Solvent Crystallization of α, β and γ Polymorphs of Oleic Acid

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The features of the solvent crystallization of α, β and γ polymorphs of ultra-pure oleic acid were examined in acetonitrile and decane. The solubilities of the three polymorphs were measured precisely, yielding a lower value for β than for the other two forms at any temperature. The solution-mediated transformation either from α to β or from γ to β was observed directly in the nearly saturated solution. It was found that this transformation occurred predominantly via the nucleation of the stable β form at the expense of the less stable ones. Finally the habit of the single crystal of each polymorph was determined for the first time. The results obtained were compared to the similar experiments of stearic acid polymorphs.

Unsaturated fatty acids are attracting considerable attention from various fields of science and technology. In particular, the functional activity of the biological membrane is dependent on the ability of biosynthesis of unsaturated fatty species of lipids (1). What is more, many fats derived from vegetable oils contain unsaturated fatty acids in their glyceride species. To better understand the physics and chemistry of the unsaturated fatty acids, obtaining a single crystal is quite important. So far, X-ray analyses for the powder sample (2) and for the single crystal having the lower-melting polymorph of oleic acid (3) were reported. The spectroscopic studies of the powder sample of some unsaturated fatty acids also were performed (4). No one, however, has been successful in growing single crystals of all the polymorphs possibly available. This is attributed to the fact that the complicated polymorphic behavior and its effects on the crystallization processes have not been fully clarified.

Very recently, Suzuki, Ogaki and Sato carried out a systematic study on the polymorphism of oleic acid by means of Differential Scanning Calorimetry (DSC) and X-ray diffractometry (5). Three polymorphs, α, β and γ, were confirmed. β is the most stable, having the highest melting point at 16.2 C. α and γ are metastable, undergoing a reversible solid-state transformation at −2.2 C on heating. α melts at 13.3 C, yet crystallizes more rapidly than β from the melt phase. A relationship between the three polymorphs is illustrated in Figure 1. This study could explain some contradictions which have appeared in the literature.

In this paper, we report fundamental data involved in a solvent crystallization: solubility of each polymorph, solution-mediated transformation between the polymorphs and the crystal habits. The results will be presented in comparison with those of stearic acid polymorphs because these two acids are the most typical saturated and unsaturated fatty acids.

MATERIALS AND METHODS

We employed oleic acid with purity of 99.999% (Nippon Oil and Fats Co., Amagasaki, Japan), acetonitrile (99%, Nakarai Chemicals, Tokyo, Japan) and decane (99%, Tokyo Kasei Co., Tokyo, Japan). These two solvents were chosen because the solubility has moderate values in an optimum temperature range for each polymorph: −2.2 C < α < 13.3 C, γ < −2.2 C and β < 16.2 C.

Solubility was determined by measuring the temperature at which the crystal of each polymorph reached equilibrium with the solution whose concentration was precisely measured. The solution was put in a thermostated growth cell (±0.05 C). We used an optical microscope to check the dissolution and growth of the crystals by fluctuating the solution temperature around the equilibrium condition. We first equilibrated the metastable forms which appear more rapidly than β (5). Then the same solution was stirred overnight so that the occurrence of β was enhanced. After all the excess β crystals were precipitated, the solution temperature was raised until the saturation temperature of β, T_s (β), was attained. As the dissolution rate of β is very low, a few hours were needed for the equilibration at each temperature around T_s (β). Next, the solution-mediated transformations from α to β and from γ to β were examined by the optical microscope at −5.0 C and 6.0 C in the stagnant solutions. This transformation, which comes from the difference in Gibbs energies of the polymorphs (6), may be important because it could occur during the crystallization process at a slow rate. The appearance and growth of β at the expense of α or γ in the solution with a passage of time were directly observed by the optical microscope. The polymorphic modifications of the crystals undergoing the transformation were examined by X-ray diffraction (5). Finally, the crystal shapes of α, β and γ were observed for the first time in the solutions at a very low supersaturation.

