Nano-dimensions for the pyrogallol[4]arene cavity†

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The cup-like cavity of pyrogallol[4]arenes has been deepened by the addition of four hydrogen bonded bipyridine molecules to the upper-rim of the calixarene, enabling the extended cup-like molecules to stack inside one another and consequently trap and completely enshroud a single guest molecule within the 250 Å^3 cavitand formed between two of these stacked "nano-cups".

Self-assembly of resorcinol[4]arene and pyridine building blocks into supramolecular architectures capable of selectively encapsulating a variety of guest molecules has proved a worthwhile area of endeavour.[1–3] Despite the growing number of resorcinol[4]arene and the related pyrogallol[4]arene supramolecular structures, to our knowledge there are no known compounds that display a pyridine–pyrogallol hydrogen bonding interaction.

Pyrogallol[4]arenes are known to spontaneously self-assemble into globular nano-capsules enclosing an internal guest environment of over 1300 Å^3.[4] This hexameric structure is reported to be more thermodynamically stable than both its resorcinol analogue and the mixed pyrogallol–resorcinol macrocyclic nano-capsules.[5–7] This increase in the stability of the nano-capsule is attributed to the larger number of hydroxyl groups at the upper rim of the macrocycle and the consequent increased number of hydrogen bonds holding the capsule together.[6] Similarly, the solvent bridged head-to-head dimeric capsules formed by the pyrogallol[4]arenes display an increased number of intermolecular hydrogen bonds in comparison to their resorcinol analogues.[8,9]

During our research focused on the development of nano-capsules as potential guest transport systems, we sought to enlarge the cavity of the pyrogallol[4]arene nano-capsules,[4,8] by inserting 4,4′-bipyridine molecules between the pyrogallol[4]arene macrocycles. However, the colourless crystals (75 mg, 0.07 mmol) formed by the slow evaporation (two days) of a solution of the 4,4′-bipyridine, **1** (22 mg, 0.14 mmol) and *C*-propylcalix[4]-pyrogallolarene, **2** (50 mg, 0.07 mmol) in acetone (5 ml) showed an extended cup-like arrangement, Fig. 1 and 2.§ Variation in the bipyridine : pyrogallol[4]arene ratio from 1 : 1 to 8 : 1 only afforded crystalline material of the 4 : 1 product **3**, Fig. 1.

The four bipyridine molecules, **1**, hydrogen bond to every third hydroxyl group at the upper rim of the pyrogallol[4]arene, **2**. Each of the four pyrogallol units that make up the pyrogallol[4]arene, **2**, are thereby hydrogen bonded to a single bipyridine molecule, **1** (O···N = 2.678–2.820 Å), as shown in Fig. 1. In all of the reported solid state structures composed of resorcinol[4]arene and pyridine,

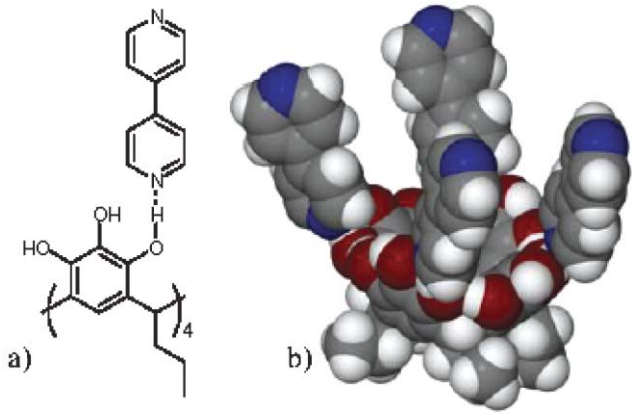

Fig. 1 (a) Hydrogen bonding interaction between the upper rim of **2** and the lower pyridine of **1**, and (b) space filling view of "nano-cup" **3**.

