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Communications to the Editor

Nanocavities with Fine Adjustment in Channel-Type Inclusion Crystals of Alkylammonium Deoxycholates. Control of Molecular Cavities by Partial Filling of Molecular Channels

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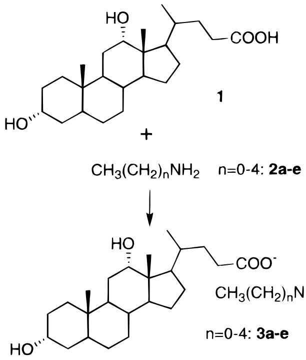
Molecular design of organic crystalline materials that have nanocavities with controlled size, shape, chirality, and chemical environment is of great interest in organic solid-state chemistry.[1,2] However, fine-tuning of nanocavities is in its infancy[3,4] because there have been few robust structural motifs that construct unchanged 3D framework against chemical modification. We present herein a novel strategy for tuning nanocavities by the binary host compounds that consist of the traditional host compound and the adjustable secondary components. This system gives us a series of the host cavities with the controlled size and shape at the finest resolution.

Deoxycholic acid (**1**) is one of the host compounds that forms molecular channels.[5] Inclusion complexes and the specific organic reactions in the crystalline state have been already well documented.[6,7] Our strategy for the fine-tuning of the molecular cavities relies on the robust porous bilayer structure of alkylammonium salts of **1**. The carboxylate anions construct a 3D framework with molecular cavities, and the alkylammonium cations partially occupy the cavities. Guest molecules are included in the remaining void space. Consequently, the steric dimensions and environments can be designed and controlled by the modification of the latter host components.

THF solutions of **1** were treated with excess **2a**−**e** to give **3a**−**e** as white precipitates in good yields (Scheme 1). They were subjected to recrystallization from various organic compounds for X-ray crystallography and the formation of inclusion crystals. Although the positions of the carboxylate anion of **1** were established for all five of the host systems, disorder of the alkyl groups of the ammonium cation and the guest compounds in **3d** was so severe that the carboxylate anion only can be refined isotropically. However, crystal structures of **3a**−**e** with the appropriate guest compounds are all isomorphic crystals.[8] A typical bilayer structure is depicted in Figure 1, and the host cavities of **3a**−**c** and **3d** in the lipophilic layers are shown in Figure 2. The arrangement of the carboxylate anion and the position of the nitrogen atoms of the ammonium cations in any salts are identical. They have the bilayer structures due to a facially amphiphilic molecular structure of **1**, and the wavy molecular shape results in the molecular channels in lipophilic layers. The alkyl group of the ammonium cations extends to the molecular channel, in which the guest molecules are also accommodated.

Scheme 1. Salt Formation of **1** with Aliphatic Amines (**2a**−**e**)



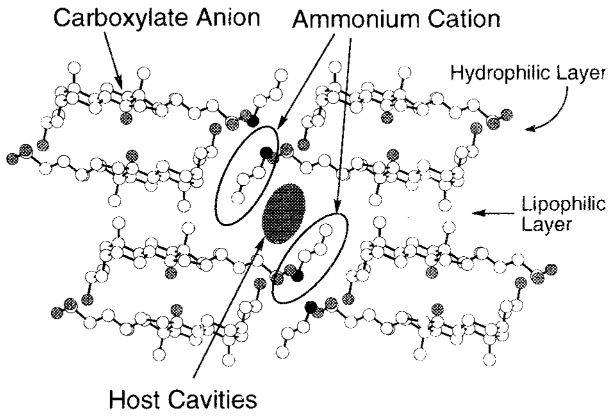


Figure 1. Crystal structures of an inclusion crystal of **3b** with 2-propanol (1:1), viewed along the screw axis (*b*-axis) with the *c*-axis horizontal. Hydrogen atoms are omitted for clarity. Empty, filled, and shadowed circles represent carbon, nitrogen, and oxygen atoms, respectively.

Steric dimensions of the cavities depend on those of the alkyl groups of **2a**−**e**. The salt **3a** has the largest cavities due to the smallest methyl group. The increase of carbon atoms of the ammonium cations decreases the size of the cavities. The salt

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(6) Reviews on inclusion compounds of **1**, Giglio, E. in ref 1d, Vol. 2, p 207; Miyata, M.; Sada, K. in ref 1e, p 147.

