

A Tale of Three Carboxylates: Cooperative Asymmetric Crystallization of a Three-Dimensional Microporous Framework from Achiral Precursors**

Jian Zhang, Shumei Chen, Ruben A. Nieto, Tao Wu, Pingyun Feng, and Xianhui Bu*

There is currently an enormous demand for practical synthetic methods to allow the preparation of chiral compounds as single enantiomers.^[1,2] While homochirality is a ubiquitous feature in living systems, the generation of homochirality using chemical methods remains highly challenging.^[3–5] For the synthesis of enantiopure or enantioenriched molecules, great progress has been achieved in the past several decades through the use of asymmetric homogeneous catalysts.^[6] In comparison, there has been very little progress in the area of asymmetric crystallization from achiral precursors to form enantiopure or enantioenriched crystalline nanoporous materials. The latter are very important for the development of heterogeneous porous asymmetric catalysts based on crystalline solids.

In the past decade, there has been an increasing interest in creating crystalline homochiral porous materials that may be utilized for enantioselective catalysis, separation, and so forth.^[1–3] The main objective is to devise homochiral 3D frameworks with tunable pore geometry and catalytic properties for enantioselective progress. With few exceptions, homochiral porous solids prepared to date acquired homochirality through the incorporation of enantiopure organic ligands that are bonded to the crystalline framework as either crosslinking or pendant ligands.^[1–3,7–9]

In the absence of enantiopure building blocks, chirality can be generated from achiral precursors through crystallization, as evidenced by many crystals (such as quartz) reported in enantiomorphous space groups.^[4] In these crystals, chirality comes from the spatial organization of achiral building blocks.

While individual crystals can be homochiral through a process called spontaneous resolution, the bulk sample tends to be a conglomerate, an equal mixture of crystals with opposite handedness.^[10]

It is worth emphasizing that the generation of chirality itself is usually not an asymmetric process (because of the formation of racemates) and is not uncommon either. In the area of homochiral crystalline porous materials, it is the generation of bulk homochirality from achiral building blocks that is still rare and highly challenging.^[11] Several well-known examples of homochiral crystallization (sometimes also called total spontaneous resolution or symmetry breaking) from achiral precursors (e.g., NaClO₃) are known.^[11a] However, these examples are based on statistical fluctuation of initial nucleation events (e.g., single-colony growth induced by secondary nucleation), and the particular handedness of crystals is not controllable. Such experiments, when repeated multiple times, would normally lead to an overall racemic product. In addition, crystals in these examples are not 3D porous materials.

One example in the control of the absolute chirality of porous materials built from achiral units was provided by Rosseinsky and co-workers, who showed that the absolute chirality of an intrinsically chiral three-connected net can be induced by the coordination of enantiopure solvent molecules to the framework.^[12] More recently, controllable homochiral crystallization in 3D open-framework materials was demonstrated by Morris and co-workers through the use of a chiral ionic liquid solvent (1-butyl-3-methylimidazolium L-aspartate).^[13] One unique and unprecedented aspect of the Morris group's work is that the handedness of the 3D framework materials is controlled without having any enantiopure ligand incorporated into the framework (neither bridging nor pendant). Complementary to the use of chiral ionic liquid solvents, naturally occurring enantiopure alkaloids such as cinchonidine and cinchonine were recently found to induce the homochiral crystallization of a metal–organic framework.^[14]

Despite this progress, the controllable asymmetric crystallization of 3D open-framework materials from achiral precursors remains poorly explored. It is unlikely that a particular chiral induction reagent can induce absolute chirality in different types of chiral crystals. It is conceivable that the controlled asymmetric crystallization of a porous material with a particular composition and topology, if possible, would require a unique chiral induction agent. It is therefore essential to study what types of open-framework

[*] Dr. J. Zhang,^[‡] Dr. S. Chen,^[‡] R. A. Nieto, Prof. Dr. X. Bu
Department of Chemistry and Biochemistry
California State University, Long Beach
1250 Bellflower Boulevard, Long Beach, CA 90840 (USA)
Fax: (+1) 562-985-8557
E-mail: xbu@csulb.edu

Dr. J. Zhang^[‡]
State Key Laboratory of Structural Chemistry
Fujian Institute of Research on the Structure of Matter, CAS
Fuzhou, Fujian, 350002 (China)

T. Wu, Prof. Dr. P. Feng
Department of Chemistry, University of California
Riverside, CA 92521 (USA)

[†] These authors contributed equally to this work.

