$(S\therefore S)^+$ is determined by the decay of the $S^{\bullet+}$ radical cation, mainly by decarboxylation. The τ_D's for the dimer decay in **7** and **8** are 700 and 900 ns, respectively, and both of the τ_D's are equal to $1/(k_{10}[\mathrm{CB}])$ within experimental error (Table II). Comparison of Φ'_{ketyl} and Φ_α values for **7** and **8** shows that diffusion apart, not proton transfer, is a dominant pathway. A significant contribution of radical ions in the quenching mechanism was also found in the benzophenone-sensitized photooxidation of 1,5-dithiacyclooctane.[40]

Conclusions

4-Carboxybenzophenone (CB) sensitized photooxidation of sulfur-containing amino acids in neutral aqueous solution occurs via electron transfer from the sulfur atom to the triplet state of CB. This was established by the large values of quenching rate constants (k_q's in the range of 10^8–10^9 M^{-1} s^{-1}, depending on the structure of the amino acid) and by the observation of free radical ions. In contrast to benzophenone/thioether systems,[25,26] where electron-transfer quenching is followed by intramolecular proton transfer within the CT complex (leading to the formation of α-(alkylthio)alkyl and ketyl radicals), electron-transfer quenching in CB/sulfur-containing amino acid systems is followed mainly by the diffusion apart of the CT complex (resulting in efficient formation of sulfur-centered radical cations and ketyl radical anions). The fast formation of ketyl radicals is ascribed mainly to the protonation of the initially produced ketyl radical anions (the proton transfer reaction within the CT complex, as it was shown for **1** and **4**, may lead to a contribution of about 35%). The slow formation of the ketyl radicals, which occurs on a microsecond time scale, is assigned to the one-electron reduction of the CB ground state by the α-aminoalkyl-type radicals. This was established by the linear dependence of the pseudo-first-order formation rate constants on the CB ground-state concentration, generation of the appropriate α-aminoalkyl radicals, and kinetic studies in the complementary pulse radiolysis experiments.

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Polymorphism in Anthranilic Acid: A Reexamination of the Phase Transitions

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Abstract: The three known polymorphs of anthranilic acid (2-aminobenzoic acid) have been examined by X-ray diffraction photography and infrared spectroscopy. The primary product of the phase transition occurring in heated crystals of polymorph I appears to be polymorph III, not polymorph II as commonly reported. The polycrystalline product III phase reverts to I on grinding. The III → I transition is also observed when an authentic sample of III is subjected to vigorous grinding. The occurrence of a II → I solid-state transition, the subject of disagreement in the literature, has been observed in samples of II subjected to vigorous grinding and sometimes spontaneously in single crystals of II. The product phase in the single-crystal II transition can be identified as I by its discrete X-ray reflections. The particular conditions required for initiating the II → I transition in intact single crystals of II have not yet been determined.

Introduction

As we have conducted our continuing investigation of hydrogen-bonded organic cocrystals, it has become clear to us that the solid-state behavior of one specific potential cocrystal component, anthranilic acid (2-aminobenzoic acid), should be reexamined.[2] This compound is commonly found on the shelves of most chemical laboratories and is structurally simple on the molecular level, but to a remarkable degree many of its solid-state properties remain ambiguous or obscure, even after over a century of investigations involving crystallographic and spectroscopic techniques. Reports concerning the properties of these polymorphs remain widely scattered throughout the literature, and some are strikingly contradictory. In this paper, we describe the results of our own investigation of the various anthranilic acid polymorphs, focusing primarily on the solid-state phase transitions that certain of these polymorphs undergo. Results obtained in our laboratory are in conflict in several areas with those published by previous workers over a period of many years.

Crystallographic investigations of anthranilic acid[3] date back at least to 1877, when Haushofer[4] published a description of the orthorhombic modification generally known today as polymorph I. X-ray and neutron crystal structure analyses have since established that this structure contains one neutral molecule and one zwitterion in the asymmetric unit.[5] A second polymorph, the one known today as polymorph II, was examined by Steinmetz;[6] this orthorhombic modification has since been shown by X-ray structure analyses to consist entirely of neutral molecules.[7,8] Steinmetz noted that heating I caused it to undergo an apparent

