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A Polyhedral Host Constructed Using a Linear Template

Tamara D. Hamilton, Giannis S. Papaefstathiou, and Leonard R. MacGillivray*

Department of Chemistry, University of Iowa, Iowa City, Iowa 52242-1294

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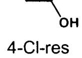
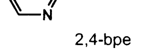
There is much interest in constructing molecular hosts (e.g., capsules, coordination cages) via self-assembly.[1] Such hosts can provide a means to stabilize reactive intermediates, to direct bimolecular reactions, and to construct molecular-scale devices.[1] By using self-assembly as a central theme,[2] the single-step construction of hosts difficult to achieve using a classical covalent route has been realized. The inspiration for designing such hosts has been largely nature (e.g., viruses), where hosts of sizes, shapes, and functionalities beyond that of nature may be achieved.[3]

Although a wide range of hosts have been constructed via self-assembly,[1] one synthetic strategy employed in the laboratory that has not addressed that of nature is the method to construct the organic subunits that assemble to form the hosts.[3] Whereas nature utilizes template-directed synthesis involving linear templates (e.g., DNA) to synthesize the subunits of biological hosts (e.g., proteins) *supramolecularly*,[3] chemists have employed a different approach that involves a classical organic route. This is surprising considering the role of the template in a biological host such as a virus. In addition to directing the synthesis of the subunits of the host, the template acts as a guest, participating in replication of the host structure.[3] Moreover, in addition to providing insight into properties of biological hosts, an ability of chemists to mimic such templating abilities could provide access to hosts less available, or inaccessible, using a more classical approach to synthesis, with applications in chemistry and biology.

With this in mind, we describe here the application of a synthetic linear template[4,5] to direct the synthesis of a molecule that assembles with a metal-ion to form a polyhedral metal-organic host. Specifically, a linear template based on resorcinol[6] is used to direct a regiocontrolled synthesis in a molecular solid, 2(4-Cl-res)·2(2,4-bpe) **1** (where 4-Cl-res = 4-chlororesorcinol; 2,4-bpe = *trans*-1-(2-pyridyl)-2-(4-pyridyl)ethylene),[7] to give a product, *rctt*-1,2-bis(2-pyridyl)-3,4-bis(4-pyridyl)cyclobutane (2,4-tpcb), that assembles with a transition-metal-ion to form a hexanuclear cage, $[Cu_6(2,4\text{-tpcb})_6(H_2O)_6]^{12+}$ **2**, with a structure that conforms to a trigonal antiprism. The internal space of the polyhedron is closed and hosts polyatomic anions as guests. Whereas entropy and solvent effects in solution have hindered chemists from applying products of linear templates with the efficiency[8] of nature, **2** represents, to our knowledge, the first example in which a synthetic linear template has provided access to a molecular host, an application largely realized owing to the ability to conduct the template-directed reaction efficiently[8] in the organized environment of the solid state.



4-Cl-res



2,4-bpe

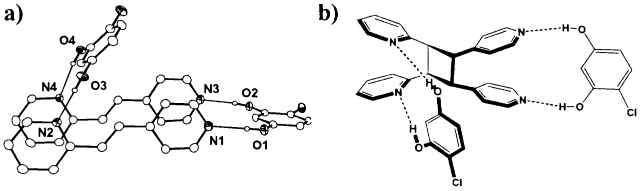


Figure 1. Template-directed synthesis of 2,4-tpcb in **1**: (a) ORTEP perspective of the assembly 2(4-Cl-res)·2(2,4-bpe) and (b) regiocontrolled synthesis of 2,4-tpcb. Interatomic distances (Å): O(1)···N(1) 2.707(3), O(2)···N(3) 2.768(3), O(3)···N(2) 2.761(3), O(4)···N(4) 2.813(3).