RESULTS AND DISCUSSION

Solubility. The solubilities are shown in Figure 2. It is clear that β is less soluble than the other two forms. This reflects the Gibbs energy relationship among these polymorphs. In decane, two solubilities exponentially increase in an almost parallel way. The difference in T_s (γ) and T_s (β) at a fixed concentration is 4.9 ± 0.1 C. In acetonitrile, the difference in T_s (α) and T_s (β) becomes a bit smaller with increasing concentration or temperature. The data are displayed in Table 1.

The molar fraction X of γ and β in decane and α and β in acetonitrile could be plotted in a straight line against $1/T(K^{-1})$ by the following van't Hoff equation:

$$\ln X = -\Delta Hd/RT + \Delta Sd/R \qquad [1]$$

where ΔHd is enthalpy of dissolution, ΔSd is entropy of dissolution and R the gas constant. The values of ΔHd and ΔSd are summarized in Table 2 together with those of B and C of stearic acid, and with enthalpy (ΔHf) and entropy (ΔSf) of fusion of α and β of oleic acid as well. It is worthy to compare the differences in the solubility

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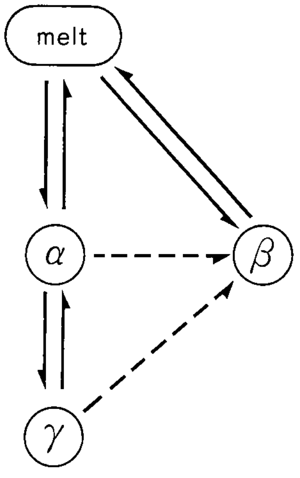

FIG. 1. A transition circuit of α, β and γ polymorphs of oleic acid, together with melt. Solid lines represent the reversible transitions, and dashed lines the irreversible ones.

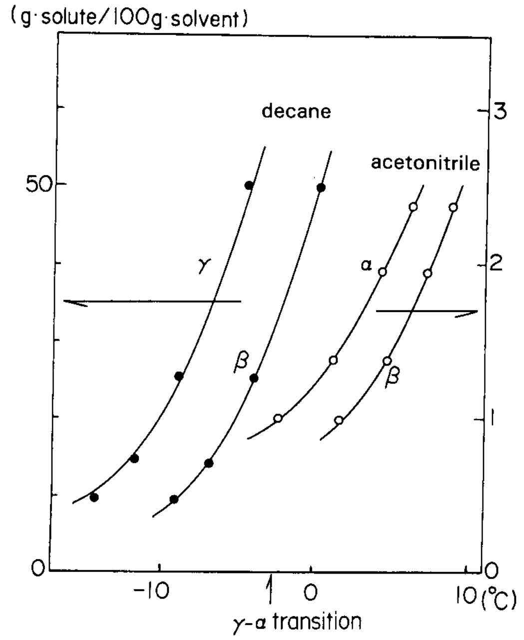

FIG. 2. Solubilities of α, β and γ polymorphs of oleic acid in decane and acetonitrile, as expressed in molar fraction.

TABLE 1

Solubility Data of α, β and γ Polymorphs of Oleic Acid

$\frac{\text{g} \cdot \text{solute}}{100\ \text{g} \cdot \text{solvent}}$	X^a (10^{-2})	$T_S{}^b$ (γ)	T_S (β)
Decane solution			
50.0	20.1	−5.1	−0.2
25.2	11.3	−8.9	−4.0
14.4	6.8	−11.9	−7.0
10.0	4.8	−13.5	−8.6

$\frac{\text{g} \cdot \text{solute}}{100\ \text{g} \cdot \text{solvent}}$	X (10^{-3})	T_S (α)	T_S (β)
Acetonitrile solution			
2.4	3.47	6.0	8.7
2.0	2.87	4.1	7.3
1.4	2.10	1.1	4.5
1.0	1.46	−2.2	1.5

