

Coding a coordination-driven self-assembly *via* a hydrogen bond-directed solid-state synthesis: An unexpected chiral tetrahedral capsule†

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An achiral ligand, synthesized in the solid state *via* a coded hydrogen bond-directed organic synthesis, self-assembles with Cu(II) ions to form a chiral tetrahedral capsule that hosts an anion as a guest.

Despite having widespread relevance to biology, the act of applying non-covalent forces in sequence to construct a functional self-assembled structure remains a relatively unexplored area of supramolecular chemistry. In this context, we have shown how a self-assembled coordination polyhedron and polygon can be obtained using a ligand constructed *via* a hydrogen bond-directed organic synthesis in the solid state. Metal-organic polyhedra and polygons¹ are of current interest owing to applications in areas such as logic gates,² reaction vessels^{3,4} and nanostructured hosts.⁵

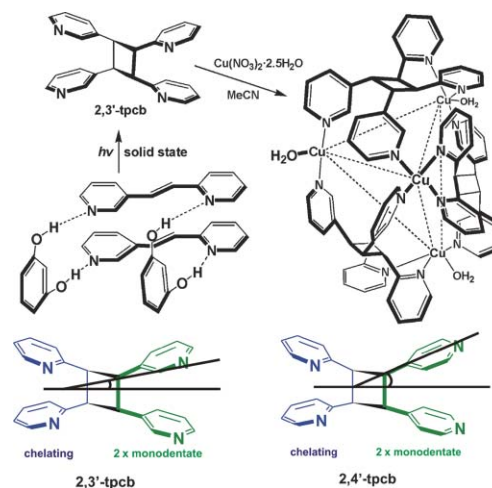
In particular, we have revealed that C_s symmetric *rectt*-1,2-bis(2-pyridyl)-3,4-bis(4-pyridyl)cyclobutane (**2,4'-tpcb**), formed *via* a hydrogen bond-directed solid-state organic synthesis, assembles with Cu(II) ions to form a M_6L_6 polyhedron, with a structure that conforms to a trigonal antiprism and encapsulates two anions as guests.^{6a} **2,4'-tpcb** has also been shown to self-assemble with Cu(II) ions to form a $M_{2n}L_2$ rhomboid (where $n = 1$ or 2).^{6b} This two-step method of (i) hydrogen bond-directed or templated organic synthesis, followed by (ii) coordination-driven self-assembly, draws inspiration from the two-step strategy of Nature (*i.e.* DNA-templated synthesis of proteins \rightarrow self-assembly) to construct self-assembled and typically polyhedral host structures (*e.g.* viruses).⁷ A key feature of the strategy of Nature is that many hosts can be generated from limited building units (*i.e.* amino acids), made possible owing to the ability of templated biosynthesis to place the building units in predefined positions or sequences that code for specific host structures.

With this in mind, we wish to report here the ability of an isomer of **2,4'-tpcb**, namely **2,3'-tpcb**, to assemble with Cu(II) ions to form a polyhedron $[Cu_4(2,3'-tpcb)_4(H_2O)_4]^{8+}$ (**1**), with a structure that conforms to a chiral tetrahedron (Scheme 1). Similar to **2,4'-tpcb**, **2,3'-tpcb** was constructed *via* a hydrogen bond-directed solid-state organic synthesis. Moreover, we anticipated that by relocating the hydrogen bond acceptors of the pyridyl groups from the 4- to the 3-position, we could code the second self-assembly to produce a smaller polyhedron, since the angle of intersection of the coordination vectors⁸ of **2,3'-tpcb** is smaller than in **2,4'-tpcb**. The self-assembly did produce a smaller polyhedron. However, to our

surprise, the structure of the self-assembled metal-organic structure conformed to a M_4L_4 tetrahedron, exhibiting a D_2 chiral topology.⁹ To our knowledge, **1** is a rare example of a chiral coordination capsule composed entirely of achiral components.¹⁰ **1** also provides the first demonstration that template-directed reactivity, conducted in either the solid state or solution,¹¹ may be used to code the construction of capsular structures.