As shown in Figure 1, the template-directed synthesis is achieved in the solid state using 4-Cl-res as a linear template. Specifically, cocrystallization of 4-Cl-res (0.015 g) with 2,4-bpe (0.025 g) (1:1 ratio) from ethanol (10 mL) produces, upon slow cooling after a period of approximately 1 day, single crystals of **1** (yield: 0.035 g, 88%). As revealed by an X-ray crystallographic analysis (Figure 1a), **1** consists of a molecular assembly, 2(4-Cl-res)·2(2,4-bpe), held together by four O−H···N hydrogen bonds, wherein two resorcinol molecules organize two olefins, linearly, for a regiocontrolled "head-to-head" [2 + 2] photodimerization.[7] Identical pyridyl groups lie stacked such that the double bonds lie parallel and separated by 3.89 Å, a position suitable for the photoreaction. Olefins of nearest-neighbor assemblies lie offset and separated by 3.97 Å such that the olefins of the hydrogen-bonded array are the double bonds expected to undergo reaction.[9] UV irradiation of **1** for a period of approximately 24 h produces 2,4-tpcb in quantitative yield (Figure 1b).

In line with our strategy, self-assembly in a second step is achieved by treating 2,4-tpcb with Cu(II). Specifically, addition of 2,4-tpcb (0.025 g) to a hot solution of $Cu(ClO_4)_2{\cdot}6H_2O$ (0.025 g) (1:1 ratio) in methanol (10 mL) produces blue crystals of $[Cu_6(2,4\text{-tpcb})_6(H_2O)_6][ClO_4]_{12}{\cdot}18H_2O$ **3** (yield: 0.027 g, 60%) upon cooling to room temperature after 1 day.

As shown in Figure 2, an X-ray crystallographic analysis of **3** reveals that 2,4-tpcb assembles with the Cu(II) ion to form a molecular polyhedron **2**, which sits around a crystallographic center of inversion, with a structure that conforms to a trigonal antiprism.[1e] The six metal ions, which occupy the six vertexes of the polyhedron (Figure 2a), exhibit two unique metal−metal separations that correspond to metal−metal separations within (1.0 nm) and between (0.9 nm) the two co-axial triangles (twist angle: 60°). Each Cu(II) ion adopts an approximate square-prism coordination environment, where the two 2-pyridyl groups and two 4-pyridyl groups, the hydrogen bond acceptor sites of the photoactive complex, occupy cis positions around the metal (Figure 2b). The remaining coordination site is filled by an oxygen atom of a water molecule located along the surface of the polyhedron.

That the template directs a regiocontrolled synthesis,[7] producing unsymmetrical 2,4-tpcb, means that the different pyridyl groups of 2,4-tpcb play different structural roles[10] within **2**. Specifically, the

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* To whom correspondence should be addressed. E-mail: len-macgillivray@uiowa.edu.

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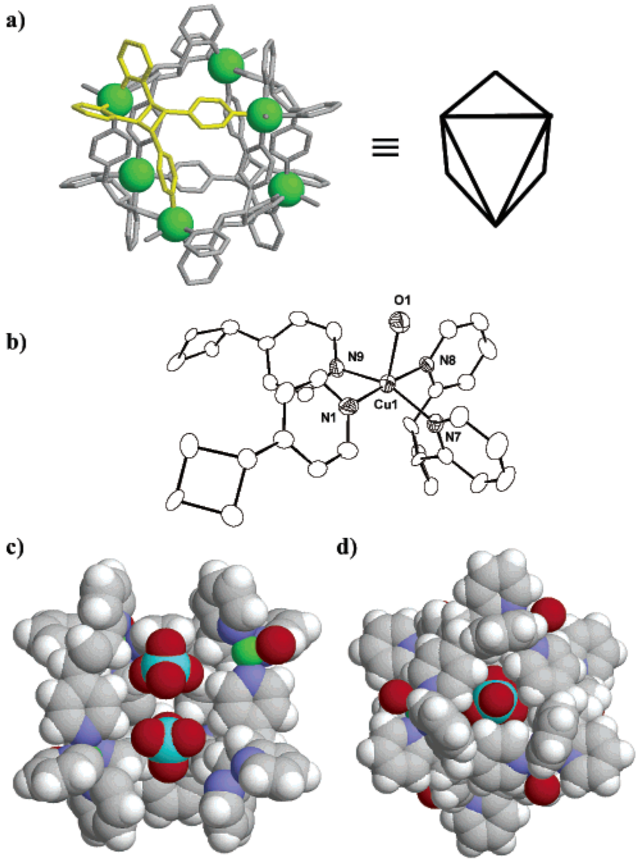