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solid-state phase transition, the initially clear crystals turning cloudy before reaching the melting point. Steinmetz suggested that the daughter phase of this transition, though similar in specific gravity to polymorph II, might, in fact, be a new phase. He therefore may deserve credit for being the first to recognize that at least three polymorphic forms of anthranilic acid exist. Steinmetz also reported that crystals of II turn cloudy on standing, possibly indicating a phase transition in this polymorph as well. The existence of monoclinic polymorph III was clearly demonstrated by McCrone and co-workers;[9] X-ray structure analyses have shown that, like polymorph II, III consists entirely of neutral molecules and is, in fact, structurally similar to II.[8,10,11] An early description of polymorphs I and II by Groth,[12] drawn in part from the work of Haushofer and Steinmetz and written at a time when polymorph III had not yet been positively characterized, simply states that the polymorph I transition yields polymorph II and does not mention the possibility that a third polymorph might be the actual product. Perhaps because this statement was made in a classic reference work, it has since been generally accepted that polymorph I is, in fact, transformed into polymorph II on heating in the solid state. Thermodynamic studies of the "I → II transition" have been published.[13-15] In addition, the polymorph II transition possibly observed by Steinmetz has been the subject of contradictory reports, with some workers testifying to its occurrence (citing X-ray photographic evidence)[15] and others stating that no unambiguous evidence for it exists.[8,14] Although spectroscopic evidence for phase transitions occurring at low temperatures (below 205 K) in anthranilic acid has appeared in the literature,[16] apparently no crystallographic evidence has been presented. Both the polymorph I and the polymorph II transformations are of particular interest in that they would involve proton transfer in the solid state; in a II → I transformation, for example, half the molecules in the crystal would be changed from neutral to zwitterionic. No solid-state transformations occurring in single crystals of III have been reported.

A potential complication in determining which anthranilic acid polymorphs might be produced in solid-state phase transitions is the reported tendency of certain of these polymorphs to be transformed by grinding. In several published infrared spectroscopic studies of the anthranilic acid polymorphs,[17-21] it has been reported that the appearance of the spectra obtained is affected by the amount of grinding required to prepare the sample pellet.[17-20] Although most of these workers have simply noted that these changes occur and have not identified the product polymorphs, Bellanato[18] has attempted to identify the product phases on the basis of their infrared spectra. She reports that polymorph I and polymorph II are usually not affected by grinding but that grinding can transform polymorph III primarily into I accompanied by a small amount of II. In addition, grinding I for an extended period (40 min) causes it to transform partly into II and partly into a new nonionic form which Bellanato reports to be different from both II and III. On the other hand, investigators conducting pressure studies on anthranilic acid have reported that although certain band positions in the infrared spectrum of this compound may change with increased pressure on the sample, no actual high-pressure phase transformations occur in their samples below applied pressures of 40 kbar (almost 40 000 atm).[17,22]

Experimental Section

Materials and Instrumentation. Anthranilic acid was obtained from Aldrich Chemical Company and from Eastman Kodak Company. X-ray powder diffraction spectra were obtained using a Siemens D-500 powder diffractometer. X-ray photographs were taken using standard Weissenberg and oscillation techniques (Cu Kα radiation). Conventional photographs were taken on Polaroid film with the use of a Nikon binocular microscope and camera. Melting points were determined using a Mettler FP80/FP84 Central Processor/Microscopy Cell DSC combined unit and are uncorrected. Infrared spectra were obtained from Nujol mulls using a Nicolet 5DXB FT-IR spectrometer.

Preparation of Polymorphs I, II, and III. Polymorph I (space group symmetry $Pna2_1$)[23] was most often obtained in our laboratory by slow evaporation of methanol or ethanol solutions of anthranilic acid. This usually resulted in the production of small brown bipyramids elongated along the *a* axis,[24] although some crystals grew quite large (several millimeters in length) and into a flattened triangular shape when evaporation occurred especially slowly (over a period of weeks). The crystals were found to be not uniformly brown; within the crystals the color was intense in some regions and absent in others, and certain crystals were almost entirely colorless. Slow cooling of a hot saturated aqueous solution of anthranilic acid yielded light brown needles of I, the needle axis corresponding to the *a* axis. A cool (room temperature) aqueous solution of anthranilic acid allowed to stand and evaporate for several days produced stout dark brown elongated prisms of I (markedly different in shape and color intensity from the other forms) with a parallelogram cross section and a long morphological axis corresponding to the *c* axis.

When heated on a hot stage or on a differential scanning calorimeter, initially clear brown crystals of I turned opaque white. Published reports state that the temperature of this transition depends on the rate of heating. Our results indicate that for a given heating rate (5 °C/min in our determinations) the transition temperature can range from 80 to 98 °C, depending on the type of I crystal being examined. There appeared to be a tendency for more intensely colored crystals (notably the dark brown elongated prisms) to transform at higher temperatures than less intensely colored ones. (The elongated prisms transformed at 98 °C, but the almost colorless bipyramids transformed at 80 °C at the same heating rate.) In each transforming crystal, the new phase appeared to begin growing at one or two sites and gradually spread throughout the crystal. It appeared that only a limited portion of the crystal could be transformed before cracks would appear that separated the transformed region from the region yet to be transformed. Growth of the new phase would then begin in a different region of the crystal. If the heat source was removed from the crystal during the transformation, the crystal remained partially transformed indefinitely. The transformed crystals ultimately melted at 147–149 °C.

