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Control of Crystalline Phases in Four-component Mixtures of 1-Naphthylmethylammonium *n*-Alkanoates

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Various eutectic mixtures and organic alloys have been prepared by changing combination of four-component mixtures of 1-naphthylmethylammonium *n*-alkanoates, which implies high-fidelity control of molecular recognition in the solid state.

Parallel construction of two or more independent supramolecular assemblies simultaneously from multicomponent mixtures in solution has attracted growing interest in supramolecular chemistry due to understanding of orthogonality of supramolecular assemblies toward construction of highly organized complex mixtures such as a living cell.[1] However, in organic solid-state supramolecular chemistry, molecular design of formation of two or more independent cocrystals or inclusion crystals from multicomponent mixtures remaines in infancy.[2] Recently, we demonstrated that some mixtures of 1-naphthylmethylammonium *n*-alkanoates with various lengths of the alkyl groups provided binary and higher-order multicomponent molecular alloys that are single-phase crystalline materials composed of all the components (Figure 1).[3] Moreover, in a series of the binary mixtures, the mixtures with pairs of salts (***i*** and ***j***)[4,5] with different lengths of alkyl chains ($\boldsymbol{j} - \boldsymbol{i} > 6$) provided eutectic mixtures ([***i***] + [***j***]),[5] the mixtures of the single-phase crystals crystallized separately. When the differences were small ($\boldsymbol{j} - \boldsymbol{i} < 3$), the binary molecular alloy ([***i***,***j***])[5] homogeneous solid solutions composed of the two components were formed.[3] These results prompted us to investigate crystalline mixtures of four-component mixtures (***i***, ***j***, ***k***, and ***l***), which should theoretically form five possible crystalline mixtures summarized in Figure 2. In this report, we demonstrate construction of various crystalline mixtures with controlled crystalline phases by changing four alkanoates.

Four-component solid mixtures were prepared by mixing four salts (***i***, ***j***, ***k***, and ***l***) in methanol–THF solution, followed by removal of the solvents. We first investigated the selective formation of eutectic mixtures consisting of two binary organic alloys as type (3) in Figure 2. The four-component mixtures comprising two sets of the salts with the successive numbers, and the differences between the pairs were changed, as formulated by ***i***, $\boldsymbol{j} = \boldsymbol{i} + 1$, ***k***, and $\boldsymbol{l} = \boldsymbol{k} + 1$. As a typical example, the four salts **4**, **5**, **13**, and **14** were employed. X-ray diffraction (XRD) of the resulting crystalline mixture is shown in Figure 3, together with coground mixtures of their single

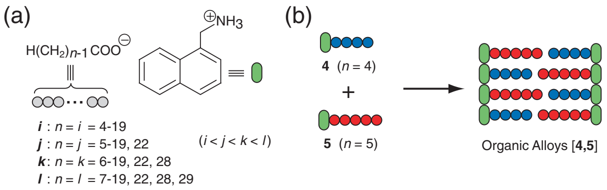

Figure 1. (a) 1-Naphthylmethylammoinum *n*-alkanoates (***i***, ***j***, ***k***, and ***l***) and (b) schematic drawing of the bilayered structure of binary organic alloy [**4**,**5**] from **4** and **5** in crystalline state.

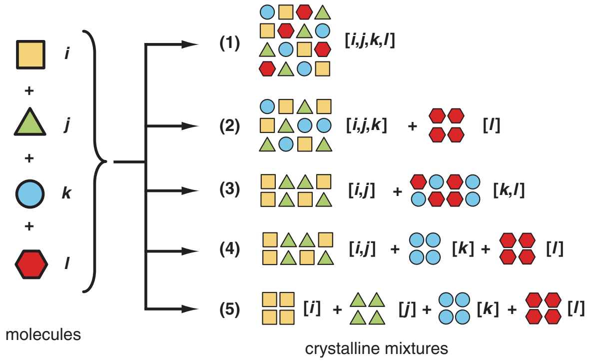

Figure 2. Possible five crystalline mixtures from four salts.