Figure 2. X-ray crystal structure of **2**: (a) ball-and-stick representation (alongside: trigonal antiprism) (color scheme: copper = green; carbon, nitrogen, oxygen = gray; one 2,4-tpcb yellow for clarity), (b) ORTEP view of a Cu(II) ion, (c) space-filling view along two-fold rotation axis showing the two encapsulated ClO_4^- ions, and (d) space-filling view along three-fold rotation axis (color scheme: carbon = gray, hydrogen = white, nitrogen = blue, oxygen = red, chlorine = cyan). Interatomic distances (Å): Cu(1)−O(1) 2.31(1), Cu(1)−N(1) 2.00(1), Cu(1)−N(7) 2.01(1), Cu(1)−N(8) 2.03(1), Cu(1)−N(9) 2.02(1).

4-pyridyl groups bond to each Cu(II) ion in a monodentate fashion, while the 2-pyridyl groups participate in bidentate bonding, serving as bifunctional chelators.[11] This dual mode of bonding renders the tetrafunctional cyclobutane, in effect, a trifunctional linker where the 4-pyridyl groups form the edges of the antiprism, while the 2-pyridyl units provide a convex surface that forms the corners. As a result, **2** possesses a cylindrical cavity of dimensions ~5.5 × 6.0 Å. To our knowledge, a metal-organic host with a structure that conforms to a trigonal antiprism has not been realized.[12]

Space-filling views of **2** illustrate roles of the counterion and cavity. Two ordered ClO_4^- ions have assembled within **2**, the three-fold rotation axis of each ion coinciding with the pseudo three-fold rotation axis of the host (Figure 2c). The equatorial oxygen atoms of the two anions lie staggered, nearest-neighbor oxygen atoms separated by 4.45 Å. The axial oxygen atom of each ClO_4^- ion points through a "pinhole",[1] of approximate dimensions 2 × 2 Å, at each end of **2**, interacting with the pyridyl groups via C−H···O forces (Figure 2d). The remaining counterions, along with solvent water molecules, lie disordered and exterior to **2**. Thus, the product of the linear template assembles with a transition-metal-ion to form a capsule that packages multiple anions as guests.

MALDI mass spectrometry with NO_3^- as the counterion suggests that **2** forms in the gas phase. The mass spectrum shows a peak at 3709 *m*/*z*, which corresponds to singly charged **2** involving 12 NO_3^- ions. A preliminary X-ray structure analysis confirms an ability of **2** to assemble with NO_3^- ions, two disordered anions filling the cavity. Notably, a peak of greater intensity is observed in the mass spectrum at 6091 *m*/*z*. This latter peak may correspond to a polyhedron larger than **2**.[13] Both peaks at 3709 and 6091 *m*/*z* exhibit clearly distinguishable signals that correspond to a parent ion complex minus *n* NO_3^- ions ($n = 1-4$).[14] Evidence supporting the formation of **2** in the gas phase with the ClO_4^- ion is not currently obtained by MALDI mass spectrometry. The signal at 6091 *m*/*z* and the absence of a peak involving ClO_4^- as the counterion may be attributed to matrix effects[14] and/or template effects involving the anions.[1]

In this report, we have revealed an ability of a product derived from a template-directed solid-state organic synthesis[6,7] to assemble with a transition-metal-ion to form a polyhedron that hosts anions as guests. Given the synthetic versatility of our templates, we are employing this two-step supramolecular approach[2] as a method to direct the synthesis of additional organic and/or inorganic host frameworks, assemblies less accessible by classical synthetic methods (e.g., size). Such interplay between the template and its final self-assembled product may lead to further structure behavior reminiscent of nature.[3]

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Supporting Information Available: Crystallographic reports, MALDI mass spectrum, and TGA analysis (PDF). This material is available free of charge via the Internet at http://pubs.acs.org.

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