Polymorph II (space group symmetry *Pbca*) was obtained by crystallization from a variety of solvents, including water, methanol, ethanol, nitrobenzene, acetic acid, and acetonitrile, often when crystallization occurred relatively rapidly (over a period of hours instead of days, as for I). This usually involved either allowing crystallization to occur while the solution was still warm or allowing a saturated solution to evaporate quickly. Like I, II displayed a variety of habits. It was obtained as almost colorless, flat laths elongated along *c* when aqueous solutions of anthranilic acid were seeded with fragments of the solidified melt in

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[21] For additional infrared studies, see: (a) Theoret, A. *Spectrochim. Acta, Part A* **1971**, *27*, 11–18. (b) Hadzi, D.; Premru, L. *Boll. Sci. Fac. Chim. Ind. Bologna* **1960**, *18*, 148–151. (c) Flett, M. St. C. *J. Chem. Soc.* **1951**, 962–967. (d) Ebert, A. A.; Gottlieb, H. B. *J. Am. Chem. Soc.* **1952**, *74*, 2806–2810.

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[23] Almost all previous literature references to I use the nonstandard $P2_1cn$ setting.

[24] For each polymorph, Weissenberg X-ray photographs were used to determine the general directions of the unit cell axes with respect to external crystal morphology, but no attempt was made to accurately index the various crystal faces. Identification of prominent crystal faces and lists of interfacial angles can be found in refs 9 and 12.