[a] X, molar fraction of the total amount of oleic acid in solution.
[b] T_S, saturation temperature (C).

parameters of the polymorphs with those of fusion (5). γ and β have almost the same ΔH_d values, but the entropy term differs by 8 J/mol.K. We evaluate ΔH_f and ΔS_f of γ by adding the enthalpy (ΔH_{tr}) and entropy (ΔS_{tr}) of the $\gamma \rightarrow \alpha$ transformation (5) to ΔH_f and ΔS_f of α: ΔH_{tr} $(\gamma \rightarrow \alpha)$ + ΔH_f (α) = 48.4 KJ/mol, ΔS_{tr} $(\gamma \rightarrow \alpha)$ + ΔS_f (α) = 170.7 J/mol.k. Thus, both differences for γ and β are in good agreement with the solubility data. In acetonitrile, ΔH_d and ΔS_d of β are larger than those of α by 16.6 KJ/mol and 56.8 J/mol.K, both of which are about 1.5 times larger than the differences in ΔH and ΔS of fusion of α and β. The origin of this discrepancy most probably is due to the experimental errors in the solubility experiments. In addition, acetonitrile/oleic acid may be far from ideal solution conditions due to a remarkable difference in the molecular structure. This may be reflected in a larger difference between fusion and solubility data.

We calculated $T' = \delta(\Delta H_d)/\delta(\Delta S_d)$ for α-β using the solubility and melting data. This T′ value is very important because T′ may be equivalent to the crossing point of the Gibbs energies of the two forms. This was found to be true for B and C of stearic acid (7). The solubility data of α and β of oleic acid yields T′ = 19.1 C, whereas T′ = 27.6 C from the fusion data. This discrepancy may also be attributed to the non-ideal solution of the acetonitrile/oleic acid system mentioned above.

Solution-mediated transformation. Figure 3 shows the solution-mediated transformation from α to β in acetonitrile at 6.0 C. The amount of the α crystals precipitated was about 0.01 g in 10 g of solution. The solution was first saturated with respect to α. Then the β crystals with a needle shape started to appear. Once the new β crystals appeared, successive nucleation and growth of β continued, while the α crystals were disappearing. The transformation was completed within 1.5 hr. This rate was dependent on the amount of the first β crystals that appeared. Yet it was confirmed that a few hours were enough for α even with an initial amount of 0.1 g in 10 g solution to convert perfectly into β. The same process was observed for γ-β in decane at −5 C. The rate was much slower than α-β in acetonitrile at 6.0 C. This may be due to the lower temperature.

We again compared the present results with B and C of stearic acid. B has lower Gibbs energy than C below 32 C and vice versa (7). As the solid state transformation from C to B is kinetically hindered, the solution-mediated transformation is the single method to achieve the actual $C \rightarrow B$ transformation. A distinctive difference in the solution-mediated transformations between the two acids is its rate. In a stagnant solution of n-hexane at 17 C, C completely transformed to B over about two days under conditions similar to those in Figure 2. This may be due