[**] We thank the support of this work by NIH (X.B. 2 S06 GM063119-05), NSF (X.B. DMR-0846958), and DOE (P.F. 004407-002). X.B. is a Henry Dreyfus Teacher Scholar.

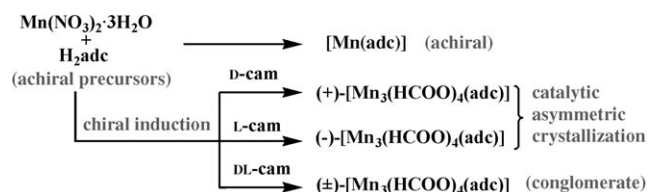
Supporting information for this article is available on the WWW under <http://dx.doi.org/10.1002/anie.200906248>.

structures can be crystallized asymmetrically and with what kinds of chiral induction agents.

Herein, we explore the enantioselective effect of enantiopure organic acids and naturally occurring amino acids. The ultimate goal is to create a library of inexpensive chiral chemicals that can effect asymmetric crystallization of 3D crystalline porous materials and to use these inexpensive asymmetric molecular catalysts, such as organic acids and amino acids, to create new crystalline heterogeneous asymmetric catalysts. Furthermore, by exploring different types of chiral induction agents, it is possible to develop a better understanding of chemical or structural factors that contribute to the asymmetric crystallization.

Crystals of (+)-[Mn₃(HCOO)₄(adc)] (denoted **1b**, H₂adc = adamantane-1,3-dicarboxylic acid) and (–)-[Mn₃(HCOO)₄(adc)] (**1L**) were solvothermally synthesized (Scheme 1). They consist of a 3D Mn–O–Mn framework of [Mn₃(HCOO)₄]_n²ⁿ⁺ units with honeycomb channels along the *c* axis. Decorative achiral organic chains of adc ligands line the honeycomb channels by attaching to the wall of [Mn₃(HCOO)₄]_n²ⁿ⁺ through Mn–adc bonds (Figure 1a,b,d). It is worth noting that [Mn₃(HCOO)₄]_n²ⁿ⁺ is chiral and forms 3₁ or 3₂ helical structures along the *c* axis. The most interesting aspect of its synthesis is the asymmetric crystallization catalyzed by chiral additives (Figure 1c). Furthermore, through a comparative study of four different crystallization processes with D-, L-, or DL-camphoric acid (H₂cam) and without additive (Scheme 1), we are able to gain a much better understanding of the chirality induction mechanism. The permanent microporosity of **1b** was characterized by the CO₂ adsorption isotherm, which shows a significant adsorption of 25.1 cm³ g^{–1} at approximately 1 atm and 273 K (Figure S5 in the Supporting Information).

Crystals of **1b** were found to be predominant in the batch synthesized using a small amount of enantiopure D-(+)-H₂cam as chiral catalyst, while crystals of **1L** were found to be predominant in the batch synthesized using a small amount of enantiopure L-(–)-H₂cam. Note that in both cases, enantiopure camphoric acid is not incorpo-



Scheme 1. Illustration of four crystallization processes showing that the camphorate ligand not only controls the absolute chirality of crystals, but also enables and catalyzes the growth of chiral crystals. The synthesis and crystallization were performed in mixed DMF/EtOH solvents at 120 °C. The formate ligand was generated in situ from the solvent DMF.

rated into the crystal structure. However, without camphoric acid, crystals of **1b** and **1L** cannot even be synthesized, much less their absolute chirality controlled.