Addition of a MeCN solution of **2,3'-tpcb**† (0.025 g, 0.0685 mmol) to a MeCN solution of $Cu(NO_3)_2 \cdot 2.5H_2O$ (0.016 g, 0.0685 mmol) (1 : 1 ratio, 25 mL MeCN total) produced a color change from light blue to dark blue-purple upon mixing. The resulting MeCN solution was left to evaporate slowly over a period of one week, after which blue prismatic single crystals of $[1][NO_3]_8 \cdot 13.5H_2O \cdot MeCN$ suitable for single-crystal X-ray diffraction were obtained (yield 0.035 g, 85%).

An X-ray structure analysis§ of $[1][NO_3]_8 \cdot 13.5H_2O \cdot MeCN$ (Fig. 1) reveals that **2,3'-tpcb** has assembled with the Cu(II) ions to give a M_4L_4 polyhedron, **1**, with a structure that conforms to a distorted tetrahedron. The polyhedron consists of four Cu(II) ions, four **2,3'-tpcb** molecules (Fig. 1a) and four water molecules. Each Cu(II) ion occupies a corner of the tetrahedron and, similar to the M_6L_6 polyhedron,⁶ sits in a square pyramidal coordination environment. The coordination consists of two chelating 2-pyridyl units [Cu–N range: 1.983(5)–2.030(6) Å] and two monodentate 3-pyridyl units [Cu–N range: 1.977(5)–2.027(5) Å], which define the base of the pyramid, and an O-atom of a water molecule, which defines the apex [Cu–O range: 2.179(5)–2.253(5) Å]. The 3-pyridyl groups of each cyclobutane coordinate to two different Cu(II) ions, such that the pyridyl groups are rotated by different magnitudes



Scheme 1

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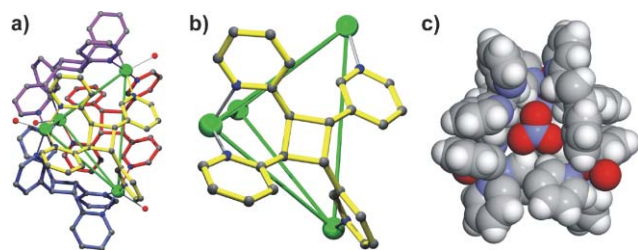


Fig. 1 X-Ray crystal structure of **1**: (a) ball-and-stick view with each **2,3'-tpcb** shown in a different colour, (b) the **2,3'-tpcb** that covers a face of the tetrahedron, and (c) space-filling view that shows the NO_3^- guest (colour scheme: green = Cu, red = O, blue = N, grey = C and white = H).

along each $\text{C}_{\text{cyclobutane}}-\text{C}_{\text{pyridyl}}$ bond [dihedral angles: $38.4(3)-41.8(4)^\circ$ and $78.0(3)-82.3(3)^\circ$]. Each **2,3'-tpcb** is, thus, coordinatively identical, bridging three Cu(II) ions (Fig. 1b). In line with our design, **1** possesses a cavity ($\text{Cu}\cdots\text{Cu}$ separations: $7.4-8.3 \text{ \AA}$) smaller than the M_6L_6 polyhedron. Consequently, **1** hosts a single NO_3^- ion as a guest (Fig. 1c). The remaining NO_3^- ions lie external to **1** and participate in hydrogen bonds with the included water and MeCN molecules.