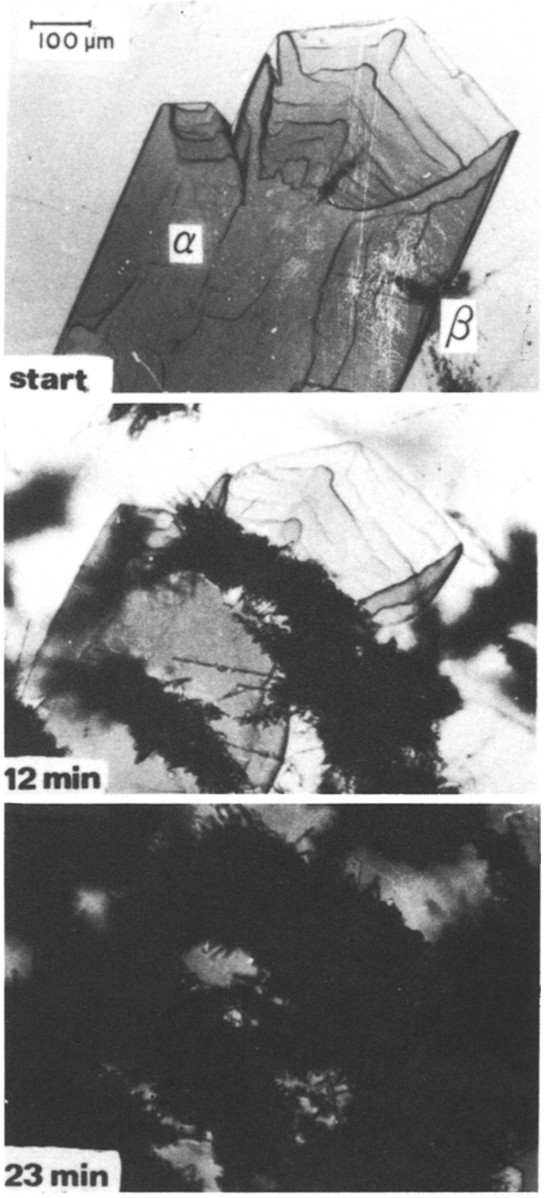

FIG. 3. A solution-mediated transformation from α to β of oleic acid in acetonitrile at 6.0 C.

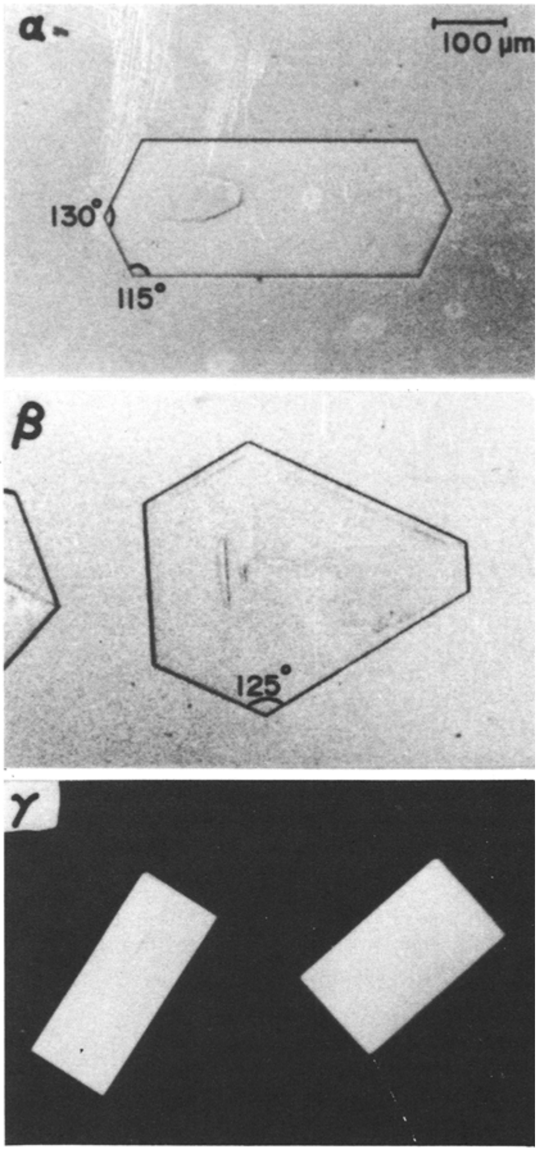

FIG. 4. Crystal habits of α (4 C in acetonitrile), β (7 C in acetonitrile) and γ (−5 C in decane) of oleic acid.

