A Novel Double-helical Assembly in Inclusion Crystals of Fumaropimaric Acid

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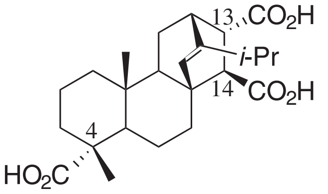
(Received July 25, 2003; CL-030681)

A crystal structure of the inclusion compound of fumaropimaric acid (FPA), a new host material, with 2-butanone reveals that the host framework is composed of novel double-helical supramolecular aggregates without hydrogen bonds between the intertwined helices.

Helical structures have fascinated many scientists because of the optical functions[1] and the structural interests.[2] In the field of bio-mimetic chemistry, design of the helical structures has become one of the largest interests. Recently, many kinds of helical structures have been reported by supramolecular methods.[3] Non-covalent helical backbones are mainly retained by the typical hydrogen bonds of each unit molecule.[4] In order to form one-dimensional assemblies, such unit molecules have at least two hydrogen-bonding groups without intramolecular hydrogen bonds. Therefore, the most judicious design of unit molecule may be that two independent hydrogen-bonding groups are located at both ends of the molecule.[5] On the other hand, multiple-helical structures are rare in crystalline states.[5b,6] This is because each intertwined single-helix is subjected to link each other in the close packing. We report here a novel double-helical structure that is composed of an asymmetric new host compound in the crystalline state.

Fumaropimaric acid (FPA), which is one of rosin mainly known as additives and modifiers for various applications,[7] has a robust asymmetric molecular skeleton with three carboxyl groups without intramolecular hydrogen bonds. One of the carboxyl groups is located at C4 position, and the others are located at the other end of the molecular skeleton, at C13 and C14 positions. From the locations of the hydrogen-bonding groups and the asymmetry of the molecular skeleton, it is thought that FPA satisfies the requirements for unit molecules of helical assemblies in the crystalline states. However, detailed study on the chemical properties has not been performed and its crystal structure has been unknown.

FPA was available from Arakawa Chemical Industries, and the acid was recrystallized from neat organic liquids. The resulting crystals were characterized by thermal gravimetric analysis and IR spectroscopy to determine the guest incorporation and stoichiometries. As shown in Table 1, FPA exhibited inclusion abilities for a wide variety of organic compounds, such as ketones, esters, acids, nitriles, hydrocarbons, alcohols, amines, and so on. Smaller guests form the inclusion crystals with 1:1 stoichiometry of host and guest, while larger ones with 2:1 stoichiometry. Much larger compounds form neither inclusion crystals nor guest-free crystals. This might be because the host cavities have size-limitations.



fumaropimaric acid (FPA)

The structure of a 1:1 inclusion compound with 2-butanone is further characterized by X-ray crystallography.[8] The molecular packing diagrams viewed down from the crystallographic *c* axis and *b* axis are illustrated in Figures 1a and 1b, respectively. The guest molecules are enclosed within the host cavities without hydrogen bonds between host and guest components. In addition, in some of the other inclusion crystals, the same host framework was directly observed by X-ray crystallography with the guest molecules disordered. Moreover, X-ray powder diffraction studies showed that the other inclusion crystals have the

Table 1. Inclusion abilities of FPA

Guest	H:G Ratio[a]	Guest	H:G Ratio
2-butanone	1:1	formic acid	1:1
2-pentanone	inc[b]	propionic acid	NC
3-pentanone	inc	*n*-valeric acid	NC
4-methyl-2-pentanone	2:1	acetonitrile	inc
cyclohexanone	2:1	benzonitrile	2:1
1-tetralone	2:1	chlorobenzene	2:1
methyl formate	1:1	cyclohexane	2:1
methyl acetate	1:1	dimethyl sulfoxide	NC
ethyl *n*-valerate	2:1	methanol	inc
acetic anhydride	2:1	ethanol	inc
ethyl methacrylate	2:1	1-propanol	inc
methyl tiglate	2:1	2-pentanol	NC
isobutyl tiglate	2:1	3-pentanol	NC
diethyl maleate	2:1	benzyl alcohol	NC
phenyl acetate	NC[c]	methylamine	inc
isopropyl benzoate	NC	*n*-butylamine	inc
n-hexyl benzoate	NC	*t*-butylamine	inc

[a]Host-guest ratio. [b]Inclusion crystals with unclear host-guest ratios were obtained. [c]Crystals were not generated from the solvent.