To confirm the asymmetric crystallization, crystal structures of twenty crystals were randomly picked from the batch catalyzed with D-H₂cam and were analyzed using single-

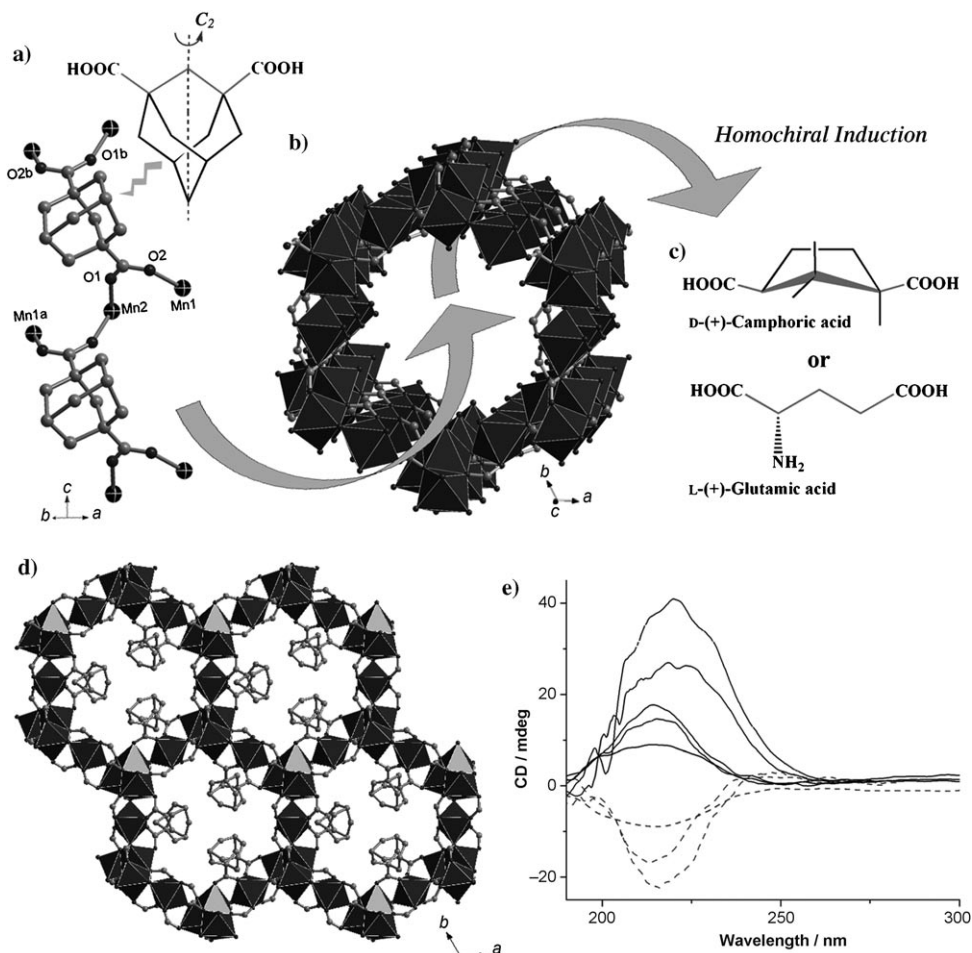


Figure 1. a) The [Mn(adc)]_n chain based on achiral adc ligand with μ₄-coordination; b) the porous [Mn₃(HCOO)₄]_n²ⁿ⁺ channel based on inorganic Mn–O–Mn connectivity; c) two types of enantiopure catalysts used for synthesis and chiral induction of **1b**; The directions of arrows show the possible mechanism of chiral induction. D-camphoric acid initially controls the absolute chirality of [Mn₃(HCOO)₄]_n²ⁿ⁺ frameworks but is later displaced by adc. d) the 3D hybrid framework of **1b**, showing the achiral [Mn(adc)]_n chains attached to the wall of the nanosized channels; e) the solid-state CD spectra of **1b** (—) and **1L** (----). Each curve represents the signal from the sample of an independent synthesis.

HCOO[−] at the beginning of the reaction led to the formation of manganese formate.

Recognizing the structural similarity between adc and camphorate ligands, we envisaged that other ligands with coordination geometry similar to H₂cam might also be able to function as the catalyst for the asymmetric crystallization of [Mn₃(HCOO)₄(adc)]. Indeed, the use of glutamic acid also leads to the asymmetric crystallization of [Mn₃(HCOO)₄(adc)], as evidenced by the CD spectra (Figure S3 in the Supporting Information). However, unlike D- and L-camphoric acids, which give **1b** and **1l**, respectively, L-glutamic acid catalyzes the formation of **1b**, while D-glutamic acid catalyzes the formation of **1l**.

