Nanocage Encapsulation of Two *ortho*-Carborane Molecules

Colin L. Raston*[a] **and Gareth W. V. Cave**[b]

Abstract: Bowl-shaped *C*-methylcalix[4]resorcinarene forms a 1:1 ball-and-socket nanostructure with *o*-carborane through two *endo*-cavity BC–H⋯π hydrogen bonds. In the presence of 4′,2:6,4″-terpyridine, two of these nanostructures are held together by four terpyridines through sixteen OH⋯N hydrogen bonds, completely shrouding two carboranes.

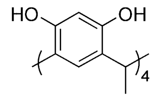
Keywords: boron · hydrogen bonds · inclusion compounds · molecular recognition · self-assembly · supramolecular chemistry

Introduction

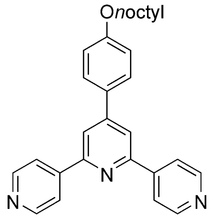
Polyhedral assemblies of the highly stable icosahedral carboranes, *o*-, *m*-, and *p*-$C_2B_{10}H_{12}$ cages and their derivatives have found wide and varied applications, including neutron-capture therapy, nonlinear optics, and conducting polymers.[1] The C–H acidity of these spherical-like carboranes has shown great potential and versatility in building up supermolecules and continuous structures through intramolecular hydrogen bonding interactions.[2–5]

The first examples of host–guest complexes of carboranes were with α-, β- and γ-cyclodextrin, as 1:1 complexes, with α-cyclodextrin also forming a 2:1 complex.[2] The only examples of structurally authenticated carborane host–guest complexes are those involving the cavitand molecules, calix[5]arene and cyclotriveratrylene (CTV).[3,4] In both of these cases and all the analogues therein, the complexes formed are based on arrays of 1:1 ball-and-socket nanostructures, whereby the carborane sits within the cleft of a bowl-shaped host. *o*-Carborane guest molecules are routinely observed to be held in place by η^6-C–$H_{(carborane)}$⋯π nonclassical hydrogen bonding or coulombic interactions involving the face of one or two of the host's phenyl groups.[3,4,6] Depending on the choice of solvent in forming cavitand complexes of *o*-carborane, and the ratio of the two components in solution, different complexes can be generated. These complexes are all built up on the 1:1 complex of the carborane and calix[5]arene or CTV, [(*o*-carborane)∩(cavitand)], with varying degrees of solvent and either additional carborane or cavitand.[3,4]

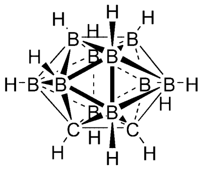
We show that the related symmetrical *C*-methyl derivative of C_{4v} calix[4]resorcinarene (**1**) readily forms a complex with *o*-carborane, and spectacularly so in the presence of a 4′,4″-terpyridyl (**2**) "molecular capsule", confining two *o*-carboranes as part of the extended structure. This represents the first structurally authenticated head-to-head (upper-rim-to-upper-rim) molecular capsule to completely encapsulate a carborane guest(s) within two or more cavitands. The water soluble ionic capsule derived from (ethylenediamine)palla-



C-methylcalix[4]resorcinarene (**1**)



4-(4‴-octyloxyphenyl)-4′,2:6,4″-terpyridine (**2**)



o-carborane

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dium(II) and 2,4,6-tri(4′-pyridyl)-1,3,6-triazine has a potentially large internal cavity that can encapsulate four *o*-carborane molecules, although their position and orientation within the host are poorly defined.[5] It should be noted that *N*-pyridine–metal complexes in general form a diverse range of molecular capsules.[7]

Results and Discussion

The complex based on the ball-and-socket, [(*o*-carborane)$\cap$(**1**)]·4 EtOH, as depicted in Figure 1 was prepared by the addition of equimolar quantities of *C*-methylcalix[4]resorcinarene (**1**), and *o*-carborane in ethanol, yield 97 %. Addition of two equivalents of 4-(4‴-octyloxyphenyl)-4′,2:6,4″-terpyridine (**2**) to a solution of one equivalent each of **1** and the carborane in ethanol afforded, upon slow evaporation, the nanocage assembly [(*o*-carborane)$_2\subset$(**1**)$_2$(**2**)$_4$]·(*o*-carborane), shown in Figure 2, yield 84 %. ^{1}H NMR studies of the two crystalline compounds confirmed that the ratios of **1**/carborane/**2** were 1:1:0 and 2:3:4, respectively. However, there was no evidence of host–guest interactions from ^{1}H or ^{11}B NMR data ([D$_4$]methanol, 300 K), so their characterization rests solely on the X-ray crystallography data. Despite the weak, poor quality data obtained for the complex based on "molecular capsules", the position and orientation of the *o*-carborane was clearly established, as was the case for the other structure. The two C–H groups of the carborane are directed towards the centroids of two adjacent aromatic rings of the calix[4]resorcinarene, as weak C–H···π hydrogen-bonding interactions.[7] These are the first reported interactions to be observed between calix[4]resorcinarene and carboranes and their derivatives. Theoretical studies on such interactions show them to be energetically favored by 2.74 kcal mol^{-1}.[6]