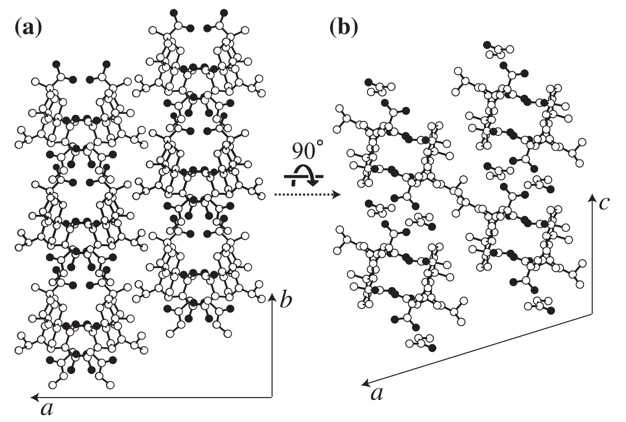


Figure 1. Molecular packing diagram of FPA with 2-butanone (1:1) viewed down from (a) *c* axis and (b) *b* axis. The empty and closed circles represent carbon and oxygen atoms, respectively.

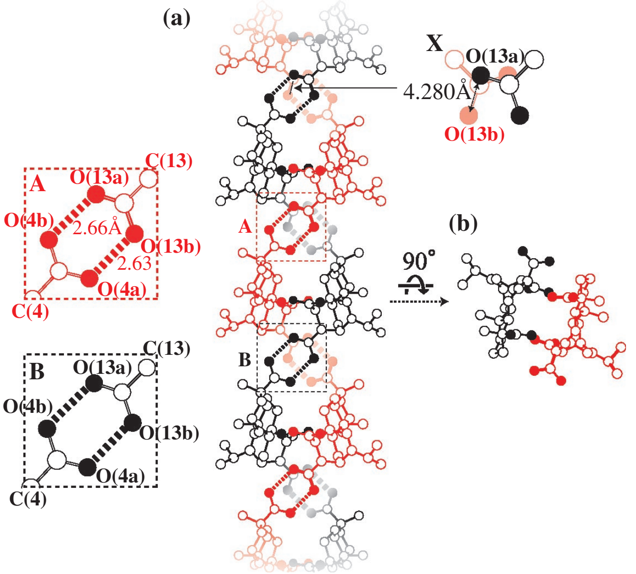


Figure 2. Double-helical assembly clipped from the crystal structure of FPA/2-butanone inclusion crystal viewed down from (a) the *c* axis and (b) *b* axis. O(4a), O(13a) and O(4b), O(13b) represent the oxygen of carbonyl group and hydroxyl group, respectively. Each hydrogen-bonding network (**A** and **B**) is used only for formation of each helical assembly. The most likely distance of hydrogen bond between red and black helices (**X**) is 4.28 A.

