

Toward Mimicking Viral Geometry with Metal-Organic Systems

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Nature embraces the principles of supramolecular chemistry, exploiting noncovalent interactions in a multitude of ways to facilitate all biological processes. Inspired by nature, the assembly of complex synthetic systems in both solution and the solid state is becoming increasingly feasible. This often requires that known systems be modeled, explored, and fine-tuned in order to develop further systems of even higher complexity. Examples include the construction of globular or spheroidal self-assembled molecular capsules, which have potential applications as drug delivery agents, van der Waals catalysts, nanoreactors, and mimics of biological systems.

Spheroidal assemblies are generally highly symmetrical and frequently assume the shapes of the Platonic or Archimedean solids. For example, the cowpea chlorotic mottle virus is comprised of 180 identical protein subunits assembled into an icosahedron. Under pH control, the overall conformation of the virion changes, giving rise to pores in the outer shell, thus allowing the passage of molecular material between the interior of the viral cavity and its environment.¹ Although gaining analogous control over the size, conformation, and composition of synthetic systems is a formidable challenge, advances have been made in influencing both the volume and composition of enclosed chemical space within the shells of hexameric capsules assembled, by means of hydrogen bonding, from resorcin[4]arenes² or pyrogallol[4]arenes.³ These molecular capsules are arranged such that the centroids of the six components reside on the vertexes of octahedra, with the hydrogen bonding pattern representing the snub cube and the small rhombicuboctahedron, respectively.

In the solid state, truncated cone-shaped amphiphilic *p*-sulfonato-calix[4]arene, **1**, favors the formation of infinite bilayer structures in which neighboring calixarenes are oriented in an antiparallel (up–down) fashion relative to one another.⁴ However, it is possible to circumvent the formation of such bilayer structures under controlled conditions for a ternary system containing pyridine *N*-oxide (PNO), a lanthanide(III) nitrate salt, and the pentasodium salt of *p*-sulfonato-calix[4]arene, Na₅**1**, where one of the phenolic groups is also deprotonated. Parallel (i.e., up–up) packing of neighboring calixarenes imparts significant curvature to the overall assembly, resulting in the formation of either spheroidal or tubular arrays.⁵ The spheroidal array consists of 12 calixarenes arranged at the vertexes of an icosahedron, **2** (Figure 1). Indeed, this is the most symmetrical way in which to arrange 12 like objects efficiently about a neospherical Platonic/Archimedean solid. The calixarenes enclose a central core

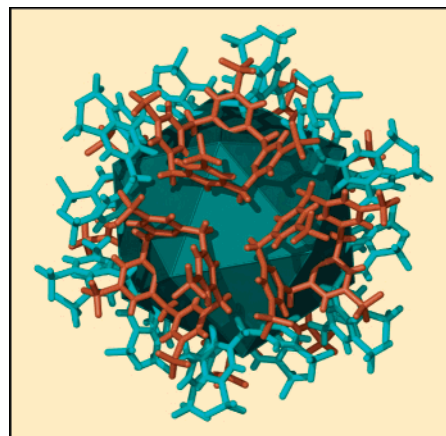


Figure 1. Arrangement of 12 *p*-sulfonato-calix[4]arene molecules at the vertexes of an icosahedron to form a compact spherical assembly. The crystallographically unique calixarenes are colored orange (three in the foreground and three in the background) and blue (six about the equator of the sphere).

comprised of two sodium ions and 30 water molecules that form an extensively hydrogen bonded regime within the capsule. Since icosahedra are unable to pack closely in three dimensions by sharing vertexes, edges, or faces, the spheroids do not form a close-packed arrangement in the extended solid. Thus, the network of vectors linking the spheroids cannot retain any vestige of icosahedral symmetry. Crucially, both the spheroidal and tubular structures possess ‘C-shaped’ dimers, each consisting of two molecules of **1** linked to a common trivalent lanthanide ion by way of metal sulfonate coordination. Furthermore, each of the calixarene cavities contains a PNO molecule, which is also coordinated to the bridging lanthanide ion. Each component of the dimer forms part of a separate spheroid or tubule, and neighboring superstructures can therefore be considered to be multiply bridged by means of first and second sphere coordination of lanthanide ions.

The host–guest interactions of **1** with 18-crown-6 generally result in the formation of superanions or “Russian dolls”.⁶ These exhibit extraordinary versatility in crystallizing in the presence of aquated polynuclear metal(III) species with the superanions typically arranged as bilayers or variations thereof. We now show that replacement of PNO by 18-crown-6 in the above-mentioned ternary system **2** results in a remarkably dissimilar spheroidal array consisting of 12 calixarenes arranged at the vertexes of a cuboctahedron, **3**.⁷ Of the two Archimedean solids that possess 12 vertexes, i.e., the cuboctahedron and the truncated tetrahedron, the former possesses higher symmetry and more closely approximates spherical geometry. We attribute the formation of this new type of spheroid

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to the constraint placed upon facing calixarenes of neighboring spheres by their shared 18-crown-6 guests. The rigidity of the shared crown ether guest forces facing calixarenes of the {1-crown ether-1} dimer in **3** to be eclipsed relative to one another, whereas the {1-PNO-lanthanide-PNO-1} dimer in **2** is bridged by multi-sphere coordination.