The above study with glutamic acid further suggests that to induce asymmetric crystallization, the chiral induction agent may need to possess proper coordination chemistry that matches well with the achiral framework building block. A similar example was recently found in the crystallization of a chiral zincophosphate.^[16] To further investigate this idea, we also studied the effect of other amino acids (L-alanine, L-histidine, and L-aspartic acid) in the crystallization of [Mn₃(HCOO)₄(adc)]. For L-alanine, the achiral compound **2** was obtained, similar to the reaction performed without the use of any induction agent. For L-histidine, the resulting product is an unknown polycrystalline phase. For aspartic acid, neither achiral [Mn(adc)] nor chiral [Mn₃(HCOO)₄(adc)] crystallized, and only aspartic acid crystals could be recovered.

In conclusion, we demonstrate herein an unusual asymmetric crystallization of a new 3D porous material constructed entirely from achiral building units by using enantiopure organic acids or amino acids as the chirality-inducing agents. In addition to controlling the absolute chirality, the chiral induction agent is also essential to initiate the nucleation of the chiral crystals. It is suggested that the chirality control is achieved through cooperative binding between enantiopure chiral reagents and achiral structural building units and that enantiopure chiral reagents control the absolute chirality of crystals by participating in the nucleation and crystallization processes but are later replaced with achiral ligands in the resulting crystals. The discovery that camphoric acid can control the absolute chirality of the 3D porous [Mn₃(HCOO)₄]²⁺ framework by either direct binding to the framework or by catalytic chiral induction (depending on whether the competing adc ligand is present or not) is truly unprecedented and extraordinary.

Experimental Section

1b: Adamantane-1,3-dicarboxylic acid (H₂adc, 0.0798 g, 0.48 mmol), D-(+)-camphoric acid (0.0280 g, 0.13 mmol), and Mn(NO₃)₂·3H₂O (0.1390 g, 0.90 mmol) in DMF/ethanol (4.0415:0.8812 g) were placed in a 20 mL vial. The sample was heated at 120 °C for 4 days and then cooled to room temperature. After washing with ethanol, colorless crystals were obtained (yield: 80 %).

Crystal data for **1b**: C₁₆H₁₈Mn₃O₁₂, *M*_r = 567.12, trigonal, space group *P*3₂21, *a* = *b* = 15.1841(9) Å, *c* = 7.8474(9) Å, *V* = 1566.9(2) Å³, *Z* = 3, ρ_{calcd} = 1.803 g cm^{−3}, Flack parameter = 0.03(5), *R*1(*wR*2) = 0.0510 (0.1366) and *S* = 1.099 for 1602 reflections with *I* > 2σ(*I*). Crystal data for **1l**: C₁₆H₁₈Mn₃O₁₂, *M*_r = 567.12, trigonal, space group

*P*3₂21, *a* = *b* = 15.2162(10) Å, *c* = 7.9063(11) Å, *V* = 1585.3(3) Å³, *Z* = 3, ρ_{calcd} = 1.782 g cm^{−3}, Flack parameter = 0.00(4), *R*1(*wR*2) = 0.0445 (0.0944) and *S* = 0.980 for 1424 reflections with *I* > 2σ(*I*). Crystal data for layered compound **2**: C₁₂H₁₄MnO₄, *M*_r = 277.17, monoclinic, space group *Cc*, *a* = 7.7609(3), *b* = 20.5827(9), *c* = 7.0717(3) Å, β = 93.411(3)°, *V* = 1127.63(8) Å³, *Z* = 4, ρ_{calcd} = 1.633 g cm^{−3}, Flack parameter = 0.59(3), *R*1(*wR*2) = 0.0393 (0.0759) and *S* = 0.956 for 1843 reflections with *I* > 2σ(*I*).

CCDC 736430 (**1b**), 736431 (**1l**), and 736432 (**2**) contain the supplementary crystallographic data for this paper. These data can be obtained free of charge from The Cambridge Crystallographic Data Centre via www.ccdc.cam.ac.uk/data_request/cif.