(7) Inclusion compounds of sodium salts of **1** have been reported, see Wahle, M. C. and Byrn, S. R. *Acta Crystallogr.* **1996**, *C52*, 2495.

(8) Crystal data for **3a** + *tert*-butyl alcohol (1:1): $C_{25}H_{45}NO_4 + C_4H_{10}O$, colorless, monoclinic, $P2_1$(No. 4), $a = 11.330(4)$ Å, $b = 7.573(8)$ Å, $c = 17.787(8)$ Å, $\beta = 107.02(3)$ Å, $V = 1459(1)$ Å^3, $Z = 2$, 298 K, $R = 0.062$, GOF = 1.69. **3b** + 2-propanol (1:1): $C_{26}H_{47}NO_4 + C_3H_8O$, colorless, monoclinic, $P2_1$(No. 4), $a = 11.205(2)$ Å, $b = 7.648(3)$ Å, $c = 17.822(2)$ Å, $\beta = 108.00(1)°$, $V = 1452.4(5)$ Å^3, $Z = 2$, 173 K, $R = 0.071$, GOF = 3.26. **3c** + methanol (1:1): $C_{27}H_{49}NO_4 + CH_4O$, colorless, monoclinic, $P2_1$(No. 4), $a = 11.177(5)$ Å, $b = 7.626(2)$ Å, $c = 17.129(8)$ Å, $\beta = 108.44(2)°$, $V = 1385.0(9)$ Å^3, $Z = 2$, 203 K, $R = 0.058$, GOF = 2.10. **3d** + 2-propanol (2:1): $C_{28}H_{51}NO_4 + {}^1/_2C_3H_8O$, colorless, monoclinic, $P2_1$(No. 4), $a = 11.280(8)$ Å, $b = 7.671(2)$ Å, $c = 17.743(4)$ Å, $\beta = 107.05(5)°$, $V = 1467(1)$ Å^3, $Z = 2$, 203 K, $R = 0.138$, GOF = 4.42. *n*-Butyl groups and guest molecules are disordered and could not be found. **3e**: $C_{29}H_{53}NO_4$, colorless, monoclinic, $P2_1$(No. 4), $a = 11.291(9)$ Å, $b = 7.622(2)$ Å, $c = 17.44(2)$ Å, $\beta = 107.68(7)°$, $V = 1430(1)$ Å^3, $Z = 2$, 203 K, $R = 0.064$, GOF = 2.31.

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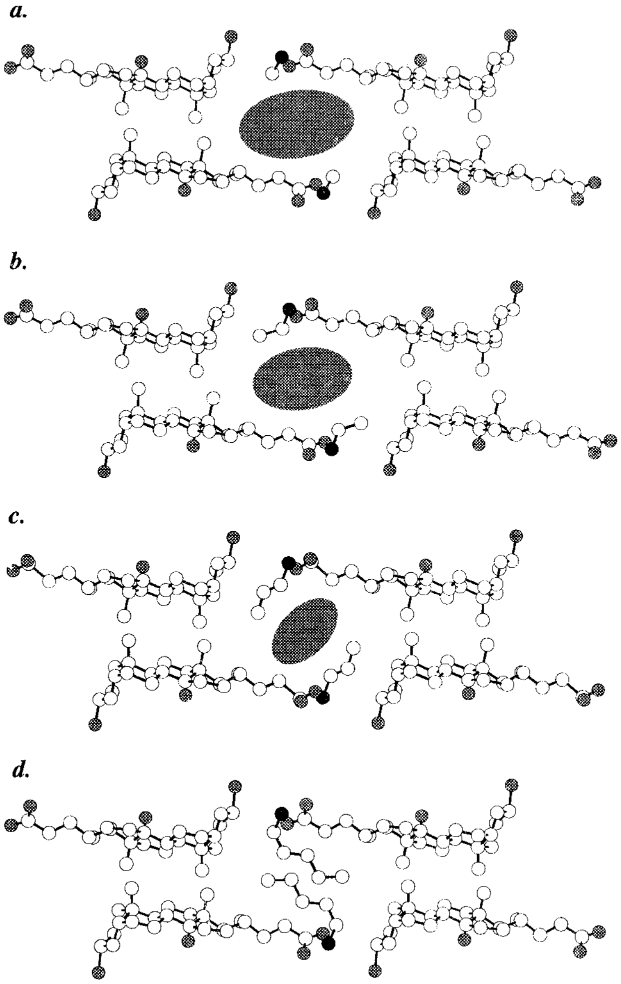

