Spontaneous Resolution of Racemic Camphorates in the Formation of Three-Dimensional Metal−Organic Frameworks

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Reported here is a rare example of enantioselective processes between organic racemic ligands (DL-camphorates) with in situ formed chiral metal complexes. Such enantioselectivity leads to a double spontaneous resolution of two pairs of distinctly different racemates [the ΛΔ-Zn(Htea) units and the DL-camphorate ligands] into two chiral three-dimensional frameworks containing only one enantiommeric form from each racemate. This work demonstrates unique enantioselectivity in the self-assembly of metal−organic frameworks containing multiple chiral features, which points to a new avenue for the preparation of chiral framework materials and for the resolution of racemates.

Chiral crystalline framework materials are of great interest because of their potential applications in enantioselective processes; however, the synthesis of such chiral materials remains a significant challenge.[1,2] For example, it has not been possible to prepare the enantipure form of zeolite *β*, despite a lot of effort. On the other hand, recently developed metal−organic frameworks (MOFs) offer fresh opportunities to study chiral phenomena and to fabricate novel chiral framework materials.[3−7]

Currently, the most successful method for the synthesis of crystalline homochiral framework materials is through the use of enantiopure ligands as cross-linking ligands.[2,4,5] To better understand the self-assembly process of chiral MOFs, there have also been some studies using racemic ligands in the starting materials so that a comparative study between the self-assembly involving enantiopure ligands and that involving racemic ligands can be made.[5a,5d,8] Moreover, the synthesis of homochiral MOFs using enantiopure ligands may also be accompanied by ligand racemization, which further increases the importance of studying self-assembly processes involving racemic ligands.[9]

Here, we report an unusual enantioselection process in which organic racemic ligands and in situ formed chiral metal complexes undergo enantioselective recognition, leading to double spontaneous resolution of both organic DL-racemates and ΔΛ-complexes during the self-assembly of three-dimensional (3D) MOFs. It is worth noting that while it is not uncommon for organic racemic molecules to undergo spontaneous resolution during crystallization, as is well-known in the discovery of chirality in sodium ammonium tartrate,[10,11] such a phenomenon has been rarely observed during the synthesis of 3D MOFs so far. For example, in all earlier studies involving racemic DL-camphoric acid, both the D and L ligands are incorporated into the same structures, leading to racemic crystals.[5d] The uniqueness of this work is the coexistence of two pairs of enantiomers and their enantioselective recognition, leading to double spontaneous resolution during the self-assembly of 3D MOFs.

In this work, such a unique enantioselective process occurred during the solvothermal assembly of DL-camphoric acid ($=H_2$cam) with $Zn(NO_3)_2 \cdot 6H_2O$ in triethanolamine ($=H_3$tea), which resulted in two chiral 3D frameworks,

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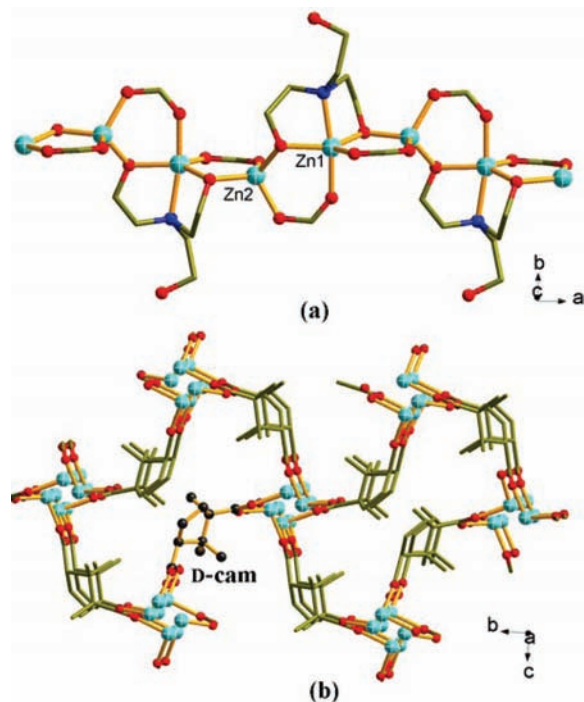
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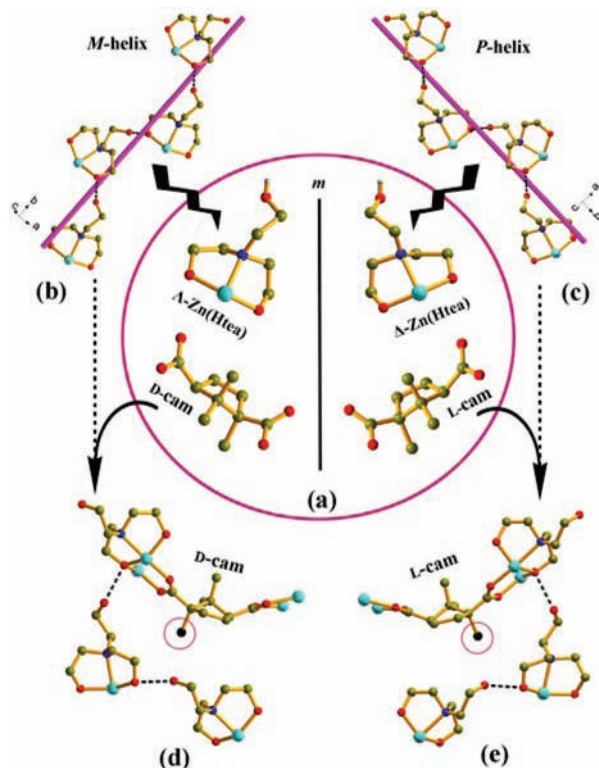
Figure 1. (a) Two types of distinct racemates with mirror symmetry. (b) Hydrogen-bonded left-handed helix based on Λ-Zn(Htea) units in **1DΛ**. (c) Hydrogen-bonded right-handed helix based on Δ-Zn(Htea) units in **1LΔ**. (d and e) Illustrations of how the handedness of the [Zn(Htea)]$_n$ helix is affected by the α-C atom (highlighted by a purple circle) of the camphorate ligand in **1DΛ** (d) and **1LΔ** (e).