to two reasons. The first one comes from the difference in solubility, which results in a driving force of transformation. The driving force of the solution-mediated transformation is supersaturation σ: $\sigma = (X'/X'') - 1$, in which X' and X'' are the solubilities (molar fraction) of the metastable and stable forms, respectively (8). In B and C of stearic acid, $\sigma(C/B)$ at 17 C is 0.20, but $\sigma(\alpha/\beta)$ of oleic acid at 6.0 C is 0.39. Therefore the driving force of the transformation of $C \rightarrow B$ is about a half of that of $\alpha \rightarrow \beta$. This causes the different mechanisms of the solution-mediated transformations. In the case of stearic acid, the nucleation of B was less enhanced because of the smaller driving force. The growth of B is rate-determining. In oleic acid, however, the large driving force accelerated the successive nucleation of β, eventually causing the higher transformation rates that were observed experimentally.

In relation to the present solution-mediated transformation from α to β, we should note a conversion from α to β in the crystal grown from the solution. We observed that the α crystals obtained from acetonitrile changed to β in about one week at 10 C. After the conversion, the crystal was destroyed. This did not take place for the melt-grown α crystal which remained unchanged for more than several months at the same temperature. One of the reasons for this is the solution-mediated transformation via inclusions of mother solution which were incorporated into the crystal during the growth process. The newly nucleated β crystals in the liquid inclusion can grow at the expense of α, and are totally transformed to β after a long duration. So, one has to keep the solution-grown single crystals of α around 0 C because the occurrence and growth of β in the liquid inclusion was significantly slower at that temperature.

Crystal habit. Figure 4 shows the crystal habits of α, β and γ. All the crystals were of a tabular shape with a well-developed basal surface, which presumably is nor-

TABLE 2

Enthalpy (ΔH) and Entropy (ΔS) of Dissolution for α, β and γ of Oleic Acid and for B and C of Stearic Acid, Fusion of α and β of Oleic Acid and for a Solid State Transformation From γ to α

	Oleic acid							Stearic acid	
	Dissolution[a]							Dissolution decane	
	Decane		Acetonitrile		Fusion		Transformation		
	γ	β	α	β	α	β	γ → α	B	C
ΔH (kJ/mol)	100	100	59.4	76.0	39.6	51.9	8.8	138.0	128.6
ΔS (J/mol • K)	360	352	222.9	279.7	138.4	179.3	32.3	410.0	379.8

[a] Experimental errors; ΔH (±3), ΔS (±15) in decane, ΔH (±1), ΔS (±4) in acetonitrile for each polymorph.

mal to the long-chain axis. The photos were taken for the crystals in the solution. α reveals a slender hexagonal shape having the angles of 130° and 115°. β shows a truncated lozenge shape with the angles of 55° and 125°. The truncation occurred normal to the bisectrix of 55°. γ reveals a rectangular shape.

Since no detailed structural determination has been performed in relation to the crystal habit, we discuss the crystal habits from a geometrical point of view. β resembles the C polymorph of a saturated fatty acid with an orthorhombic subcell in a monoclinic unit cell (9). However, no conclusive statement between the subcell structures of β and C may be deduced because the lateral packing of the hydrocarbons having one double bond must be different from the saturated acyl chains. No shape similar to α and γ has been reported for the saturated fatty acids. The feature of γ is consistent with a subcell structure of $O'_{\parallel}$ consisting of the co-planar acyl chains which Abrahamsson et al. reported.

It is noteworthy to mention a morphological change from the shapes in Figure 4 to the needle shape when supersaturation of the solution is increased. The directions of the needle of α and γ are along the long wedges in Figure 4. The β crystal, however, was elongated along the bisectrix of 125°. The skeletal patterns of β in Figure 3 are the coagulated needle crystals which appeared in the solution with supersaturation of 39% with respect to β.

These crystal habits and their morphological changes will be interpreted precisely with the aid of the molecular structure data and growth rate experiments using the single crystals of the three polymorphs. Both experiments are in progress.

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