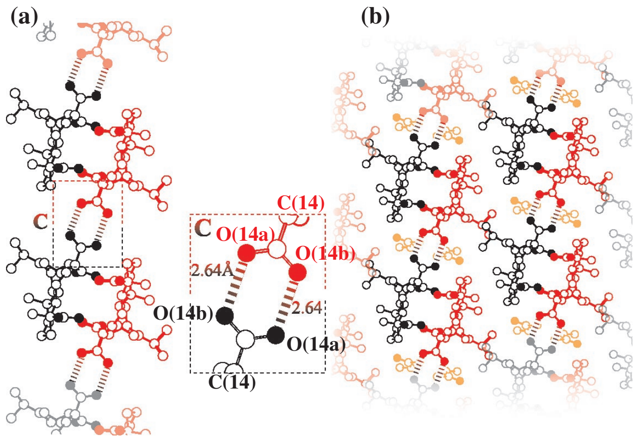


Figure 3. Bundle of the double-helical assemblies viewed down from *b* axis. (a) Sheet-like motif retained by the hydrogen-bonding network (**C**) between the neighboring helices and (b) three-dimensional molecular assembly resulted from the packing of the sheet-like motif and guest molecules (drawn with orange color). O(14a) and O(14b) represent the oxygen of carbonyl group and hydroxy group, respectively.

same host framework.

Insight of the hydrogen-bonding modes in the host framework gave us interesting structural information that the host framework is composed of a kind of double-helical assemblies. Figure 2 depicts the closeup of the double-helical assembly mode and the hydrogen-bonding networks viewed down from the *c* axis. For clarity, one of the intertwined helices is drawn with red color, and the other one with black. Each helix is retained by the cyclic hydrogen-bonding network with the sequence OH(4b)···O(13a)=C–OH(13b)···O(4a), where the hydrogen-bonding distances are 2.66 and 2.63 Å, respectively. Tracing the red network (A) embosses the red helix, whereas the black network (B) the black helix. It is noteworthy that there are no hydrogen bonds between the red and black helices. The closest distance between O(13b) of black(red) helix and O(13a) of red(black) one (X) is 4.28 Å. This may be because the two carboxyl groups at C4 and C13 are located in the both ends of the planar molecule and are fixed in the direction that twists mutually by 90 degrees. As the result, FPA prefers the twisted molecular packing with C_2 symmetry without hydrogen bonds between the opposite molecules. On the other hand, the carboxyl group at C14 position does not work to build the double-helical assembly.

The carboxyl group at C14 position is directed to outside vertical to the helical axis. Figure 3a highlights the manner of hydrogen-bonding networks between the neighboring helices viewed down from the *b* axis, which is also the axis of the helical assembly. The carboxyl groups at C14 work as linkages between neighboring double-helical assemblies to form the cyclic hydrogen-bonding network (C) with the sequence OH(14b)··· O(14a)=C–OH(14b)···O(14a), where the hydrogen-bonding distances are 2.64 and 2.64 Å, respectively. This network consists of the red helix and the neighboring black helix. As the result, the red-and-black networks align the double-helical assemblies to form hydrogen-bonded sheet motifs along the *c* axis. Subsequently, as illustrated in Figure 3b, these sheet motifs are further piled up with interdigitation of the isopropyl groups of FPA host molecules with guest molecules. The guest molecules are enclosed within the host cavities between the hydrogen-bonded double-helical assemblies to satisfy the dense packing for crystallization.

In this manner, FPA forms the characteristic host framework based on the novel double-helical assembly, which is also constructing the host frameworks of other inclusion crystals shown in Table 1. This robust host framework may be mainly due to the different roles of three carboxyl groups; the ones at C4 and C13 form the double helix, whereas the one at C14 links the neighboring double-helices. This might indicate that a hierarchical classification method is applicable to a series of inclusion crystals of FPA. Further insight into the robust helical assembly with various chemical modifications will be reported in due course.

References and Notes

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8 Crystal data for the inclusion crystal of FPA·2-butanone (1:1): $C_{24}H_{34}O_6{\cdot}C_4H_8O$, M = 490.64, monoclinic, $a = 23.921(6)$, $b = 9.996(1)$, $c = 11.670(3)$ Å, $\beta = 107.35(2)^\circ$, $V = 2573(5)$ Å^3, space group C_2 (No. 5), $Z = 4$, $D_c = 1.223$ g cm^{-3}, $R_1 = 0.083$, $_wR_2 = 0.208$, for 1602 with $|F_o|$.

Published on the web (Advance View) September 15, 2003; DOI 10.1246/cl.2003.952