Zn(Λ-Zn(Htea))(D-cam) (**1DΛ**) and Zn(Δ-Zn(Htea))(L-cam) (**1LΔ**).[12,13] These frameworks contain either all-D-Λ form or all-L-Δ form. It is found that such enantioselection is promoted by an in situ formed racemic chiral metal complex. Here, H$_3$tea acts not only as a solvent but also as a ligand to generate a racemic building unit via chelation to Zn^{2+}. The chiral recognition between enantiomers of camphorates and chiral zinc complexes results in the enantioselection and spontaneous resolution of both pairs of racemates (Figure 1).

The asymmetric unit of **1DΛ** consists of two independent Zn^{2+} ions, one D-cam ligand and one Htea ligand. One Zn^{2+} site (Zn1) possesses a distorted trigonal-bipyramidal geometry [ZnO$_4$N] in which three sites are occupied by two O atoms

(12) Synthesis of conglomerate Zn(Λ-Zn(Htea))(D-cam) (**1DΛ**) and Zn(Δ-Zn(Htea))(L-cam) (**1LΔ**): Zn(CH$_3$COO)$_2$ (0.1094 g), Na$_2$CO$_3$ (0.0583 g), DL-camphoric acid (0.1037 g), and triethanolamine (1.9582 g) were mixed in a 23-mL Teflon cup, and the mixture was stirred for 20 min. The vessel was then sealed and heated at 140 °C for 5 days. The autoclave was subsequently allowed to cool to room temperature. Transparent colorless crystals were obtained. The homochiral form Zn(Λ-Zn(Htea))(D-cam) (**1DΛ**) or **1LΔ** can be obtained by using a similar reaction except D-camphoric acid (or L-camphoric acid) instead of DL-camphoric acid was used.

(13) Crystal data for **1DΛ**: C$_{16}$H$_{27}$NZn$_2$O$_7$, M_r = 476.13, orthorhombic, space group $P2_12_12_1$, a = 12.1362(11) Å, b = 12.2752(16) Å, c = 12.7945(14) Å, V = 1906.1(4) Å^3, Z = 4, Flack parameter = −0.01(6), R1 (wR2) = 0.0768 (0.1782), and S = 1.087 for 1618 reflections with $I > 2\sigma(I)$. Crystal data for **1LΔ**: C$_{16}$H$_{27}$NZn$_2$O$_7$, M_r = 476.13, orthorhombic, space group $P2_12_12_1$, a = 12.1540(5) Å, b = 12.3292(7) Å, c = 12.8100(8) Å, V = 1919.57(18) Å^3, Z = 4, Flack parameter = 0.06(4), R1 (wR2) = 0.0665 (0.1652), and S = 0.985 for 1809 reflections with $I > 2\sigma(I)$. The structure was solved by direct methods followed by successive difference Fourier methods. Computations were performed using *SHELXTL*, and final full-matrix refinements were against F^2.

and one N atom from the same Htea ligand and the remaining two sites are completed by two carboxylate O atoms from two D-cam ligands. In comparison, the second Zn^{2+} site (Zn2) adopts tetrahedral geometry and is coordinated by two O atoms from two Htea ligands and two carboxylate O atoms from two D-cam ligands (Figure 2a).
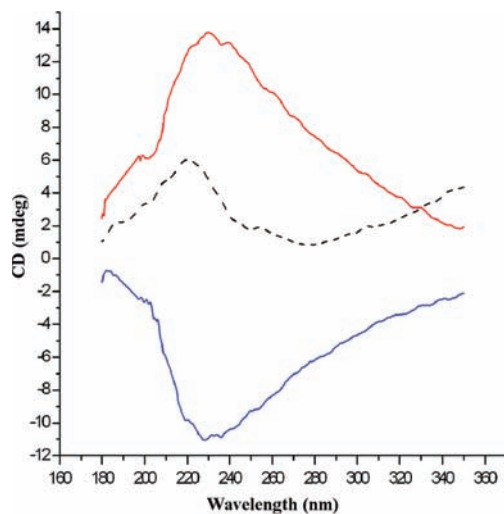
The dinegatively charged Htea ligand affords two deprotonated O donors and the central N donor to chelate one five-coordinate Zn1 site and also bridges two symmetry-related tetrahedral Zn2 sites. This leads to a [Zn(Λ-Zn(Htea))]$_n$ chain along the a axis (Figure 2a). One interesting feature of Λ-Zn(Htea) comes from the nondeprotonated −CH$_2$CH$_2$OH end of the Htea ligand, which helps create the chirality of the Λ-Zn(Htea) unit. The orientation of this flexible tail-like −CH$_2$CH$_2$OH end directs the handedness of the central N atom, leading to racemic ΛΔ-Zn(Htea) units (Figure 1a).