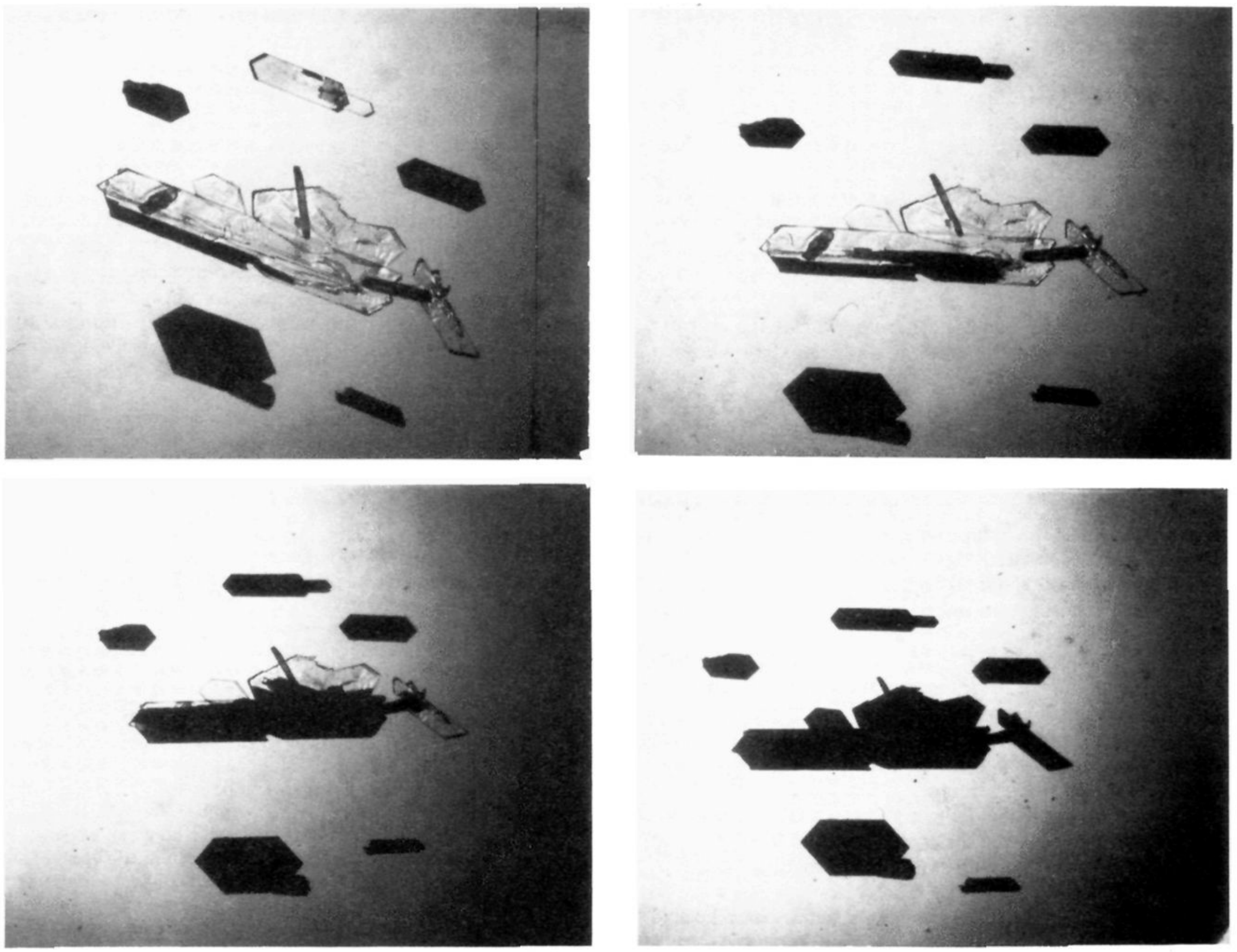

Figure 1. Clear prisms of II undergoing transformation into I on a microscope slide at room temperature. Photographs were taken at 2-week intervals in transmitted light. The opaque white I phase appears dark in these photographs. The large narrow crystal in the center of the photographs is 7 mm long.

attempts to obtain polymorph III from solution. A strikingly different form, yellow needles elongated along *b*, was obtained upon rapid crystallization from nitrobenzene. Polymorph II was occasionally obtained upon slow evaporation of saturated ethanol solutions, in which case it was obtained as flat, six-sided, clear and almost colorless prisms markedly elongated along the *c* axis, with the *b* axis located perpendicular to the largest crystal face. Under these conditions, the crystal batch usually included a few brown bipyramids of I. When these large flat prisms of II were allowed to stand under solvent for several days, they gradually disappeared and were replaced by I bipyramids.

The melting point of presumably untransformed II was found to be 147–148 °C, practically the same as that of I. No phase transformations of II other than melting were observed on the DSC during the melting point determinations. On the other hand, certain batches of crystals were observed to turn from clear and almost colorless (or clear yellow, in the case of the fine needles obtained from nitrobenzene) to opaque white on standing on microscope slides over a period of weeks (Figure 1). Like the I transformation, the II transformation appeared to begin at isolated points in the crystal and then spread throughout its bulk. In many cases, the initial site from which the new phase grew coincided with a place where two or more crystals had intergrown. Not every batch of crystals underwent this transformation, nor did every crystal in a transforming batch. Although some crystals began to transform within hours after being removed from the crystallization medium, others remained untransformed indefinitely. Some have remained untransformed for months. The reason for this striking difference in reactivity could not be determined. Attempts to initiate the transformation by pricking the crystals with a needle, exposing them to solvent vapors, and subjecting them to drastic temperature changes were not successful, although the slowness of the transformation was expected to make initiation difficult to observe. Neither exposing the crystals to light nor shielding them from it had any obvious effect on the occurrence of the transformation. Some of the crystals that had begun to transform were observed to remain partially transformed for weeks, and heating them caused them to simply melt without any further advance in the position of the phase boundary.

Polymorph III (space group symmetry $P2_1/c$) could be obtained in our laboratory only by sublimation or from the melt, despite repeated attempts to grow crystals of this polymorph from solution by seeding saturated solutions of anthranilic acid with fragments of the solidified melt or with crystals grown by sublimation. Batches of III crystals grown by sublimation were found (by single-crystal X-ray photography) to include crystals of II as well. The crystals of III grown by this method were clear, colorless, flat needles, with the unique *b* axis located perpendicular to both the needle axis and to the most well-developed face of the crystal. Crystals obtained from the melt were light brown, and those that actually possessed a well-defined morphology were needle-shaped. No transitions other than melting were observed when crystals of III were heated to their melting point of 147–148 °C (a melting point practically indistinguishable from that of I and II). The fine needles grown by sublimation tended to sublime further at room temperature if they were left in the open on a microscope slide.

Examination of the Phase Transitions. The identity of each type of anthranilic acid crystal as polymorph I, II, or III was determined by means of single-crystal X-ray photography, involving chiefly Weissenberg and oscillation techniques. The variety of habits assumed by the various polymorphs made it extremely difficult to distinguish reliably between one polymorph and another simply by appearance and without some kind of instrumental assistance.[25] The cell constants determined by means of Weissenberg photography were consistent with those already reported in the literature, with no new polymorphs of anthranilic acid being uncovered by our investigations. A further goal of our study was to determine the identity of the daughter phase within transforming crystals and to determine whether there was a unique and reproducible geometrical relationship (that is, a topotactic relationship) between the unit cell axes of the parent phase and the unit cell axes of the daughter phase. In this regard, X-ray photography proved to be extremely useful.