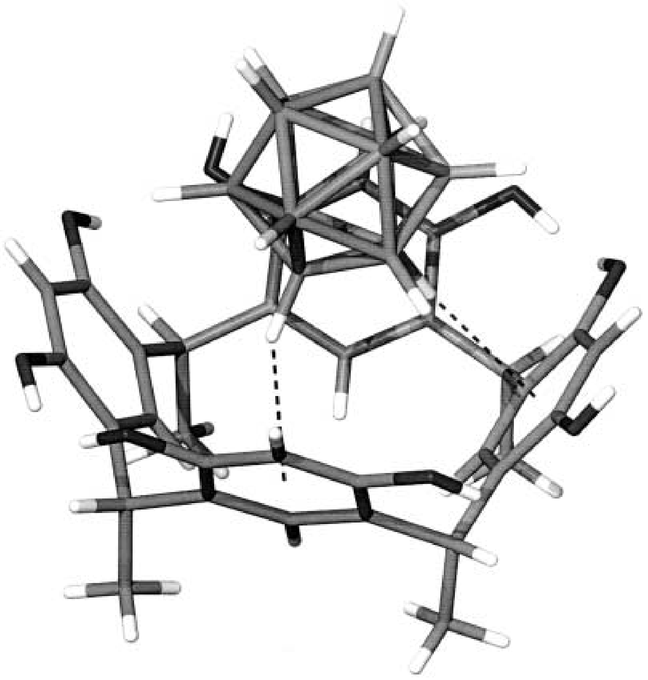

Figure 1. The ball-and-socket structure in [(*o*-carborane)$\cap$(**1**)]; C–H···π hydrogen bonds are shown as dashed lines (solvent molecules have been removed for clarity).

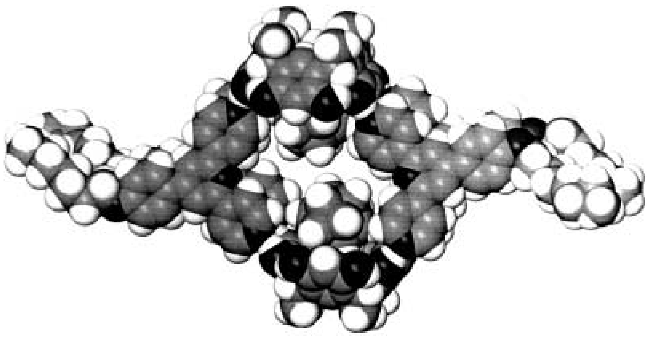

Figure 2. The [(*o*-carborane)$_2\subset$(**1**)$_2$(**2**)$_4$] capsule assembly (exo-molecules have been removed for clarity).

Both solid-state structures show that one of the C–H$_{\text{carborane}}$ bonds is almost symmetrically orientated towards one of the aromatic rings; the C$_{\text{carborane}}$···aromatic-ring centroid distances are 3.502 and 3.452 Å for the ball-and-socket and capsule, respectively, with the corresponding C–H···aromatic-ring centroid distances at 2.452 and 2.357 Å. These interactions are comparable to those observed for the calix[5]arene and CTV structure distances of 3.44 and 3.77 Å, respectively.[3,4] Both the ball-and-socket and cage structures accommodate the carborane snugly, with the base of the carborane sitting deep within the cavity, C$_{\text{carborane}}$···centroid (generated from the resorcinarene aromatic carbons *para* to both OH groups) distances of 3.788 and 7.749 Å, respectively. The reported carborane$\cap$calix[5]arene structure demonstrates how an increase in size of cavitand results in the carborane being directed towards one side of the orifice, seemingly optimized by the two adjacent C–H$_{\text{carborane}}$···π interactions.[3,6] In the case of CTV structures, the cavity is very shallow and there is good complementarity of curvature and size of the two components.[4] In the present cage structure, the second C–H$_{\text{carborane}}$ bond is disordered equally over two positions, each aligning with the centroids of the aromatic rings adjacent to the principal ring (C$_{\text{carborane}}$···aromatic-ring centroid and B$_{\text{carborane}}$···aromatic-ring centroid 3.620 and 3.666 Å, corresponding H···centroid distances 2.719 and 2.701 Å). The carborane in the ball-and-socket structure is held within the cavity by a second C$_{\text{carborane}}$···aromatic-ring centroid bond from the C–H$_{\text{carborane}}$ bond (3.523 Å, corresponding H···centroid distance 2.544 Å). In a similar fashion to the carborane$\cap$calix[5]arene structure, the carborane in the ball-and-socket structure is disordered over two sites, whereby the C–H$_{\text{carborane}}$ bonds are orientated towards adjacent aromatic rings.