Because of the enantioselective interaction with camphorates, the resulting Zn(Htea) units with the same handedness (Λ in **1DΛ** and Δ in **1LΔ**) are further organized into either a left-handed 2$_1$ helix in **1DΛ** or a right-handed 2$_1$ helix in **1LΔ** through the O−H···O hydrogen-bonding interactions (Figure 1b,c). Here, the absolute helicity of the hydrogen-bonded helices is determined by the chirality of the camphorate ligands. For example, the D-cam ligand favors the left-handed helices (Figure 1d), while the L-cam ligand favors the right-handed helices (Figure 1e).

The enantioselective crystallization observed here is believed to come from supramolecular interactions during the self-assembly and is likely controlled by the α-C atom of the camphorate ligand. As illustrated in Figure 1d,e, the flexible hydrogen-bonded helices have to adjust their handedness to effectively accommodate the α-C atom of the camphorate ligand. The chiral recognition between hydrogen-bonded helices and camphorate ligands also contributes to the final cooperative double spontaneous resolution.

Figure 2. View of the 1D chiral connectivity [Zn(Λ-Zn(Htea))]$_n$ from achiral sources (a) and the 3D chiral connectivity [Zn(D-cam)]$_n$ from the enantiopure camphorates (b) in **1DΛ**.

Figure 3. Solid-state circular dichroism spectra of the homochiral samples (red line, **1DΛ**; blue line, **1LΔ**; dashed line, D-cam).

Within the overall $[Zn(\Lambda\text{-}Zn(Htea))(D\text{-}cam)]_n$ framework, the one-dimensional (1D) chiral connectivity $[Zn(\Lambda\text{-}Zn(Htea))]_n$ from achiral precursors is embedded within the 3D chiral connectivity $[Zn(D\text{-}cam)]_n$ from enantiopure chiral precursors (Figure 2b), which is unprecedented in chiral MOFs. In **1DΛ**, each $[Zn(\Lambda\text{-}Zn(Htea))]_n$ chain is connected to four adjacent chains by the D-cam ligands. Each D-cam ligand is a μ_4 linker, and each carboxylate group of the D-cam ligand bridges two independent Zn^{2+} ions. Even without considering the connectivity of the Htea ligands, the D-cam ligands link the Zn^{2+} sites into a 3D chiral framework with diamond topology.

To further confirm the enantioselective interaction observed in the DL-camphorate reaction system, we also explored the use of enantiopure D-camphoric acid in the synthesis. Consistent with our prediction, only the Λ-Zn(Htea) form is selected during crystallization, resulting in the formation of the homochiral form **1DΛ** only. Similarly, the use of L-camphoric acid gave homochiral **1LΔ** (Figure 3).

Scheme 1. Spontaneous Resolution and Cooperative Enantioselectivity between Two Pairs of Distinctly Different Racemates into Chiral 3D Frameworks **1DΛ** and **1LΔ**
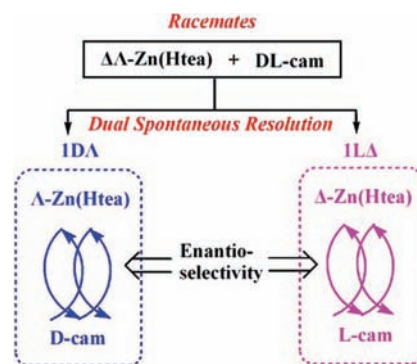
In conclusion, we present here two chiral 3D frameworks. Of particular interest is the cooperative double spontaneous resolution of two pairs of distinctly different racemates: the ΛΔ-Zn(Htea) units and the DL-cam ligands (Scheme 1). It is demonstrated that this self-assembly process for the formation of a chiral framework entails cooperative enantioselectivity [Λ-Zn(Htea) ↔ D-cam and Δ-Zn(Htea) ↔ L-cam] to produce two enantiopure frameworks. This work represents an interesting example that shows how multiple chiral features in MOFs interact with each other to produce new chemical, structural, and chiral phenomena. Furthermore, this process points to a new avenue for the resolution of racemates, which may have practical value in enantioseparation.

Supporting Information Available: Experiment details and additional structural figures, powder X-ray diffraction, TGA, and CIF files. This material is available free of charge via the Internet at http://pubs.acs.org.