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(25) For a discussion of the dependence of anthranilic acid crystal habit on crystallization conditions, see: Wells, A. F. *Philos. Mag.* **1946**, *37*, 184–199.

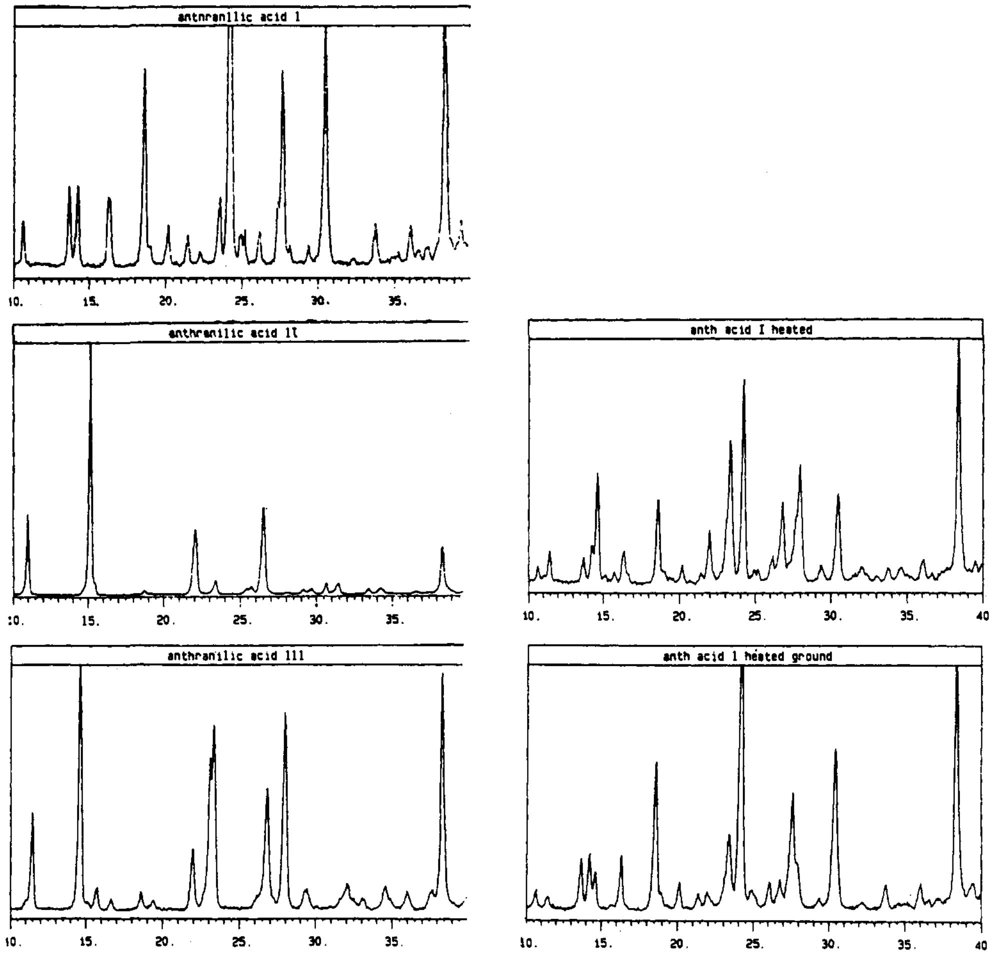

Figure 2. X-ray powder diffraction spectra of I, II, III, heated I, and heated I after additional grinding.

Oscillation X-ray photographs of I crystals transformed by heating showed powder diffraction rings, not well-defined single-crystal reflections, indicating that the daughter phase of this transformation was highly polycrystalline. Photographs of partly transformed crystals showed well-defined reflections associated with the parent I phase and powder rings associated with the daughter phase. In order to identify the daughter phase, powder photographs of ground samples of I, II, and III were taken on the Weissenberg camera and compared to those of transformed I single crystals and transformed I powders. (The powders were transformed by heating a thin layer of sample on a microscope cover slip placed on a Fisher-Johns melting point apparatus. The temperature was raised until a single crystal placed on top of the powder was seen to transform. The temperature required was usually less than 110 °C.) Although the powder patterns of II and III were found to be very similar to each other, the pattern of polymorph III (obtained from the melt, thus far the most reliable souce of this polymorph) appeared to match that of the transformed crystals and powders more closely, the difference between II and III being most readily apparent on the films in the difference in spacing between the two lowest-angle powder lines. Strong powder lines on the films were found at 2θ values of 14.3°, 16.3°, 18.6°, 24.2°, 27.7°, and 30.5° for I; 11.0°, 15.2°, 22.1°, and 26.5° for II; and 11.5°, 14.6°, 23.1°, 26.8°, and 28.0° for III. (The exact values reported here were obtained from subsequent X-ray powder diffraction spectra.) The strong lines in the patterns from transformed single crystals and powders appeared to be the same strong lines reported here for III. The fact that transformed single crystals of I (as well as the powdered samples) gave the pattern corresponding to III made it unlikely that III was present simply as the product of sublimation at the expense of any II produced. The pattern ascribed to III was obtained from both the ground melt and from a sample of unground melt that had been allowed to solidify in a capillary tube, indicating that the observed pattern was authentically that of III and not of II produced from III by grinding. The daughter phase, on the other hand, did prove to be sensitive to grinding. If the transformed powder was subjected to a few minutes of vigorous grinding in a mortar and pestle, the powder pattern that resulted was that of untransformed I.