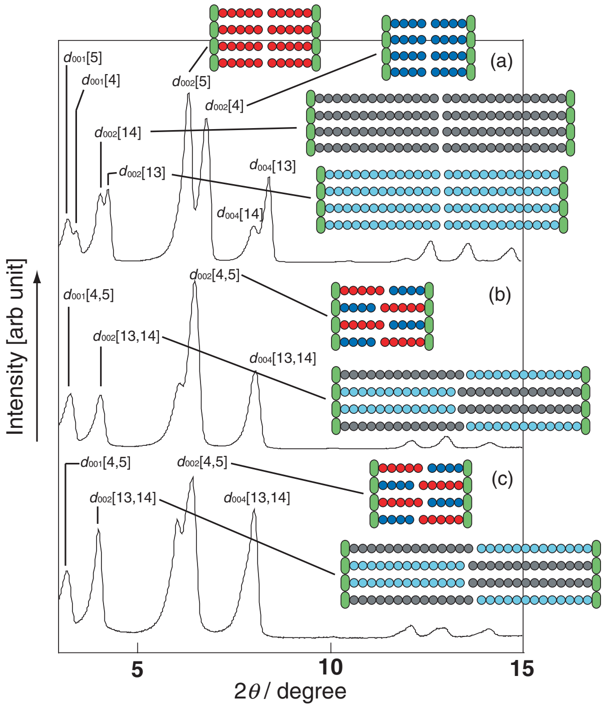

Figure 3. XRD patterns of (a) coground mixture of the single-component salts; [**4**], [**5**], [**13**], and [**14**], (b) crystalline mixture from 1:1:1:1 solution mixture of **4**, **5**, **13**, and **14**, and (c) coground mixture of the two binary organic alloys; [**4**,**5**] and [**13**,**14**].

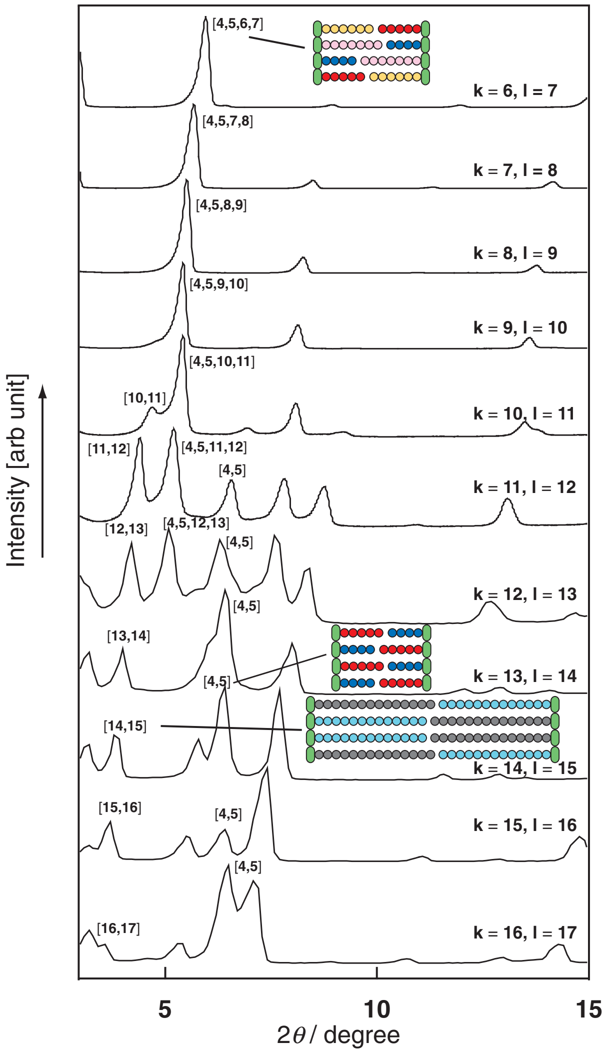

Figure 4. XRD patterns of crystalline mixtures from 1:1:1:1 quaternary solution mixtures of **4**, **5**, $\boldsymbol{k}$, and $\boldsymbol{k+1}$ ($\boldsymbol{k} = \mathbf{6}$–$\mathbf{16}$).