Figure 2. Lipophilic layers with host cavities of (a) **3a** with *tert*-butyl alcohol (1:1), (b) **3b** with 2-propanol (1:1), (c) **3c** with methanol (1:1), (d) **3e**. Guest molecules and hydrogen atoms are omitted for clarity, and gray ovals represent the host cavities.

3e provides, so far, no void space for guest molecules because the *n*-pentyl moiety fills the entire space. The steric dimensions of the void space are controlled by those of the ammonium cations that fill the molecular channels partially. Therefore, the carboxylate anion builds the robust framework with the large molecular cavities, and the ammonium cations adjust the size and shape of the molecular cavities.

Characteristics of the molecular cavities in **3a**−**e** appear in formation of inclusion complexes with small aliphatic alcohols. Table 1 summarizes the host−guest ratios of **3a**−**e** with a series of aliphatic alcohols. XRD patterns of the inclusion crystals indicate that they are all isostructural in this range of the guest compounds. The salts **3a** and **3b** form 1:1 inclusion compounds with larger alcohols and give no crystalline materials with small alcohols at all. **3c** and **3d** form inclusion crystals with a wide range of alcohols, but the host−guest ratios are much different. The salt **3c** yields mostly 1:1 host−guest ratios, but **3d** has the variable host−guest ratios that are dependent on the steric dimension of the guest alcohols. **3e** does not form inclusion crystals at all.

Table 1. Host−Guest Ratios of **3a**−**e** with a Series of Aliphatic Alcohols

guests	**3a**	**3b**	**3c**	**3d**	**3e**
methanol	NC	P	1:0.6	P	P
ethanol	NC	P	1:1.0	1:0.5	GF
1-propanol	NC	1:1.4	1:1.1	1:0.7	P
2-propanol	1:1.0	1:1.2	1:0.8	1:0.7	P
1-butanol	NC	P	1:0.9	1:0.5	GF
2-butanol	P	1:1.0	1:0.8	1:0.3	GF
iso-butanol	1:1.0	1:1.3	1:1.1	1:0.5	GF
tert-butanol	1:1.0	1:1.3	1:0.9	1:0.3	GF

[a] Host−guest ratios are shown, as determined by proton NMR. [b] NC: not crystallized. P: guest-free powder. GF: guest-free crystals.

This paper describes adjustable nanocavities by the salt formation of **1** with small aliphatic amines(**2a**−**e**). The carboxylate anion of **1** acts as a framework, and the ammonium cations as adjusters of nanocavities. Two-dimensional hydrogen bond networks in hydrophilic layers and steric complementary in lipophilic layers construct the robust bilayer structures with nanocavities in **3a**−**d**. This indicates that the 3D hydrogen bond network of the divergent multifunctional compounds are not always required to design the robust motifs in crystalline state.[2,3] Steric complementary of the lipophilic parts also plays an important role for the formation of the robust motifs. Moreover, Ward's nanoporous molecular sandwiches[4] and our results indicate that binary host systems that assemble by noncovalent bonds must be a powerful and facile strategy to construct the nanocavities with fine adjustment by changing one of the two component. A survey of guest compounds and systematic structural investigation of **3a**−**d** will reveal the robustness and flexibility of the host frameworks. The development of new host compounds with adjustable cavities by various combination of ammonium carboxylates is under investigation.

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Supporting Information Available: Tables of crystal data, structure solution and refinement, atomic coordinates, bond lengths and angles, and anisotropic thermal parameters for **3a**+*tert*-butyl alcohol (1:1), **3b**+2-propanol (1:1), **3c**+methanol (1:1), **3d**+2-propanol (2:1), and **3e** (50 pages, print/PDF). See any current masthead page for ordering information and Web access instructions.

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