Powder X-ray diffraction spectra of I, II, and III, of a heated powder sample of I, and of the heated I powder sample after further grinding were obtained and were found to be in accord with the photographic results.[26] When the ground sample of I was heated above its transition temperature, its powder diffraction spectrum gave way to a spectrum

Table I. X-ray Powder Diffraction Maxima (d, I/I_0) Greater than 10%

I	II	III	heated I	heated, ground I
	8.04, 32%			
		7.72, 41%	7.72, 15%	
6.48, 10%				6.48, 16%
6.21, 12%			6.21, 16%	6.23, 16%
		6.06, 100%	6.06, 41%	6.06, 12%
	5.84, 100%			
5.43, 10%			5.42, 14%	5.43, 17%
4.77, 28%			4.77, 36%	4.78, 45%
	4.03, 26%	4.05, 26%	4.05, 22%	
		3.85, 63%	3.86, 22%	
		3.81, 77%	3.81, 59%	3.80, 23%
3.67, 100%			3.67, 79%	3.68, 100%
			3.41, 13%	
	3.36, 35%		3.37, 12%	
		3.32, 50%	3.32, 33%	
3.22, 27%			3.22, 24%	3.23, 33%
		3.18, 81%	3.19, 48%	3.18, 13%
2.93, 33%			2.93, 37%	2.94, 49%
		2.79, 11%		
		2.59, 10%		
			2.35, 100% (Al)	

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(26) The X-ray diffraction spectra of I, II, and III measured here agree with those calculated using data from the published single-crystal structure determinations (refs 5, 7, and 10) and the DISPOW program from the N.R.C. Vax Crystal Structure System (Gabe, E. J.; Lee, F. L.; Le Page, Y. The N.R.C. Vax Crystal Structure System. In *Crystallographic Computing 3: Data Collection, Structure Determination, Proteins, and Databases*; Sheldrick, G. M., Kruger, C., Goddard, R., Eds.; Oxford University Press: Oxford, 1985.) The results of these calculations are available as supplementary material.

containing maxima corresponding to a mixture of III and untransformed I. This same sample was then subjected to further grinding, and a subsequent diffraction spectrum gave evidence that the sample was reverting to I (Figure 2 and Table I).

The X-ray results were confirmed by FT-IR spectroscopy. The spectrum of I is substantially different from those of II and III, which are quite similar to each other. However, all three polymorphs can be readily distinguished from each other by the positions of their N–H stretching bands. For I we observed these bands at 3324 and 3240 cm^{-1}, for II at 3474 and 3374 cm^{-1}, and for III at 3495 and 3382 cm^{-1} (all in Nujol). A sample of I that had been heated and then subjected to grinding showed bands at 3324 and 3239 cm^{-1}, indicative of I, and bands at 3495 and 3382 cm^{-1}, indicative of III, in addition to other bands indicative of III and not of II. Infrared spectra taken of ground mixtures of I and II, II and III, and I and III showed N–H bands characteristic of both polymorphs in the samples, demonstrating that the three polymorphs could be ground together pairwise (at least briefly) without any polymorph being readily transformed due to the presence of the other.

Unlike those obtained from transformed I crystals, X-ray photographs of transformed II crystals showed single-crystal daughter-phase reflections. When the daughter phase was brought into alignment, Weissenberg photographs taken of it were found to be reflection-for-reflection superimposable on corresponding photographs of untransformed I. For several partially transformed crystals, it was found possible to consecutively align the parent (II) and daughter (I) phases and note the relationship between the two sets of unit cell axes, although the failure of any daughter-phase axis to align itself exactly coincident with any parent-phase axis often made some tedious searching for the daughter phase necessary. As had already been suggested by differences between reflection patterns in corresponding Weissenberg photographs of different partially transformed crystals, the mutual orientation of the two phases was found to vary from crystal to crystal. No difference could be seen between X-ray photographs of II crystals that seemed reluctant to transform and photographs of the parent phase in II crystals actually undergoing the transformation.

