Confinement of dimeric sulfuric acid in a self-assembled molecular capsule: [(H_2SO_4)$_2$⊂(calix[5]arenesulfonic acid)$_2$]

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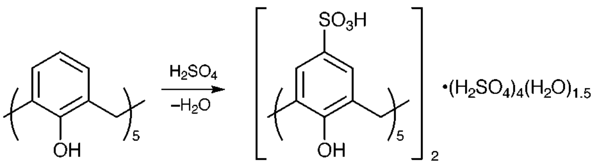
Self-assembled molecular capsules are formed on crystallisation of calix[5]arenesulfonic acid resulting from treating calix[5]arene with sulfuric acid; the calix[5]arenesulfonic acid molecules dimerise *via* hydrogen bonding through the sulfonic acid groups, shrouding two hydrogen-bonded sulfuric acid molecules as the supermolecule [{H_2SO_4)$_2$}⊂{(calix[5]arenesulfonic acid)$_2$].

Highly charged water soluble sulfonated calix[4,5,6,8]arenes form a diverse range of complexes and structural types depending on the counter ion/degree of protonation.[1–13] We recently showed that *p*-sulfonatocalix[4]arenes form superanions or ionic capsules in water at low pH in which two calixarenes shroud an 18-crown-6 molecule bearing sodium and two *trans*-water molecules, or a tetra-protonated cyclam molecule, the counter ions being chromium(III) oligomeric species.[12,13] This work relates to a surge in contemporary studies on the formation of self-assembled molecular capsules using hydrogen bonding,[14–18] and the formation of other ionic capsules held together by coordination interactions.[19,20] In general, molecular/ionic capsules are of interest in building large polyhedral structures similar to those in biological systems, trapping and stabilising molecules, and for novel functions such as drug delivery, separation problems and chemical transformations.[14–20]

We now report the synthesis and structural characterisation of a molecular capsule comprised of two calix[5]arenesulfonic acid molecules which encapsulate two sulfuric acid molecules as a hitherto unknown hydrogen bonded dimer. Treatment of calix[5]arene† with sulfuric acid then cooling the brown solution to –15 °C for several weeks gave the corresponding *para*-substituted penta-sulfonic acid isolated as a mixed sulfuric acid/water adduct, (calix[5]arenesulfonic acid)(H_2SO_4)$_4$(H_2O)$_{1.5}$ **1** (Scheme 1). The composition of the material was established from single crystal X-ray diffraction data collected at 123(1) K.[24] The samples appeared uniform but attempts to isolate the crystals were compounded by the extremely fragile, hygroscopic and indeed deliquescent nature of the material on removal from the mother liquor. The decomposed material can be converted to the corresponding sodium salt, as a derivative of compound **1** (yield 50%). NMR studies to ascertain the formation of the capsules in DMSO-d_6 and other solvents were inconclusive. While sulfuric acid is the reagent of choice for sulfonating calixarenes,[1–13] the formation of a sulfuric acid adduct of a calixarene, indeed a host–guest complex, is without precedence.

Details of the structure of **1** are shown in Fig. 1.‡ The compound crystallises in space group $P\bar{1}$ with one supermolecule or molecular capsule, [(H_2SO_4)$_2$⊂(calix[5]arenesulfonic acid)$_2$], in the unit cell and thus the capsules lie on inversion centres. In addition to the capsule the unit cell contains six sulfuric acid molecules, disordered over several positions with partial occupancies, and three water molecules of crystallisation, also disordered. The capsules and solvent molecules form a 1D hydrogen bonded network. In contrast the two symmetry equivalent encapsulated sulfuric acid molecules are fully occupied. The S–O bond lengths indicate that S–OH/S=O disorder is likely for the encapsulated sulfuric acids, with one S=O and one S–OH linkage clearly identifiable and the remaining S–O bonds similar within estimated standard deviations. There are several salient features of the capsule. The calixarenes are in the cone conformation, although two of the phenol groups disposed in the 1,3 positions in the calixarene ring are noticeably more tilted away from the principle axis of the calixarene than the other phenolic groups. The tilt angles relative to the plane defined by the five phenolic O-centres are sequentially 150.8, 113.0, 148.7, 125.5 and 123.7° (tilt angle defined as angle from arene centroid to centroid of O_5 plane at the phenolic oxygen). The most tilted phenol group is hydrogen bonded to a sulfuric acid molecule in the cavity of the calixarene, with an O··O separation of 2.92 Å. While the precision of the structure precluded location of the hydrogen atoms, the O··O distances in general are indicative of hydrogen bonding interactions.