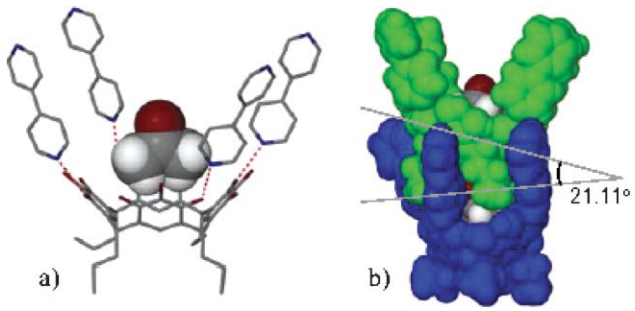

Fig. 2 (a) Molecular view of the acetone guest at the base of **3**, and (b) space filling view of two "nano-cups" stacked at 21° from one another enshrouding the acetone guest.

the four pyridine moieties hydrogen bond to two of the four resorcinol units at opposite sides of the macrocycle, namely the 1,3 positions. The solid state structures of the resorcinol[4]arene analogues of these nano-cups show that the two resorcinol units not hydrogen bonded to a pyridine form intramolecular hydrogen bonds to the hydroxy groups that hydrogen bond to the pyridine entities.[1–3] The "brick wall" and "ladder" nano-architectures of resorcinol[4]arene and pyridine show that the resorcinol units which are not hydrogen bonded to a pyridine, hydrogen bond to adjoining resorcinol[4]arene building blocks in an infinite one-dimensional rod-like array in the solid state.[1] In both isomers the pyridine-extended cone conformation of the resorcinol[4]arene is open on two sides, compared to the extended pyrogallol[4]arene structure, **3**. The extra hydroxyl group of pyrogallol thereby demonstrates an increased ability, with respect to resorcinol, to form non-porous host networks, a phenomenon mirrored in our nano-capsule work.[5–7]

† Electronic supplementary information (ESI) available: structure of **3**. See http://www.rsc.org/suppdata/cc/b4/b413829e/

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A single acetone guest molecule resides at the base of the pyrogallol[4]arene, **2**, as shown in Fig. 2a. A second nano-cup, **3**, resides above the guest with its alkyl chains interpenetrating the four bipyridine units, **1**, thereby trapping the guest, as shown in Fig. 2b. The carbonyl oxygen of the acetone molecule is orientated towards the base of the upper nano-cup with its methyl groups positioned in the cleft of the lower nano-cup. The guest occupies 24% of the 250 Å^3 cavity formed by this head-to-tail arrangement, without any significant disorder.[10] This packing coefficient is significantly lower than the reported optimal value (55%), calculated for encapsulating neutral molecules in solution.[11] The four hydrogen bonded bipyridine molecules sterically forbid the two nano-cups from embedding further. The nano-cups therefore arrange themselves to minimize the interstitial space between them. The upper and lower rims of the two pyrogallol[4]arene units that make up this cavity are skewed by 21° (angle between centroids generated from C1,11,21,31, C8,18,28,38 and C7,17,27,37) with respect to one another, as shown in Fig. 2b.

Within the extended structure, the molecular nano-cups stack one inside another in an infinite array, entrapping a single guest molecule per supramolecular nano-cup. The four pyridine entities at the upper rim of the nano-cups hydrogen bond to three adjoining pyrogallol[4]arenes in a transverse manner, as shown in Fig. 3. Two of the bipyridine molecules of the nano-cup hydrogen bond to the same adjoining hydroxyl face of a second pyrogallol[4]arene building block. The two remaining bipyridine units hydrogen bond to the hydroxyl faces of two different pyrogallol[4]arens, creating a bilayer with the upper rims of the nano-cups aligned toward one another, resembling an "egg box" motif.

The extended structure of **3** reveals that the hydroxyl rim of each pyrogallol[4]arene hydrogen bonds to the hydroxyl rims of three neighbouring pyrogallol[4]arenes (O···O 2.784–2.832 Å). Fig. 4 shows that the central hydroxyl group on three of the four pyrogallol units that make up the pyrogallol[4]arenes hydrogen bond to the remaining hydroxyl which is bound to a bipyridine molecule. The fourth pyrogallol face is shielded by a bipyridine and is unable to form a hydrogen bonding interaction.