Intact crystals of polymorph III were not observed to undergo any solid-state phase transitions. During our study, we noticed that upon standing for several days, previously well-shaped needles of III produced by sublimation began to curl and to assume a "corroded" appearance. To determine whether a transformation into a different polymorph was involved in this process, a rotation X-ray photograph of a corroded crystal was taken. The resulting photograph showed powder rings matching those of the solidified melt, indicating that despite its change in appearance while apparently subliming, the crystal was still III.

To determine whether long, hard grinding (in contrast to the brief grinding required for infrared and X-ray powder sample preparation) could cause any of the polymorphs to transform, all three were individually subjected to vigorous grinding in a small mortar and pestle. Powder photographs revealed no change in a sample of I that had been ground vigorously for 2 h. In contrast, X-ray photographs showed that 1 h of grinding converted II into I. A photograph of a III sample after 1 h of grinding showed very weak new bands, so another sample was ground vigorously for 2 h. The subsequent photograph showed that this III sample had been converted to I.

Discussion

Our conclusion that the product of the polymorph I transition is predominantly polymorph III and not polymorph II is in conflict with several published studies. However, in none of these studies is convincing proof provided that the product phase really is II. The earliest published evidence we have found is the similarity in specific gravity between II and the product of the solid-state transition, but as noted previously this agreement was not cited in the publication itself as positive proof that a third polymorph was not involved. (Densities calculated from crystal structure analyses of I, II, and III are 1.409 g/cm^3, 1.372 g/cm^3, and 1.39 g/cm^3, respectively.[5,7,10] The cracks and voids that always appear in the growing daughter phase may lower its measured density.) Those workers using X-ray photographic methods to identify the various phases have cited the resemblance between the pattern of the product phase and that of II, but we have found that the powder patterns of II and III on film are very similar and are perhaps easily confused. The failure of this transition to yield a product sufficiently ordered to produce single-crystal reflections greatly contributes to the difficulty of positively identifying the product phase. Our observation that the temperature at which the transition occurs appears to depend on the crystal color may be related to the reported capacity of I crystals to differ from each other in their degree of lattice order;[14] perhaps a low degree of lattice order is reflected in faintness of color and in a low transition temperature.

There now can be no question that polymorph II undergoes a transition that yields polymorph I as its product. We have observed this transition in transforming single II crystals and also in powdered II samples subjected to thorough grinding. The conflicting opinions over this transition's occurrence are probably the result of the failure of this polymorph to undergo the transformation readily and reproducibly in intact crystals under a prescribed set of conditions. Although our photographic evidence clearly shows that the II → I transformation can occur in intact single crystals, we do not yet know the conditions required for triggering its occurrence in this medium. For us, it has not clarified the situation to find that the anthranilic acid in a long-standing bottle of the commercially available material (Eastman) from our laboratory consisted primarily of II (as shown by X-ray photography and FT-IR analysis), prompting us to wonder why II persists indefinitely in this case and not in others. Perhaps the presence of solvent is necessary for the initiation of the transition but not necessarily for its continuation. The failure of the parent and daughter phases to assume the same mutual orientation from one transformed crystal to another is surprising, given the degree of crystallographic order that is required to be maintained for a transformation yielding a single-crystal product. It has been suggested that this absence of topotaxy in other systems may indicate the presence of a disordered intermediate phase during the transformation.[27]

Our results indicate that the product of the polymorph I transition is transformed back to I by grinding. Deciding then whether the product phase is actually II or III on the basis of this aspect of its solid-state behavior is impossible; as we have found, grinding converts both II *and* III to I. Unlike Bellanato, we did not observe a phase transition on simply grinding I, but we would not find it surprising if such a change actually were to take place under conditions different from those in our laboratory (at a higher temperature, perhaps). The possibility of an additional transition, a transformation of III into II, has been raised by reports from several investigators that III is often found to be contaminated with II. Although a III → II transition triggered by grinding under conditions of temperature and pressure different from those we have provided cannot be ruled out, our discovery of II needles in batches of III needles produced by sublimation suggests that workers using sublimation as their source of III may accidentally obtain some II as a cosublimate and not necessarily as a product of a solid-state transition. That II and III do not transform under grinding sufficient for the preparation of infrared or X-ray powder samples but *do* transform under some additional grinding is a fine example of polymorph behavior at its most subtle. An unnoticed transformation of II or III to I triggered by accidentally favorable conditions could easily contribute to confusion in the literature (for a possible example, see ref 9).