We believe that a *discrete* spheroidal entity comprising 12 molecules of **1** would favor placement of the components at the vertexes of an icosahedron, since this arrangement is the most compact of the 12-vertex Platonic and Archimedean solids. However, when the spheres are arranged to form a three-dimensional solid, either cubic or hexagonal close-packed arrangements of the multicomponent entities should be favored. Therefore, we would expect that the extended structure will arrange itself such that the spheres are situated along vectors representing the vertexes of either a cuboctahedron (Archimedean solid, cubic close-packed) or a triangular orthobicupola (a Johnson solid capable of hexagonal close-packing by vertex-vertex alignment).

Formation of the cuboctahedral assembly is ascribed to the constraint of face-to-face alignment of calixarenes arranged as Russian doll superanions enshrouding a metal ion complex of the crown ether molecule. Within this dimeric arrangement, both calixarenes have C_{2v} symmetry in contrast to the structure of **2** in which one calixarene adopts C_{2v} symmetry while the other adopts approximate C_{4v} symmetry (symmetry assignment is based on dihedral angles between planes of aromatic rings and the basal plane of the hydroxyl groups). The restricted C_{2v} symmetry of the calixarenes in the Russian doll predetermines the interrelationships of the calixarenes on the surfaces of neighboring cuboctahedra, as well as the internal volume of the capsule. Furthermore, this arrangement results in the formation of pores in the capsule. Such pores are not evident in the compact icosahedral arrangement of **2**. However, unlike **2**, the cuboctahedron is capable of close packing in a vertex-to-vertex arrangement: upon linking the centroids of neighboring spheres, infinite networks of cuboctahedra become evident. The structural differences between the icosahedral and cuboctahedral arrangements are illustrated in Figure 2.

The internal volume of the icosahedral arrangement is calculated to be 975 \AA^3 . Similar calculations for **3** show an internal volume of 1258 \AA^3 , representing an increase of $\sim 30\%$ upon reorganization from icosahedral to cuboctahedral packing. The dramatically larger internal volume is occupied by six homoleptic aquated lanthanide ions, with the metal centers arranged at the vertexes of an octahedron. Diffuse electron density located around the six lanthanide metal centers in the central core, which could not be modeled adequately, is presumably due to disordered coordinated water molecules. The disparate packing of calixarenes has a dramatic effect on both the chemical composition and porosity of the outer shell. The calixarenes are arranged such that the casing of each sphere contains six pores in which disordered water molecules are situated. These pores have a van der Waals diameter of 4.18 \AA and are arranged at the vertexes of an octahedron centered on the core of the capsule and residing along the vectors radiating from the centroid of the capsule to the vertexes of the above-mentioned octahedron of lanthanide ions. This arrangement can be thought of as a channel for the communication of molecular material between the hydrophilic interior of the capsule, through the hydrophobic shell, to the hydrophilic exterior.

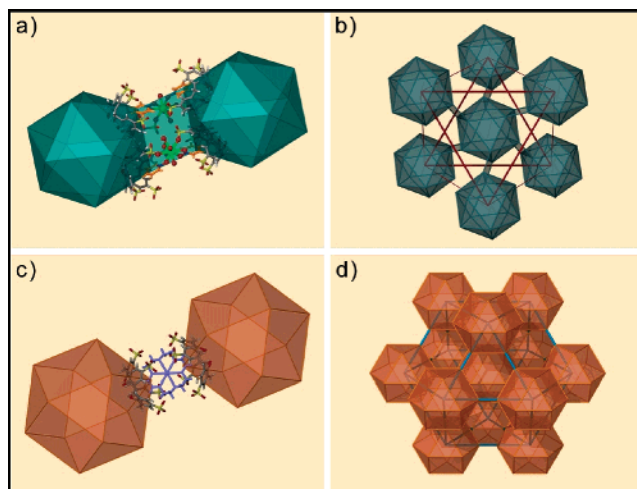


Figure 2. Differences between the dodecameric icosahedral and cuboctahedral arrangements of **1** in **2** and **3**, respectively. (a) In **2**, the calixarenes form a compact spherical assembly with neighboring spheres doubly linked by first and second sphere coordination of lanthanide ions. (b) Thus, each icosahedral assembly has six nearest neighbors arranged in a trigonal antiprismatic formation (red). In **3**, the calixarenes are positioned at the vertexes of a cuboctahedron. (c) Neighboring cuboctahedra are linked by formation of a single {1-crown ether-1} dimer. (d) Each cuboctahedral assembly thus has 12 nearest neighbors positioned in a fashion characteristic of the cubic close-packed system. Vectors between the centers of the 12 nearest neighbors (blue) also form a cuboctahedron centered on the central dodecameric assembly.

We have shown that it is possible to dramatically control the inherent symmetry of a spherical nanostructure consisting of 12 calixarene building blocks. The assembly can manifest itself as either a Platonic or an Archimedean solid. The latter yields a significant increase in the internal volume of the sphere and introduces porosity to the shell of the extended structure. These new findings provide new insight into ways of tailoring self-assembled structures to eventually mimic features of biological systems.

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Supporting Information Available: Crystallographic data of **3** (CIF) and experimental preparations (PDF). This material is available free of charge via the Internet at <http://pubs.acs.org>.

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