Interpenetrated nano-capsule networks based on the alkali metal assisted assembly of *p*-carboxylatocalix[4]arene-*O*-methyl ether†

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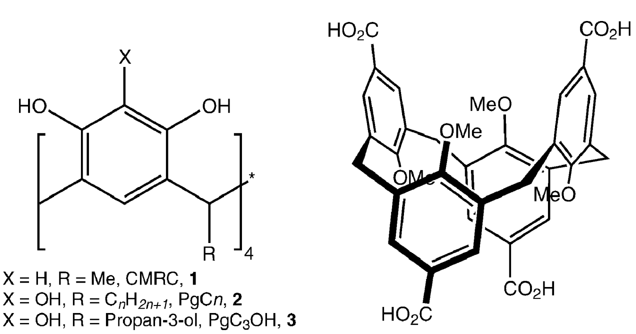
Reaction of *p*-carboxylatocalix[4]arene-*O*-methyl ether with either rubidium or caesium hydroxide results in the formation of interpenetrated nano-capsule networks with the calixarene in the 1,3-alternate conformation.

The formation of large capsule based assemblies with voluminous interiors by either introducing chemical complementarity to molecular frameworks, or by covalent/metal directed assembly remains a significant challenge in supramolecular chemistry. Although this is the case, a number of such assemblies have been constructed, many of which are based on various types of calix[4]arene or typically 'bowl-shaped' molecules, the likely reason for which is the relative rigidity of the molecular building blocks.[1]

The first of the *very* large molecular nano-capsules to be discovered is composed of *C*-methylresorcin[4]arene (CMRC, **1**, Scheme 1), six molecules of which assemble with eight structural water molecules to form a chiral nano-scale hydrogen-bonded arrangement that encloses ~1500 Å^3 of solvent occupied space.[1a] Replacement of structural water molecules by specific alcohols has recently been shown to afford an achiral version of the CMRC capsule.[1q] *C*-Alkylpyrogallol[4]arenes (general notation Pg*Cn*, **2**, Scheme 1) are closely related to CMRC and form analogous hydrogen-bonded nano-capsules without the need for structural water molecules due to additional 'upper-rim' hydroxyl groups.[1b] Nano-capsules based on both **1** and **2** have been found to be stable in the solution phase in a number of recent studies and these nano-capsules can host various guest species of different sizes.[2]

With respect to large metal–organic nano-capsule systems, we recently showed that *C*-propanolpyrogallol[4]arene (PgC$_3$OH, **3**, Scheme 1) can react with copper(II) nitrate to form a metal–organic nano-capsule (MONC) which is analogous to the hydrogen-bonded motif based on **2**, with 24 copper centres replacing all the hydrogen atoms of the 'upper-rim' Pg hydroxyl groups.[1g] The PgC$_3$OH MONC was found to link through 'lower-rim' propanol tail coordination to copper centres from neighbouring capsules, rendering the material only sparingly soluble. More recently we have found that *any* known *C*-alkylpyrogallol[4]arene can be instantly reacted with methanolic copper(II) nitrate to form a precipitate of the corresponding MONC.[1t] This technique can also be used to form MONC's composed of mixed Pg*Cn*'s, and notably all of these resultant materials are highly soluble in most common organic solvents. Other recent results in this area showed that reaction of gallium(III) nitrate with short chain *C*-alkylpyrogallol[4]arenes affords MONC's in which only 12 gallium centres insert into the hydrogen-bonded seam, causing deformation to the motif and resulting in the introduction of structural water molecules at what can be termed 'gates' to the interior.[1h,l]

We recently expanded our interests in the area of calixarene self-assembly to include that of the *p*-carboxylatocalix[*n*]arenes. To our knowledge, all of the large calixarene based assemblies reported to date (including those described above) have involved these molecules in the commonly observed cone conformation, and therefore result in the formation of discrete architectures.[1] In our preliminary experiments with these molecules, we found that *p*-carboxylatocalix[4]arene (in cone conformation) forms large diameter non-covalent nanotubes (when crystallised from pyridine) through parallel π-stacking between host molecules, as well as through the well known carboxylic acid–pyridine interaction.[3] Here we show that the



X = H, R = Me, CMRC, **1**
X = OH, R = C_nH_{2n+1}, Pg*Cn*, **2**
X = OH, R = Propan-3-ol, PgC$_3$OH, **3**

p-Carboxylatocalix[4]arene-*O*-methyl ether, **4**

Scheme 1 Diagrams of *C*-methylresorcin[4]arene (**1**), the general structure of the *C*-alkylpyrogallol[4]arenes (**2**), *C*-propan-3-olpyrogallol[4]arene (**3**), and *p*-carboxylatocalix[4]arene-*O*-methyl ether (**4**) shown in the 1,3-alternate conformation.

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† Electronic supplementary information (ESI) available: Figure of additional rubidium–carboxylate bonding. See DOI: 10.1039/b716777f

reaction between *p*-carboxylatocalix[4]arene-*O*-methyl ether, **4**, and either rubidium or caesium hydroxide in water results in the formation of a new nano-capsule motif with the calixarene in the 1,3-alternate conformation (as shown in Scheme 1). This conformational distortion, in addition to coordination polymer formation, affords three-dimensional networks of nano-capsules which are found to interpenetrate with one another.