Other features of the capsule are that it is flattened in the direction of the principle axes of the calixarenes, and that the calixarenes are slipped relative to each other (Fig. 1). This gives



1

Scheme 1

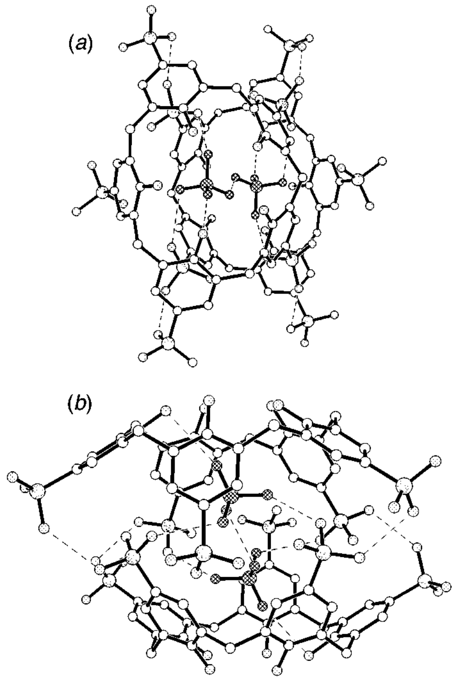


Fig. 1 Projections of the molecular capsule [(H_2SO_4)$_2$⊂(calix[5]arenesulfonic acid)$_2$] in the structure of **1** showing (*a*) the alignment of the calixarenes and sulfuric acid molecules in the capsule involving hydrogen bonding, and (*b*) the flattening of the molecular capsule. Hydrogen bonds are shown as dashed lines and the sulfuric acid molecules are cross-hatched.

a snug fit of the sulfuric acid dimer in the capsule, with one sulfuric acid molecule in each of the cavities of the calixarenes, and hydrogen bonding of the sulfonic acid groups of one calixarene with the other. There are four such inter-calixarene (intracapsule) hydrogen bonds (Fig. 1) at O··O separations of 2.62 and 2.64 Å, with inter-digitation of some of the sulfonic acid groups of one calixarene with those of the other calixarene. The binding of the sulfuric acid molecules is driven by four hydrogen bonding interactions per molecule, one for each of the oxygen centres of each sulfuric acid molecule. The oxygen centre residing deepest in the cavity has a hydrogen bond to one of the phenolic O-centres which is skewed furthest from the average cone conformation. Two others are to sulfonic groups of the other calixarene, at 2.39 and 2.79 Å, and this also is a manifestation of the flattened nature of the capsule. The other hydrogen bond involves an oxygen atom of its centrosymmetric related sulfuric acid molecule at an O··O distance of 2.63 Å.

The single hydrogen bond linking the sulfuric acid dimer is particular noteworthy in the context of the structure of crystalline sulfuric acid. Here there is a continuous two-dimensional puckered sheet-like array of acid molecules held together by hydrogen bonding interactions such that each oxygen in the tetrahedral arrangement of O-atoms around each sulfur forms a single hydrogen bond to another sulfuric acid molecule (O··O separation 2.62 Å).[21] Thus the present structure has two adjacent sulfuric acid molecules interacting with each other through vertices of the tetrahedra analogous to the continuous structure of sulfuric acid itself. Furthermore the S–O··O angles are similar (109.9 *cf.* 120.4° in **1**). This is also the type of hydrogen bonding in the few sulfuric acid adducts which have been structurally authenticated.[22] Alternative hydrogen bonding modes are possible including face-to-face linking of the tetrahedra. Effectively we have stabilised a dimer of a similar spatial arrangement as two adjacent sulfuric acid molecules in the continuous structure.