component salts (**4**, **5**, **13**, and **14**) and the two binary organic alloys of [**4**,**5**] and [**13**,**14**]. The peaks of 002 and 004 diffractions indicated that the crystalline mixture from the four-component solution mixture comprised two binary organic alloys of [**4**,**5**] and [**13**,**14**]. Neither other combinations of the binary solid solutions ([**4**,**13**], [**5**,**13**], [**5**,**14**], and [**4**,**14**]) nor single-component salts ([**4**], [**5**], [**13**], and [**14**]) were observed. Therefore, the solution mixture provided the eutectic mixture of the the two single-phase binary organic alloys among the five possible patterns of the crystalline mixtures. The effect of the differences between the two pairs was then investigated. One of the two pairs was fixed at $\boldsymbol{i} = \mathbf{4}$ and $\boldsymbol{j} = \mathbf{5}$, and the other pair was changed from $\boldsymbol{k} = \mathbf{6}$ to **16** (i.e., $\boldsymbol{l} = \boldsymbol{k} + \mathbf{1} = \mathbf{7}$ to **17**) as shown in Figure 4. In the region of the 002 diffraction, a sole peak was observed in the cases of the mixtures with $\boldsymbol{k} = \mathbf{6}$–$\mathbf{9}$, and shifted to the lower 2θ with increasing $\boldsymbol{k}$. It was assigned to the single-phase quaternary organic alloys ([**4**,**5**,$\boldsymbol{k}$,$\boldsymbol{k+1}$]), which was classified as type (1) in Figure 2. This should be achieved by complementary of **4** and **8**, and **5** and **7**. On the other hand, in the XRD patterns of the mixtures with $\boldsymbol{k} = \mathbf{13}$–$\mathbf{16}$, no peaks

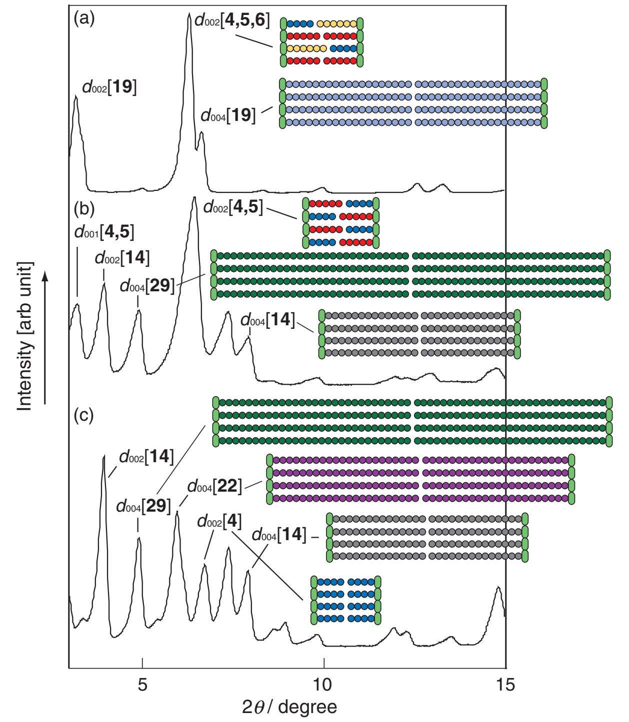

Figure 5. XRD patterns of 1:1:1:1 quaternary solution mixtures: (a) **4**, **5**, **6**, and **19** (b) **4**, **5**, **14**, and **29**, and (c) **4**, **14**, **22**, and **29**.

corresponding to the quaternary organic alloys were observed, and they were split into two peaks. One was constant against $\boldsymbol{k}$ and the other was shifted to lower 2θ with increase of $\boldsymbol{k}$. They should be assigned as [**4**,**5**] and [$\boldsymbol{k}$,$\boldsymbol{k+1}$], respectively. In the cases of the mixtures with $\boldsymbol{k} = \mathbf{10}$–$\mathbf{12}$, they yielded the eutectic mixtures of the quaternary organic alloys of [**4**,**5**,$\boldsymbol{k}$,$\boldsymbol{k+1}$] and binary organic alloys of [**4**,**5**] and [$\boldsymbol{k}$,$\boldsymbol{k+1}$]. No other pairs were observed. The mixtures of **4**, **5**, $\boldsymbol{k} \geq \mathbf{13}$, and $\boldsymbol{k+1}$ yielded the eutectic mixture of the two binary organic alloys ([**4**,**5**] + [$\boldsymbol{k}$,$\boldsymbol{k+1}$]), indicating the parallel cocrystallization of the two organic alloys among the four-component mixtures.