As was the case for *p*-carboxylatocalix[4]arene,[3] **4** was found to be poorly soluble in water, and attempts to crystallise the material from solvent mixtures such as methanol–water were unsuccessful, affording crystals that appeared to be twinned and/or were weakly diffracting. As this was the case, we explored the large alkali metal cations as a type of conformational locking mechanism, as they have been previously shown to form interesting poly-hapto aromatic interactions with calix[*n*]arene π-systems.[4] Addition of excess aqueous rubidium or caesium hydroxide resulted in instant dissolution of an aqueous suspension of **4**. Slow evaporation of each resulting solution afforded large colourless single crystals that were subsequently found to be weakly diffracting and to be only suitable for synchrotron X-ray diffraction studies. For the caesium complex, the crystals were of cubic symmetry and, for this reason, it was not possible to obtain a satisfactory structural solution given the conformation of **4**, although it was possible to observe some atom connectivities and therefore deduce a number of structural features that correspond to the rubidium complex.‡ Crystals of the rubidium complex were of trigonal symmetry, and this afforded a more meaningful structural solution, although there is significant disorder present. As the extended structure is complex, different features will be described in parts.

The asymmetric unit was found to contain two molecules of **4** in the 1,3-alternate conformation. In this arrangement, each of the resulting *pseudo*-cavities is occupied by a rubidium centre that coordinates to both methoxy groups and aryl rings of the calixarenes (an example is shown in Fig. 1). In each case, the rubidiums are coordinated to three of the six aromatic carbons with a total of 24 Rb–C distances in the range of 3.271–3.760 Å. In addition, the eight Rb–O distances lie in the range of 2.869–3.016 Å. Each of the *pseudo*-cavity-bound rubidium centres also possesses disordered aquo ligands that point outwards from the centre of the *pseudo*-cavities in the molecules of **4**, although these are not shown in Fig. 1.

In addition to the *pseudo*-cavity bound rubidium centres, there is an additional rubidium centre that is disordered over two positions, that possesses disordered aquo ligands, and that coordinates to four carboxylato groups: one from each molecule of **4** in the asymmetric unit, and one from two neighbouring symmetry equivalent molecules of **4** (Fig. S1, ESI†). This bonding results in the formation of a three-dimensional coordination polymer.

Symmetry expansion of the asymmetric unit shows that each crystallographically unique molecule of **4** forms nano-capsule type arrangements that enclose a total of ~700 Å^3 in the absence of the rubidium centres (Fig. 2). This occurs by the convergence of six *pseudo*-cavities around a central node in each case. Unlike the case in which *p*-carboxylatocalix[4]arene forms nano-tubular arrays by intermolecular π-stacking and CH···O interactions from aryl hydrogen atoms to oxygens of carboxylato groups,[3] there appears to be no such interactions between molecules of **4** within any crystallographically unique capsular arrangement in the present structure.

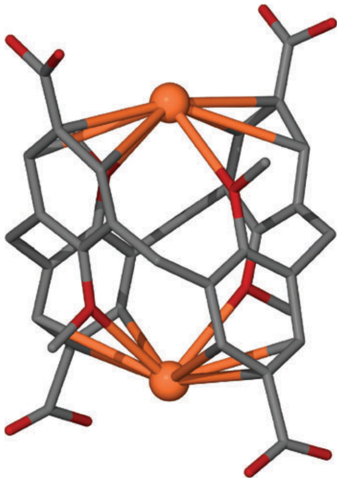

Fig. 1 Binding of two rubidium centres within a molecule of **4** in the 1,3-alternate conformation, showing the coordination to the aromatic rings of the host and to the oxygen atoms of the OMe groups. Disordered aquo ligands of the rubidium centres and hydrogen atoms have been omitted for clarity.

Although the quality of the data precludes the location of hydrogen atoms, as well as full resolution of all disordered rubidium aquo ligands for example, it was possible to observe likely interactions between fragments of the structure. An example of this is the distances found between oxygen atoms of carboxylato groups and the oxygen centres of the