The M_4L_4 polyhedron exhibits D_2 symmetry and is, therefore, chiral. A useful way to understand the origin of the chirality is to place the M_4L_4 tetrahedron within a rectangular prism, such that the metal atoms coincide with the four vertices of the prism. In this setting, the cyclobutane rings sit on the remaining four vertices and the bridging 3-pyridyl groups correspond to eight of the twelve edges (Fig. 2). This perspective shows that the positioning of the 3-pyridyl groups preclude any element of mirror symmetry in the polyhedron. The chirality of **1** is, thus, the result of the geometric fit of the metal and the organic components. The solid-state structure involving **1** is centric, with one complete polyhedron in the asymmetric unit and both enantiomers in the unit cell. **1** is a rare example of a chiral polyhedron composed of achiral components.¹⁰

We have evidence that supports the M_4L_4 polyhedron forming in solution. In particular, the visible spectrum of $\text{Cu}(\text{NO}_3)_2 \cdot 2.5\text{H}_2\text{O}$ ($2.0 \times 10^{-4} \text{ M}$) in MeCN shows a weak absorption at 744 nm , while **1** ($2.0 \times 10^{-4} \text{ M}$) displays a strong absorption at 565 nm . These observations are consistent with the Cu(II) ions being in a square pyramidal coordination environment with pyridine donors.¹² Moreover, spectra of $1.00 \times 10^{-3} \text{ M}$ $\text{Cu}(\text{NO}_3)_2 \cdot 2.5\text{H}_2\text{O}$ in MeCN, obtained with increasing concentration of **2,3'-tpcb** at 565 nm , reveal that the absorbance increases with increasing **2,3'-tpcb** up to a 1 : 1 molar ratio. Further addition of **2,3'-tpcb** does not change the absorbance. Although the mechanism of capsule formation is likely to be complex, this behaviour is consistent with the formation of the capsular 1 : 1 structure in MeCN.

In this report, we have demonstrated that a hydrogen bond-directed solid-state organic synthesis can be modified to code a second self-assembly process. Specifically, a relocation of pyridine N-atoms has produced a M_4L_4 tetrahedron that exhibits a chiral and tetrahedral topology. These results demonstrate that template-controlled syntheses involving linear templates can be used generally to construct capsules obtained from coordination-driven self-assembly. Studies are under way to construct additional linkers using this method, with an aim of increasing the diversity of structures accessible using the approach. This, and subsequent studies, will enable this supramolecular methodology to be utilized in more mainstream synthetic settings.

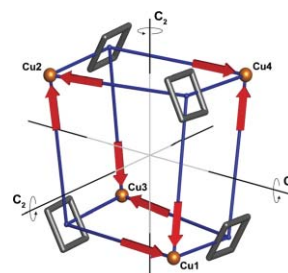


Fig. 2 The directionalities of the bridging 3-pyridyl groups in the chiral M_4L_4 tetrahedron. C_2 axes illustrate the D_2 symmetry. The bridging precludes mirror symmetry (scheme: red arrows = 3-pyridyl groups, grey squares = cyclobutane rings).

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Notes and references

‡ The synthesis of **2,3'-tpcb** involved a resorcinol and afforded the product stereospecifically and in 100% yield. Details will be reported at a later date.
 § Crystal data of **1**: $[\text{Cu}_4(2,3'\text{-tpcb})_4(\text{H}_2\text{O})_4][\text{NO}_3]_8 \cdot 13.5\text{H}_2\text{O} \cdot \text{CH}_3\text{CN}$, $M = 2564.33$, triclinic, $P\bar{1}$ space group, $a = 15.121(2)$, $b = 16.250(2)$, $c = 25.150(3) \text{ \AA}$, $\alpha = 104.966(5)$, $\beta = 100.672(5)$, $\gamma = 105.931(5)^\circ$, $V = 5518(1) \text{ \AA}^3$, $Z = 2$, $F(000) = 2658$, $\rho = 1.543 \text{ g cm}^{-3}$, $\mu = 0.861 \text{ mm}^{-1}$, $T = 190(1) \text{ K}$, total of 29031 collected reflections, 17095 unique reflections ($R_{\text{int}} = 0.0378$), 11522 observed reflections [$I > 2\sigma(I)$], $R_1(\text{obs}) = 0.0778$, $wR_1(\text{obs}) = 0.2140$, $R_2(\text{all}) = 0.1234$, $wR_2(\text{all}) = 0.2428$, CCDC 633746. For crystallographic data in CIF or other electronic format see DOI: 10.1039/b700748e

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