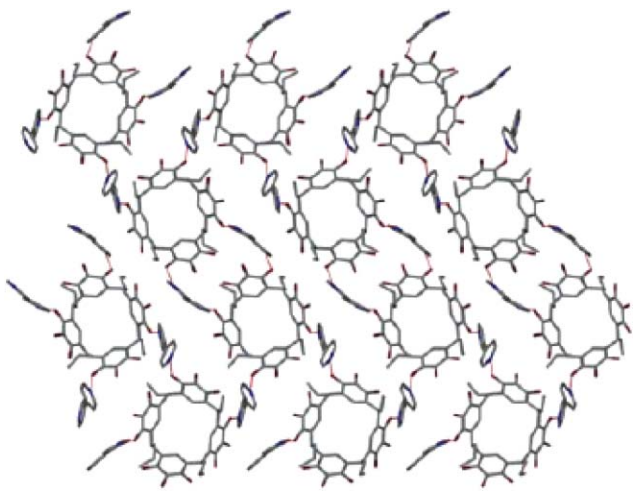

Fig. 3 Molecular packing diagram of **3**, showing the **2**···**1**···**2** hydrogen bonded network. (Guest molecules and hydrogen atoms have been removed for clarity.)

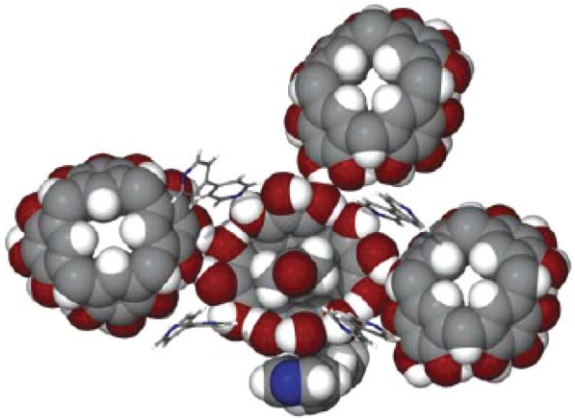

Fig. 4 Molecular packing diagram of **3**, showing the **2**···**2** hydrogen bonded network. (The four building blocks of **1** hydrogen bonded to the upper rim of the central **2** are shown in stick representation and the alkyl chains of **2** have been removed for clarity.)

In this communication, we have demonstrated how using supramolecular methodologies to increase the depth of a cup-like container molecule is attainable. The extensive hydrogen bonded network that occurs in the crystal lattice of **3** can be followed from any one building block to another, demonstrating the potential for communicative response between these nano-containers. The solid state molecular confinement of a volatile guest with a very low packing coefficient represents a new phase of matter.[12] We are continuing our studies of these molecular containers, investigating their binding properties in solution, and the possible communication and recognition between nano-containers and guest molecules.

4,4′-Bipyridine and acetone (99.9%) were used as supplied. *C*-propylcalix[4]pyrogallolene was prepared using a modified solvent free literature procedure in high yield.[13]

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Notes and references

§ Crystallographic data: $2(NC_5H_4C_5H_4N)\cdot(C_6O_3H_4CHC_3H_7)_4\cdot CH_3COCH_3$; 1091.3 g mol^{-1}; monoclinic; space group: $P2_1/c$; a = 21.480(8), b = 15.086(6), c = 18.231(7) Å; β = 109.750(6)°; V = 5560(4) Å^3, T = 173 K; Z = 4; D_{calc} = 1.304 g cm^{-3}, $F(000)$: 2320; number of data measured: 61206; number of data with $I_{net} > 2\sigma(I_{net})$: 12344; number of variables: 812; $R1$ = 0.0875; $wR2$ = 0.2575; goodness-of-fit = 1.004. One of the pyridine rings of **1** has been modelled over two positions each at 50% occupancy. All non-hydrogen atoms were refined anisotropically while the hydrogen atoms were included at geometrically calculated positions, and allowed to ride on their parent atoms. All hydroxyl hydrogen atoms were located in order that a detailed understanding of the hydrogen bonding interactions can be understood. CCDC 249861. See http://www.rsc.org/suppdata/cc/b4/b413829e/ for crystallographic data in CIF or other electronic format.

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