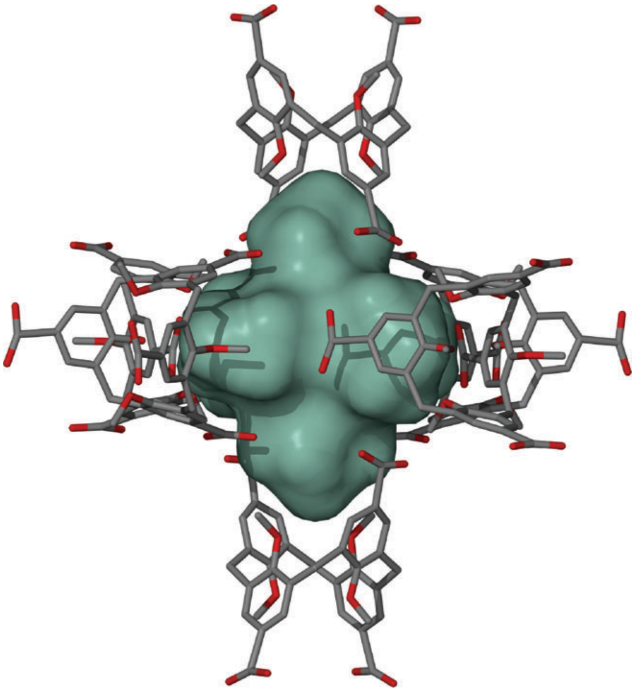

Fig. 2 Representation of the space occupied by the *pseudo*-cavity bound rubidium centres, metal aquo ligands and disordered water molecules. The calixarene enclosed volume (shown in green) has been calculated at ~700 Å^3.

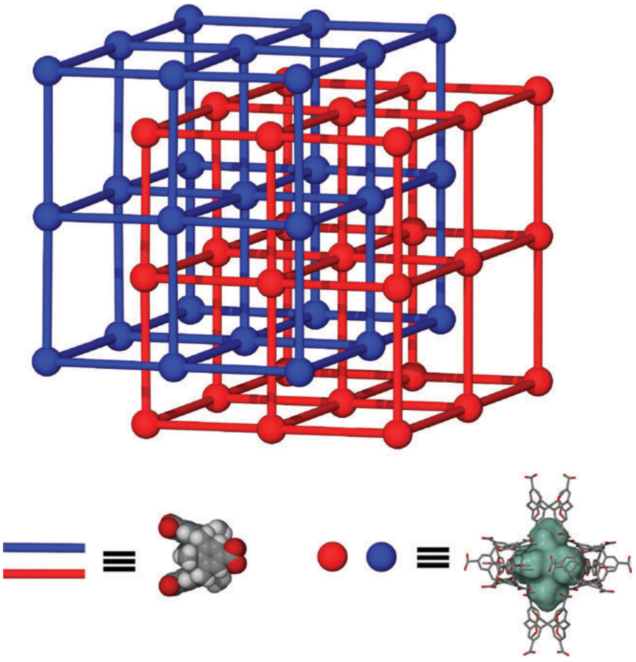

Fig. 3 Network diagram showing the interpenetrated three-dimensional capsule networks. Balls and rods represent capsule centroids and molecules of **4** (in the 1,3-alternate conformation), respectively.

calixarene-bound rubidium aquo ligands (that protrude from the cavity centres) that are consistent with hydrogen-bonding interactions. These oxygen centres are also located at distances consistent with hydrogen-bonding to intramolecular carboxylato groups, albeit with the presence of disorder. The limited data quality also precluded exact resolution of the capsule interior, and as this was the case, the diffuse electron density was modelled as disordered water molecules. Consequently, it is not possible to identify which of the carboxylato groups are de-protonated, but this is highly likely given the basic media employed in the crystallisation conditions.

Conformational distortion in each molecule of **4** results in six *pseudo*-cavities pointing away from the central node of each nano-capsule along the vertices of individual octahedra (Fig. 2). These cavities are also involved in symmetry equivalent nano-capsule formation, the result being the formation of two three-dimensional networks of nano-capsules (Fig. 3). Although the two networks are cross-linked through the abovementioned bridging rubidium centres, they are interpenetrated. Fig. 3 shows both networks represented in red and blue, with capsule nodes and linking molecules of **4** depicted as (red or blue) spheres and rods, respectively.

In summary, we have shown that **4**, when crystallised under the conditions outlined above, forms a new type of nano-capsule through conformational control based on alkali–aromatic bonding as a locking mechanism. Notably this is also the first example of three-dimensional network formation with directly linked large capsule assemblies, while also forming discrete water pockets. This, along with the formation of non-covalent nanotubes with *p*-carboxylatocalix[4]arene (when crystallised from pyridine) suggests that this family of calix[*n*]arenes may prove very useful for the assembly of new, interesting, and potentially functional supramolecular architectures on the nanometre scale.

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Notes and references

‡ **Crystallographic data for 4·Cs**: cubic, $a = 19.096$ Å, space group $I\bar{4}3m$. Due to high symmetry, it is only possible to observe connectivities between heavy atom positions and the calixarene, the conformation of which is disordered over two positions. **Crystallographic data for 4·Rb**: $C_{72}H_{107}Rb_5O_{44}$, $M = 2103.93$, trigonal, $a = 28.0956(3)$, $c = 64.0922(12)$ Å, $U = 43\,813(9)$ Å^3, $T = 100(2)$ K, space group $R3c$, $Z = 18$, synchrotron radiation (wavelength $\lambda = 0.6710$ Å), GOF = 2.073, agreement index $R1 = 0.1202$, 92 284 reflections measured, 16 420 unique ($R_{int} = 0.1047$) which were used in all calculations. The final w$R(F)$ was 0.3280 (all data). CCDC 665753. For crystallographic data in CIF or other electronic format, see DOI: 10.1039/b716777f.

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