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A Homochiral Microporous Hydrogen-Bonded Organic Framework for Highly Enantioselective Separation of Secondary Alcohols

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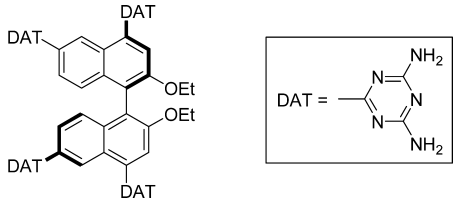
Supporting Information

ABSTRACT: A homochiral microporous hydrogen-bonded organic framework (HOF-2) based on a BINOL derivative has been synthesized and structurally characterized to be a uninodal 6-connected $\{3^3 5^5 6^6 7\}$ network. This new HOF exhibits not only a permanent porosity with the BET of 237.6 $m^2\ g^{-1}$ but also, more importantly, a highly enantioselective separation of chiral secondary alcohols with ee value up to 92% for 1-phenylethanol.

Porous hydrogen-bonded organic frameworks (HOFs)[1,2] have lagged significantly behind metal−organic frameworks (MOFs)[3,4] in terms of their development on their framework design, topological rationalization, and functional exploration, although the concepts of constructing such porous materials by making use of hydrogen bonding and coordination bonding, respectively, were proposed during the same time period as those of MOFs.[5,6] Such a situation is mainly due to the weaker hydrogen-bonding interactions within HOFs, which are typically not strong enough to stabilize the frameworks and establish their permanent porosities.[7] It is, therefore, not surprising that only recently a few HOFs have been shown to possess permanent porosities,[8−11] although a large number of HOFs have been structurally characterized and reported in the literature. Nevertheless, it is expected that the establishment of these few porous HOFs will initiate the rebounding interest in the exploration of functional porous HOF materials for their potential applications in gas storage and separation, sensing, and heterogeneous catalysis. Thus, further research endeavors to figure out the basic and strong hydrogen-bonding motifs to stabilize the frameworks, rationalizing that the basic principles for constructing the frameworks of the desired topologies and controlling the pore sizes, dimensions, and functionalities of the porous HOF materials for their diverse applications are warranted. Specifically, new hydrogen-bonding motifs need to be explored for the construction of porous HOFs and examined comprehensively on their universal applicability and feasibility to build a series of expanded HOFs whose pore sizes and functionalities can be systematically tuned and explored for their applications.

The hydrogen-bonding motif of 2,4-diaminotriazinyl (DAT), pioneered by Wuest, is of particular interest for constructing functional porous HOFs.[6f] This motif has recently been utilized not only to assemble a series of structurally porous HOFs[12] but also to achieve the first porous HOF-1 for the highly selective separation of C_2H_2/C_2H_4 at room temperature.[9] Given the fact that 1,1′-bi-2-naphthol (BINOL) is a very powerful organic backbone for asymmetric induction,[13−15] we incorporated the (*R*)-BINOL scaffold into 2,4-diaminotriazinyl hydrogen-bonding motif to synthesize a new chiral organic building block for the self-assembly of HOFs (Scheme 1).

Scheme 1. Organic Building Block To Build HOF-2



Herein we report the crystal structure of this new homochiral HOF-2 of the uninodal 6-connected $\{3^3 5^5 6^6 7\}$ network topology. More importantly, this homochiral HOF-2 exhibits highly enantioselective separation of chiral secondary alcohols, with the enantiometric excess (ee) up to 92% for 1-phenylethanol because of the specific recognition of HOF-2 for the 1-phenylethanol molecule.

The chiral organic building block, shown in Scheme 1, can be readily synthesized in 52% yield by reacting known chiral nitrile with dicyandiamide (see Scheme S1 in the Supporting Information [SI]).

Single crystals of HOF-2 suitable for X-ray diffraction study can be easily obtained by slow evaporation of a solution of the organic building block in 2-methoxyethanol at room temperature. The purity of HOF-2 was confirmed by ^{1}H NMR spectroscopy, thermogravimetric analysis (TGA), and powder X-ray diffraction (PXRD) (Figures S1−S3 in the SI).

