wR = 0.105$ ($R = 0.063$, $wR = 0.112$ for all data), GOF = 1.00. Intensity data were collected at 100(2) K on a Nonius KappaCCD diffractometer using MoKα radiation ($\lambda = 0.71073$ Å). Data corrected for Lorentz and polarisation effects but not for absorption. The structure was solved by direct methods and Fourier techniques (SHELXS-86) and refined on $|F|^2$ (SHELX-97). H-atoms were included in geometric positions and refined as 'riding' atoms (except those of hydroxyl groups which were located on Fourier difference maps with positional parameters refined) with isotropic thermal parameters based upon the corresponding bonding carbon atom [$U_{iso} = 1.2U_{eq}$ ($U_{iso} = 1.5U_{eq}$ for CH_3 and OH hydrogens)]. CCDC 289490. For crystallographic data in CIF or other electronic format see DOI: 10.1039/b516065k

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