These nonconventional hydrogen-bonding interactions coupled with the surrounding hydrogen-bonded cage result in the complete containment of the two carborane guest molecules within the cagelike structure, as shown in Figure 2. We therefore presume that the carborane must first enter into the cavity of the resorcinarene and be held in place by the C–H$_{\text{carborane}}$···π bonding network, followed by the self-assembly of the cage network around it.

Six molecules of *C*-methylcalix[4]resorcinarene have been shown to spontaneously self-assemble with eight water molecules into a molecular capsule held together by a total of sixty O···H–O hydrogen bonds, the so-called snub cube.[8] In the absence of the terpyridine, the ball-and-socket motif in [(*o*-carborane)∩(**1**)] hydrogen bonds to itself directly through two of its phenolic groups, as well as through intercalated ethanol molecules, forming polymeric sheets, as shown in Figure 3. The ball-and-socket motif is prevented from assembling into a snub cube by size constraints arising from the inclusion of the carborane guest into the calix[4]resorcinarene. We can, however, assume that the hydrogen-bonded network observed for our ball-and-socket motif is a prerequisite for the formation of the snub-cube Archimedean solid.[8]

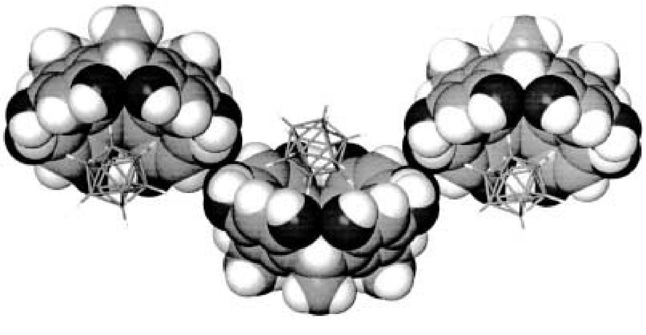

Figure 3. Cross section of the hydrogen-bonded ball-and-socket assembly [(*o*-carborane)∩(**1**)] (ethanol molecules have been removed for clarity).

The self-assembly of calix[4]resorcinarene with pyridines is not without precedent.[9,10] All previously reported head-to-head hydrogen-bonded nanocage structures of *C*-methylcalix[4]resorcinarene are dominated by those held together by 4,4′-bipyridine.[10] These capsules have a limited potential due to their constrained structure, size, and solubility and are capable of encapsulating only one or two small guest molecules. We have previously shown how the same calix[4]resorcinarenes can assemble with substituted terpyridines to form capsules held together by a total of 16 hydrogen-bonding interactions. These are capable of selectively encapsulating four guest solvent molecules in the solid state.[9] The inclusion of two *o*-carborane guest molecules into the capsule [(*o*-carborane)$_2$⊂(**1**)$_2$(**2**)$_4$] demonstrates the diversity of this cage to selectively accommodate a variety of guests. The solid-state structure shows a previously unseen 2D structural motif for such a capsule, depicted in Figure 4. Here the calix[4]resorcinarene molecules are doubly skewed relative to each other in two dimensions in order to readily contain the two ball-like guests.

The ability to encapsulate two globular molecules of about 8.1 Å in diameter sets the scene for constructing capsules that can bind larger molecules, such as fullerenes, with a careful choice of tectons. The increase in effective molarity brought about by encapsulating two or more molecules within a nanocage holds great potential for molecular reactors and beyond.