The single-crystal X-ray structure of HOF-2 reveals that it crystallizes in a chiral space group P65.[16] HOF-2 is a three-dimensional porous material in which each organic building block is connected with six neighboring ones by multiple strong hydrogen bonds (Table S1 in the SI) among the 2,4-

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diaminotriazine groups (Figure 1a. Topologically, it can be viewed as a uninodal 6-connected $\{3^3 5^5 6^6 7\}$ network (Figure 1b). There exist one-dimensional hexagonal pores with a diameter of about 4.8 Å based along the *c* axis, taking into account the van der Waals radii (Figure 1a,b). The chiral pore spaces within the framework encapsulate a certain amount of disordered 2-methoxyethanol and H_2O solvent molecules. The solvent-accessible void space of porous HOF-2 is 54.3% by PLATON analysis. The homochiral channels are formed by rotational axes that are composed of building blocks 2 linked with each other by quadruple hydrogen bonds (Figure S4 in the SI). The framework is further enforced by multiple aromatic $\pi-\pi$ interactions among the organic building blocks. The collaborative hydrogen bonding and aromatic $\pi-\pi$ interactions have featured the HOF-2 as the rare example of potentially robust HOFs.

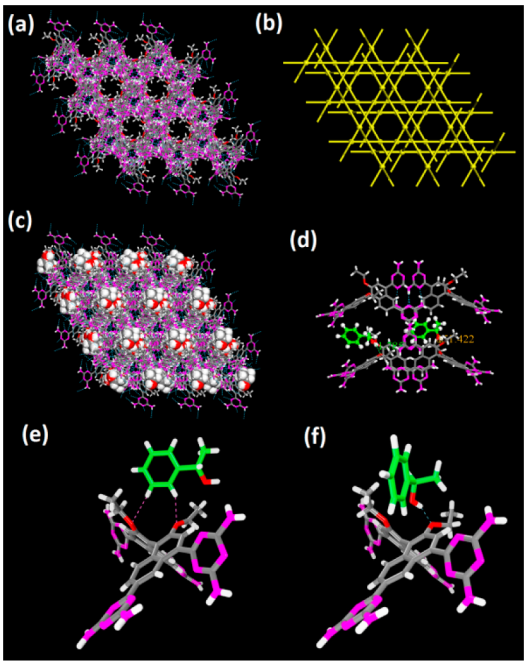

Figure 1. X-ray crystal structure of HOF-2 featuring (a) multiple hydrogen bonding (light-blue dashed lines) among adjacent units to form three-dimensional hydrogen-bonded organic framework exhibiting 1D hexagonal pores with the diameter of about 4.8 Å along the *c* axis and (b) the uninodal 6-connected $\{3^3 5^5 6^6 7\}$ network topology. X-ray crystal structure of HOF-2⊃*R*-1-PEA indicating (c) the enantiopure *R*-1-PEA molecules residing in the channels of the framework along the *c* axis and (d) the chiral cavities of the framework for the specific recognition of *R*-1-PEA which is further enforced by the hydrogen-bonding interactions among the −OH groups of *R*-1-PEA (green molecule) and oxygen atoms of the diethoxy groups from the HOF-2 framework. Comparison of X-ray crystal structures of (e) HOF-2⊃*S*-1-PEA and (f) HOF-2⊃*R*-1-PEA, indicating the different recognition of the HOF-2 for these two enantiomers (C, gray; H, white; N, pink; O, red).

Before performing the adsorption properties test and the chiral alcohol separation experiment, the guest solvent molecules in HOF-2 were removed by solvent exchange with diethyl ether, and the resulting samples were further activated at room temperature under high vacuum for 24 h to obtain desolvated HOF-2a. Such activation completely removed the guest molecules, as confirmed by ^{1}H NMR spectroscopy (Figure S7 in the SI). The PXRD pattern of the activated HOF-2a is only slightly shifted from that of the as-synthesized HOF-2 crystals (Figure S3 in the SI), indicating that the framework is retained. TGA shows that HOF-2a is thermally stable up to 350 °C (Figure S2 in the SI). The porosity of HOF-2a was evaluated by CO_2 gas sorption at 196 K. The type I isotherm shows a very sharp uptake at $P/P_0 < 0.1$, which indicates a microporous material. The CO_2 isotherm gives an apparent Brunauer−Emmett−Teller (BET) surface area of 237.6 m^2/g for HOF-2a, corresponding to a pore volume ~0.13 mL/g (Figure S5 in the SI). Its permanent porosity was further confirmed by C_2H_2 sorption isotherm at 273 K (Figure S6 in the SI).