Conclusion

The results of our X-ray and infrared studies on the three known polymorphs of anthranilic acid indicate that polymorph I is transformed predominantly, if not entirely, into polymorph III on heating, not into polymorph II as commonly stated in the literature. Grinding the transformed crystals reconverts them to polymorph I. This III → I transition is also observed when an authentic sample of III is subjected to vigorous grinding. Crystals of polymorph II have been found to transform into polymorph I upon thorough grinding and sometimes (but not always) simply on standing. The conditions required for reproducibly accomplishing this transformation in intact crystals of II have yet to be determined.

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[27] For other examples, see: Byrn, S. R.; Curtin, D. Y.; Paul, I. C. *J. Am. Chem. Soc.* **1972**, *94*, 890–898, and references therein.

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Supplementary Material Available: Calculated X-ray diffraction spectra of polymorphs I, II, and III (see ref 26) (12 pages). Ordering information is given on any current masthead page.

Singlet Oxygen Mediated Fragmentation of Amino Alcohols, 1,2-Diamines, and Amino Ketones[1]

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Abstract: Irradiation of aerated solutions of singlet oxygen sensitizers such as Rose Bengal, Rose Bengal derivative, or palladium tetraphenylporphyrin in the presence of substituted amines (amino alcohols, 1,2-diamines, and amino ketones) results in oxidative fragmentation of the amine in good chemical yield and with low-to-moderate quantum efficiency. For the amino alcohols and 1,2-diamines the reaction course is similar to that initiated by irradiation of electron-transfer "sensitizers" such as thioindigo or cyanoaromatics. In these cases the reaction has been shown to proceed via single electron transfer oxidation of the amine and subsequent cleavage of the amine cation radical. A similar mechanism is proposed for the reaction with singlet oxygen sensitizers in which singlet oxygen initiates reaction by SET oxidation of the amine donors and subsequent reaction from the resulting superoxide–amine cation ion radical pair. For reaction with amino ketones under the same conditions, irradiation results in formation of novel fragmentation products incorporating oxygen. Labeling studies with O-18 enriched oxygen indicate that air is the source of certain of the incorporated oxygen in the products and suggest a mechanism closely related to the other fragmentation processes.

Introduction

Oxidative fragmentation reactions of vicinally substituted amines such as amino alcohols, 1,2-diamines, and amino ketones can be initiated by excited-state single electron-transfer (SET) from ground-state amine to photoexcited acceptors under a variety of conditions.[3-10] These reactions frequently involve relatively clean and moderately efficient reaction in which the substituted amine is converted to two-electron redox products concurrent with cleavage of the carbon–carbon bond between the two functional groups. While the reaction may involve an unassisted fragmentation of the amine cation radical in a number of cases, reaction for certain donor–acceptor combinations may be facilitated by a direct reaction between the acceptor anion radical and amine cation radical generated in the SET quenching process.[7,9] In a number of cases, particularly in those involving amino ketones as donors, reaction can lead to intermediates or products in which a fragment from the donor has been added to the acceptor.[9,10] In a previous communication we reported that similar oxidative fragmentation reactions occur for amino alcohols under conditions (dye sensitization) generally employed to generate singlet oxygen.[1] This study demonstrated that SET quenching of singlet oxygen, especially in nonpolar solvents, can lead to clean cleavage of a variety of amino alcohols under very mild conditions but with moderately low efficiencies. These were attributable, at least in part, to relatively inefficient redox quenching of singlet oxygen. In the present paper we report results which show that the singlet oxygen mediated cleavage of a variety of substituted amines by a similar mechanism is a fairly general process. While the products produced by the SET quenching and subsequent reactions for amino alcohols and 1,2-diamines are similar to those afforded with other photoexcited acceptors, the reaction using singlet oxygen sensitization with amino ketones leads to novel redox chemistry including the formation of a variety of products which result from the attack of superoxide anion on the amino ketone cation radical.

Experimental Section

Materials. The syntheses of amino alcohols, amino ketones, and diamines used in this study, with the exception of **7a**, have been reported.[7,8] Amino alcohols **1** and **2** and amino ketone **7** were further purified by repeated crystallization from ethanol. Amino ketone **7** was synthesized and characterized as follows: 2-Hydroxy-1-(4-methylphenyl)-2-phenyl-1-ethanone was prepared using published procedures.[11,12] Trimethylsilyl cyanide (4.96 g, 50.0 mmol) was added to 4.78 g (45.0 mmol) benzaldehyde with stirring. After the mixture cooled 25 mL of methylene chloride was added, and the solution was allowed to stir overnight. A Grignard reagent was prepared in the usual manner by combining 8.55

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