In order to prepare all other possible patterns summarized in Figure 2, the four salts $\boldsymbol{i}$, $\boldsymbol{j}$, $\boldsymbol{k}$, and $\boldsymbol{l}$, were properly selected, according to the rule for the formation of the binary organic alloys.[3] For type (2), three salts with the successive numbers of methylene groups ($\boldsymbol{i}$, $\boldsymbol{j} = \boldsymbol{i} + \mathbf{1}$, $\boldsymbol{k} = \boldsymbol{i} + \mathbf{2}$) and one salt that had six methylenes longer than that of the largest number among the other three ($\boldsymbol{l} > \boldsymbol{k} + \mathbf{6}$) were chosen. Figure 5a shows the XRD patterns of the mixture from the four salts; **4**, **5**, **6**, and **19**. It was identical to the summation of those of the single-phase ternary organic alloy [**4**,**5**,**6**] and the single-component salt [**19**]. The formation of the ternary organic alloy was caused by the formation of the alkyl bilayer structures consisting of [**5**,**5**] and [**4**,**6**]. For the type (4) and type (5), similar design of the mixing components could be applied. In the former class, requirement was as follows; $\boldsymbol{j} \leq \boldsymbol{i} + \mathbf{3}$ for the binary organic alloy, $\boldsymbol{k} > \boldsymbol{j} + \mathbf{6}$, and $\boldsymbol{l} > \boldsymbol{k} + \mathbf{6}$ for the eutectic mixture of two single-component crystals. Figure 5b shows the XRD patterns of the mixture from the four salts; **4**, **5**, **14**, and **29**. The XRD pattern was assigned as the organic alloy of [**4**,**5**] and two single-component salts of [**14**] and [**29**]. In the latter, the eutectic mixture with four single-component crystals was achieved from the mixture of **4**, **14**, **22**, and **29** as shown in Figure 5c. All the possible combinations of the binary organic alloys among the four salts did not form at all. Thus, no organic alloys were observed in the XRD pattern, and it was identical to the sum of each salt. Consequently, the appropriate choices of the starting mixtures of four *n*-alkanoate salts enable us to control cocrystallization and their crystalline phases precisely.

In conclusion, we demonstrated selective formations of various eutectic mixtures and organic alloys with designable crystalline phases among many possible crystalline mixtures. It implies high-fidelity control of self-recognition and cocrystallization in the solid state. In our best knowledge, this is the first example of controlling the phases in the solid mixtures of four-component mixtures of organic compounds. This is a good contrast to the extensive studies of the phases in inorganic solid mixtures. The precise control should provide access to design complex organic solid materials with integrated functions.

References and Notes

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1 For examples, see: P. Mukhopadhyay, P. Y. Zavalij, L. Isaacs, *J. Am. Chem. Soc.* **2006**, *128*, 14093; A. Brizard, M. Stuart, K. van Bommel, A. Friggeri, M. de Jong, J. van Esch, *Angew. Chem., Int. Ed.* **2008**, *47*, 2063, and references cited in.

2 A. I. Kitaigorodsky, *Mixed Crystals*, Springer Verlag, Berlin, New York, **1984**; C. B. Aakeröy, D. J. Salmon, *CrystEngComm* **2005**, *7*, 439; M. Dabros, P. R. Emery, V. R. Thalladi, *Angew. Chem., Int. Ed.* **2007**, *46*, 4132.

3 K. Sada, K. Inoue, T. Tanaka, A. Epergyes, A. Tanaka, N. Tohnai, A. Matsumoto, M. Miyata, *Angew. Chem., Int. Ed.* **2005**, *44*, 7059; K. Inoue, N. Tohnai, M. Miyata, A. Matsumoto, T. Tani, Y. Goto, S. Shinkai, K. Sada, *Cryst. Growth Des.* **2009**, *9*, 1072.

4 The bold and italic letters (***i***, ***j***, ***k***, and ***l***) represent not only the molecules, but also the numbers of the methylene groups in the *n*-alkanoate anions.

5 Single-phase crystalline mixtures are represented in the letters in the square blankets, and "plus (+)" indicates phase-separated crystalline mixtures.