The chiral porous nature of HOF-2 has enabled us to examine its potential for enantioselective separation of small alcohols, 1-phenylethanol (1-PEA), 1-(4-chlorophenyl)ethanol (1-(4Cl-PEA)), 1-(3-chlorophenyl)ethanol (1-(3Cl-PEA)), 2-butanol (2-BUT), 2-pentanol (2-PEN), 2-hexanol (2-HEX), and 2-heptanol (2-HEP) at room temperature. As shown in Table 1, HOF-2 shows different recognition behaviors for these small alcohols. For aromatic secondary alcohols, HOF-2 exhibits higher chiral separation for 1-phenylethanol (1-PEA) (ee of 92%, entry 1) than its derivatives 1-(4Cl-PEA) (ee of 79%, entry 2) and 1-(3Cl-PEA) (ee of 66%, entry 4), while for the aliphatic secondary alcohols, the HOF-2 shows enantioselective separation selectivity in the order of 2-BUT > 2-PEN > 2-HEX > 2-HEP (entries 3, 5−7). HOF-2 systematically displays higher enantioselective separation for aromatic secondary alcohols than for aliphatic secondary alcohols. The significantly high enantioselective separation of HOF-2 for the chiral aromatic 1-PEA (ee of 92%) is remarkable.[17] In fact, HOF-2 is superior to our best demonstrated MOF (ee of 82%)[18] for such an industrially important separation, given the fact that the chiral secondary alcohols are valuable intermediates in the synthesis of a variety of pharmaceutical, agricultural, and fine chemicals.[19,20]

Table 1. Resolution of Racemic Secondary Alcohols with HOF-2a at Room Temperature[a]

entry	secondary alcohols	ee (%)[b,c]
1	1-phenyethanol	92
2	1-(4-chlorophenyl)ethanol	79
3	2-butanol	77
4	1-(3-chlorophenyl)ethanol	66
5	*2-pentanol*	48
6	*2-hexanol*	<10
7	*2-heptanol*	<4

[a]See SI for experimental details. [b]Determined by HPLC. [c]*R* isomers are preferred.

In order to rationalize why HOF-2 exhibits highly enantioselective separation for 1-PEA, we characterized the X-ray single-crystal structure of the 1-PEA included HOF-2, which is prepared by soaking single crystals of the as-synthesized HOF-2 in racemic 1-PEA. The crystal structure clearly indicates that HOF-2 exclusively encapsulates *R*-1-PEA from the racemic mixture of the 1-PEA (Figure 1c) to form the HOF-2⊃*R*-1-PEA. Furthermore, the specific recognition of HOF-2 for *R*-1-PEA is not only attributed to the confinement of the chiral pockets induced by the chiral BINOL scaffolds but is also enhanced by the strong hydrogen bonding among the hydroxy (−OH) groups of *R*-1-PEA molecules and oxygen atoms of the diethoxy groups of the HOF-2 framework (d(O_3−

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H···O_1) = 2.585 Å) (Figure 1d, f). Comparative studies of the crystal structure of HOF-2⊃*S*-1-PEA show that the interactions between *S*-1-PEA molecules and host HOF-2 framework are much weaker; there only exist close contacts of C−H···O in the range of 3.284−3.574 Å.) (Figure 1e). To the best of our knowledge, this is the first example of homochiral porous HOFs for the enantioselective separation of small molecules.

In summary, we have not only confirmed that 2,4-diaminotriazinyl (DAT) is a very powerful hydrogen-bonding motif for the construction of porous robust HOFs, but even more importantly, we have also demonstrated the first example of homochiral HOFs for the highly enantioselective separation of small molecules. Because HOFs have some advantages such as solution processability and characterization, easy purification, and straightforward regeneration and reusage by simple recrystallization over porous MOF materials, some porous HOF materials might be potentially implemented in industrial and/or pharmaceutical applications. It is anticipated that the emerging HOF chemistry will prosper and more functional porous HOF materials will be targeted for their applications in gas storage, separation, sensing, and heterogeneous catalysis in the near future.

■ ASSOCIATED CONTENT

Supporting Information

Crystallographic data, TGA, PXRDs, HPLC plots, isotherm fit parameters, gas sorption isotherms, and additional figures. This material is available free of charge via the Internet at http://pubs.acs.org.

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Notes

The authors declare no competing financial interest.

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(16) See SI for the crystal data of HOF-2, HOF-2⊃*R*-1-PEA, and HOF-2⊃*S*-1-PEA.

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