Measurement of solid CD spectra: A mixture of about 3 mg sample and 40 mg dried KBr powder was well ground and then pressed into a disk for use in the CD measurements using a J-810 spectropolarimeter.

Received: November 5, 2009

Published online: January 14, 2010

Keywords: asymmetric amplification · chirality · homogeneous catalysis · metal–organic frameworks · microporous materials

- a) B. Kesanli, W. Lin, *Coord. Chem. Rev.* **2003**, 246, 305; b) L. Ma, C. Abney, W. Lin, *Chem. Soc. Rev.* **2009**, 38, 1248–1256.
- J. S. Seo, D. Whang, H. Lee, S. I. Jun, J. Oh, Y. J. Jeon, K. Kim, *Nature* **2000**, 404, 982.
- a) G. Férey, *Chem. Soc. Rev.* **2008**, 37, 191; b) J. Sun, C. Bonneau, Á. Cantín, A. Corma, M. J. Díaz-Cabañas, M. Moliner, D. Zhang, M. Li, X. Zou, *Nature* **2009**, 458, 1154–1157; c) Y. Han, D. L. Zhang, L. L. Chng, J. L. Sun, L. Zhao, X. D. Zou, J. Y. Ying, *Nat. Chem.* **2009**, 1, 123–127.
- A. J. Alexander, *Cryst. Growth Des.* **2008**, 8, 2630.
- M. Lahav, L. Leiserowitz, *Cryst. Growth Des.* **2006**, 6, 619.
- P. J. Walsh, M. C. Kozlowski, *Fundamentals of Asymmetric Catalysis*, University Science Books, Sausalito, California, **2009**.
- R. Vaidhyanathan, D. Bradshaw, J.-N. Rebilly, J. P. Barrio, J. A. Gould, N. G. Berry, M. J. Rosseinsky, *Angew. Chem.* **2006**, 118, 6645; *Angew. Chem. Int. Ed.* **2006**, 45, 6495.
- D. N. Dybtsev, A. L. Nuzhdin, H. Chun, K. P. Bryliakov, E. P. Talsi, V. P. Fedin, K. Kim, *Angew. Chem.* **2006**, 118, 930; *Angew. Chem. Int. Ed.* **2006**, 45, 916.
- E. V. Anokhina, Y. B. Go, Y. Lee, T. Vogt, A. J. Jacobson, *J. Am. Chem. Soc.* **2006**, 128, 9957.
- L. Pérez-García, D. B. Amabilino, *Chem. Soc. Rev.* **2002**, 31, 342.
- a) D. K. Kondepudi, R. J. Kaufman, N. Singh, *Science* **1990**, 250, 975; b) T. Ezuhara, K. Endo, Y. Aoyama, *J. Am. Chem. Soc.* **1999**, 121, 3279; c) S. Wu, Y. Wu, Q. Kang, H. Zhang, L. Long, Z. Zheng, R. Huang, L. Zheng, *Angew. Chem.* **2007**, 119, 8627; *Angew. Chem. Int. Ed.* **2007**, 46, 8475; d) S. K. Tulashie, H. Lorenz, A. Seidel-Morgenstern, *Cryst. Growth Des.* **2009**, 9, 2387.
- D. Bradshaw, T. J. Prior, E. J. Cussen, J. B. Claridge, M. J. Rosseinsky, *J. Am. Chem. Soc.* **2004**, 126, 6106.
- Z. Lin, A. M. Z. Slawin, R. E. Morris, *J. Am. Chem. Soc.* **2007**, 129, 4880.
- J. Zhang, S. Chen, T. Wu, P. Feng, X. Bu, *J. Am. Chem. Soc.* **2008**, 130, 12882.
- J. Zhang, S. Chen, H. Valle, M. Wong, C. Austria, M. Cruz, X. Bu, *J. Am. Chem. Soc.* **2007**, 129, 14168.
- J. Zhang, S. Chen, X. Bu, *Angew. Chem.* **2009**, 121, 6165; *Angew. Chem. Int. Ed.* **2009**, 48, 6049.