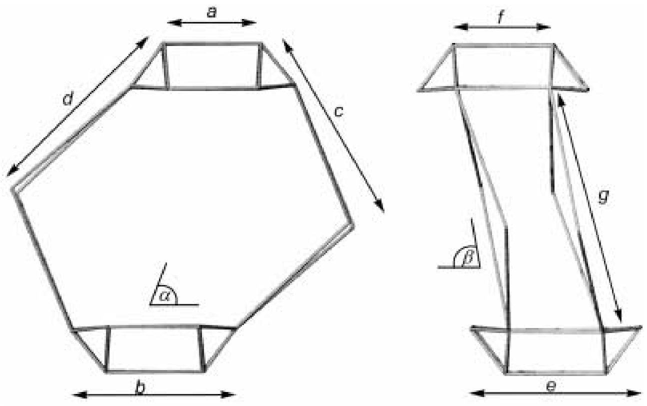

Figure 4. Doubly skewed cage dimensions. $a_{(\mathrm{C10–C18})}=4.994$, $b_{(\mathrm{O1–O6})}=8.447$, $c_{(\mathrm{C26–pyridine\text{-}ring\ centroid})}=10.883$, $d_{(\mathrm{C10–pyridine\text{-}ring\ centroid})}=11.048$, $e_{(\mathrm{C18–C26})}=5.089$, $f_{(\mathrm{O4–O7})}=8.624$, $g_{(\mathrm{O5–O1})}=13.408$ Å, $\alpha_{(\mathrm{C10–C18–C2})}=80.52$, $\beta_{(\mathrm{O5–O1–O2})}=101.87°$.

Experimental Section

Preparation of ball-and-socket structure [(*o*-carborane)∩(*C*-methylcalix[4]resorcinarene)]·4EtOH: *C*-methylcalix[4]resorcinarene (10 mg, 1.8×10^{-3} mmol) was added to a solution of *o*-carborane (5 mg, 3.5×10^{-3} mmol) in ethanol (ca. 1 cm^3). Yellow crystals of the ball-and-socket complex [(*o*-carborane)∩(*C*-methylcalix[4]resorcinarene)]·4EtOH formed following slow evaporation of the solvent overnight at RT. Yield: 97%.

Preparation of the capsule assembly, [(*o*-carborane)$_2$⊂(*C*-methylcalix[4]resocinarene)$_2${4-(4‴-octyloxyphenyl-4′,2:6,4″-terpyridine}$_4$]·*o*-carborane: 4-(4‴-Octyloxyphenyl)-4′,2:6,4″-terpyridine)$_4$ (18 mg, 4.1×10^{-3} mmol) was added to a solution of *C*-methylcalix[4]resocinarene (10 mg, 1.8×10^{-3} mmol) and *o*-carborane (5 mg, 3.5×10^{-3} mmol) in ethanol (ca. 1 cm^3). Colorless crystals of the nanocage complex [(*o*-carborane)$_2$⊂(*C*-methylcalix[4]resocinarene)$_2$(4-(4‴-octyloxyphenyl)-4′,2:6,4″-terpyridine)$_4$]·*o*-carborane formed after slow evaporation of the solvent over four days at RT. Yield: 84%.

Crystallographic data: An Enraf–Nonius KappaCCD area-detector diffractometer was used with Mo$_{K\alpha}$ radiation ($\lambda=0.71073$ Å) at 150(2) or 123(1) K. Data were measured using Phi and omega scans of 1° per frame over 60 s. The structures were solved by direct methods and refined by full-matrix least-squares cycles on F^2 with SHELX software.[11] All non-hydrogen atoms were refined anisotropically. Hydrogen atoms were included at geometrically calculated positions.

Crystal data for ball-and-socket structure, [(*o*-carborane)∩(*C*-methylcalix[4]resocinarene)]·4EtOH: $C_{83}H_{133}B_{20}O_{23}$, $M_r=1715.09$, orthorhombic, space group *Cmca*, $a=21.118(4)$, $b=22.279(5)$, $c=20.266(4)$ Å, $V=9535(3)$ Å^3, 150(2) K, final R_1, wR_2, and S values are 0.1101, 0.3478, and 1.494, respectively, for 372 parameters.

Crystal data for capsule assembly, [(*o*-carborane)$_2$⊂(*C*-methylcalix[4]resocinarene)$_2${4-(4‴-octyloxyphenyl)-4′,2:6,4″-terpyridine}$_4$]·*o*-carborane: $C_{178}H_{185}B_{34}N_{12}O_{20}$, $M_r=3179.92$, monoclinic, space group *C*2/*c*, $a=39.4680(11)$, $b=25.8690(6)$, $c=19.5857(6)$ Å, $\beta=92.0070(10)°$ $V=19984.7(9)$ Å^3, 123(2) K, final R_1, wR_2, and S values are 0.1608, 0.3622, and 1.155, respectively, for 1092 parameters.

CCDC- 205771 and 205770 (ball-and-socket and capsule assemblies, respectively) contain the supplementary crystallographic data for the structures reported in this paper. These data can be obtained free of charge via www.ccdc.cam.ac.uk/conts/retrieving.html (or from the Cambridge Crystallographic Data Centre, 12 Union Road, Cambridge CB2 1EZ, UK; fax: (+44)1223-336-033; or deposit@ccdc.cam.ac.uk).

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