The structure of compound **1** is notably different from that of the corresponding Na salt where the calixarenes do not form molecular capsules.[3,9] This is in direct contrast to the only other structurally authenticated calixarenesulfonic acid, {calix[6]arenesulfonic acid}.23H_2O, which is isostructural with its corresponding Na salt, and has the calix[6]arene in a double partial cone conformation, effectively excluding the possibility of capsule formation.[23]

The results herein extend the range of molecular capsules which can be assembled using the principles of supramolecular chemistry, from the initial studies on calix[4]arene[12,13] to the larger calix[5]arene. Success here suggests that a range of species may be encapsulated, depending on interaction complementarity between the molecules and with calixarenes and between the calixarenes. It is likely that the larger calix[5]arene has greater flexibility, able to form a flattened, slipped structure, as in **1**, or an expanded structure able to encapsulate larger molecules, beyond the crown ether in the above calix[4]arene studies.[12,13]

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Notes and references

† *Synthesis:* *p-tert*-Butylcalix[5]arene was prepared by the literature method (ref. 24) and debutylated by standard procedures (ref. 25). Calix[5]arene (0.25 g, 0.47 mmol) was treated with 98% sulfuric acid (3 ml) at 80 °C for 10 h, and the resulting brown solution cooled then stored at –15 °C for several weeks, whereupon colourless crystals of deliquescent (calix[5]arenesulfonic)$(H_2SO_4)_4(H_2O)_{1.5}$ deposited which proved difficult to isolate in an analytically pure form. δ_H(DMSO-d_6) 7.15 (s, ArH), 6.22 (s, broad, COH/SOH, shifts downfield with increasing [H_2SO_4]), 3.85 (s, $ArCH_2Ar$). For H_2SO_4: δ_H(DMSO-d_6) 12.32 (s, SOH).

‡ *Crystal data* for **1**: A prismatic crystal of dimensions 0.25 × 0.20 × 0.15 mm was mounted on a glass capillary under oil and quickly placed under a stream of cold nitrogen. The crystal lost clarity during mounting, indicating a degree of deterioration. X-Ray data were collected at 123(1) K on an Enraf-Nonius KappaCCD single crystal diffractometer with Mo-Kα radiation (λ = 0.71073 Å). Data was corrected for Lorentzian and polarisation effects, but not absorption. The structure was solved by direct methods with SHELXS-97 and refined by full-matrix least-squares on F^2 using SHELXL-97. (Calix[5]arenesulfonic acid)$(H_2SO_4)_4(H_2O)_{1.5}$: $C_{35}H_{49}O_{37.5}S_9$, M_r = 1358.28 g mol^{-1}, triclinic, space group $P\bar{1}$, a = 11.7770(3), b = 15.9118(4), c = 16.0580(4) Å, α = 105.459(1), β = 90.871(1), γ = 105.767(1)°, U = 2778.68(12) Å^3, Z = 2, ρ_{calc} = 1.623 g cm^{-1}, μ = 0.464 mm^{-1}, 2.6 < 2θ < 55.0, 57663 reflections measured, 12660 unique reflections (R_{int} = 0.073), 7156 observed [($I > 2\sigma(I)$], 846 parameters, 2 restraints, R_1 = 0.1267 (observed data), wR_2 = 0.4012 (all data), S = 1.384. C–H hydrogen atoms of the calixarene were fixed at geometrically estimated positions with a riding refinement. A number of the sulfuric acid molecules and the waters were disordered and given partial occupancies. Two disordered sulfuric acid groups were modelled with restrained S–O bond lengths. CCDC 182/1459. See http://www.rsc.org/suppdata/cc/1999/2409/ for crystallographic data in .cif format.

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