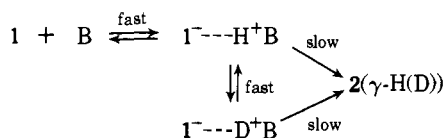Scheme II

tions of olefinic thiol esters similar to **1**. pH–rate profiles for thioester isomerases implicate general catalysis in isomerization of *N*-acetylcysteaminyl but-3-enoate to *N*-acetylcysteaminyl crotonate[6] and β-methylbut-3-enoyl coenzyme A to β-methylcrotonyl coenzyme A.[7] For the latter isomerization in tritium oxide, no incorporation of tritium into product was detected, suggesting βH is transferred to γ carbon without exchanging with solvent; the active site by its nature may exclude solvent water, or it may mediate an efficient intramolecular proton transfer.[35] Results of the isomerization of **1** to **2** suggest general acid catalyzed proton transfer to the γ carbon of either an ion pair, or a carbanion may be rate determining for the enzyme catalyzed reactions; apparent general base catalysis may in fact be general acid–specific base catalysis. It has been shown for the enzyme catalyzed isomerization of Δ^5-3-ketosteroids that a large isotope effect in ν_{max} results when 4-deuterio substrate is isomerized and that the proton at C-4 is transferred to the C-6 position. The favored mechanism was rate-determining enolization although proton transfer to γ carbon was not excluded.[37] Similarities of chemistry of ketones and thiol esters as carbon acids and the results of this study suggest rate-determining intramolecular proton transfer from β to γ carbon be more seriously considered in enzyme catalyzed isomerizations.

References and Notes

(1) This work was supported in part by grants from the U.S. Public Health Service.
(2) Taken in part from the M.S. thesis of P.H.G.
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Dehydration of a Carbinolhydrazine in the Solid State. Correlation with Crystal Structure of the Dehydration of 2-Hydroxy-2-(β-benzoyl-β-phenylhydrazyl)indan-1,3-dione[1,2]

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Abstract: 2-Hydroxy-2-(β-benzoyl-β-phenylhydrazyl)indan-1,3-dione (**1**) has been found to undergo thermal dehydration in the solid state to indantrione 2-(*N*-benzoyl-*N*-phenylhydrazone) (**2**). The white crystals of **1** are monoclinic, $a = 10.069$ (5), $b = 9.205$ (5), $c = 24.913$ (16) Å, and $\beta = 124.2$ (1)°; the space group is $P2_1/c$, and the structure has been refined to an R factor of 0.058 on 2589 nonzero reflections. The relationship of the crystal structure to the mechanism of dehydration in the solid state is discussed. The structure of **1** appears to be the first example of a structure of the type of intermediate that is formed in the reactions of carbonyl compounds with arylhydrazines and related compounds.

A recent upsurge of interest in organic reactions in the solid state[3,4] and in reactions between organic crystals and gases[4,5] has resulted in studies which have included thermal and photochemical intramolecular transformations and photochemical dimerizations of unsaturated compounds.

A particularly interesting type of thermal reaction is that in which reactants crystallize together as a complex which can then be caused to undergo reaction in the solid state. (Such reactions would be somewhat analogous to the well-known photochemical dimerizations that occur in the crys-
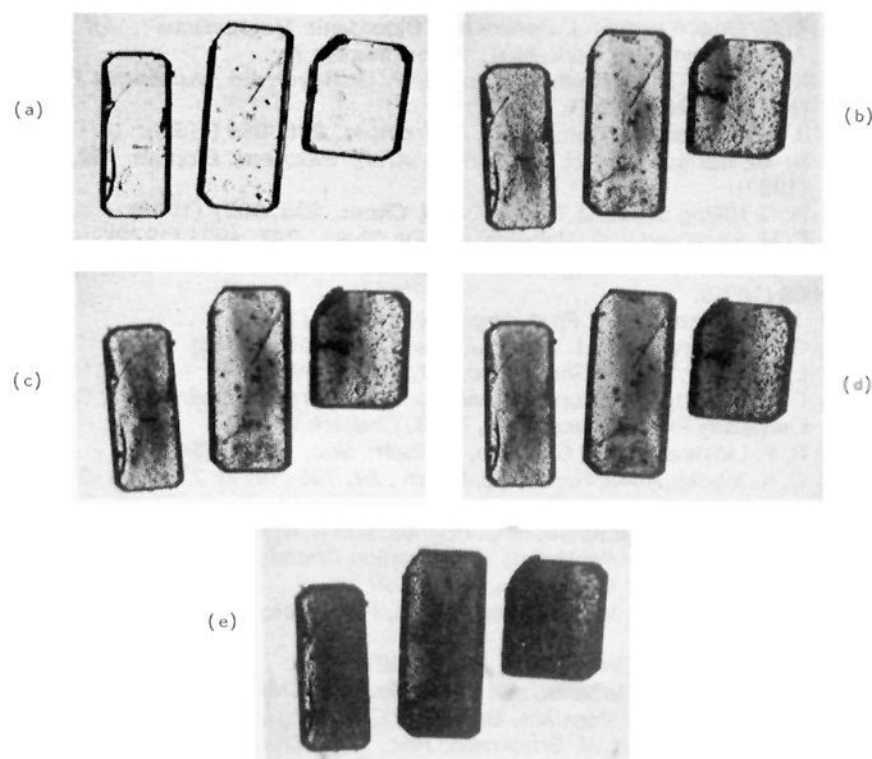
Figure 1. Solid-state dehydration of **1** followed on a microscope hot stage, illumination through the crystal. The dark regions formed as reaction proceeds appear red by incident light. (a) Initial crystals, 30°; (b) 61 h, 61°; (c) 90 h, 61°; (d) 119 h, 61°; (e) 332 h, 61°.

talline state.)[4] For example, triphenylcarbinol and pyridinium chloride form a 1:1 complex, mp 178°, which has been shown to decompose under vacuum at 200° to give the products indicated.[6] It has not been reported whether or not reaction can be made to proceed below the melting point of the complex.

$$(C_6H_5)_3COH + PyH^+Cl^- \rightarrow (C_6H_5)_3CCl + H_2O + Py$$
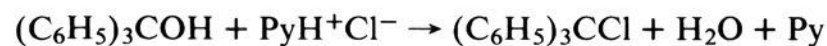
This example is one of a very large number of solution reactions in which both an acid (or electrophilic agent) and a base (or nucleophilic agent) must cooperate in causing the substrate to react.[7] Impressive rate enhancements have been obtained by partial ordering of the cooperating acid and base by the use of bifunctional catalysts,[8] macromolecular catalysts,[9] and, above all, enzymes.[8b,10]

This paper will present the crystal structure and preliminary results on the thermal dehydration in the solid state of 2-hydroxy-2-(β-benzoyl-β-phenylhydrazyl)indan-1,3-dione (**1**) to indantrione 2-(*N*-benzoyl-*N*-phenylhydrazone) (**2**). The crystal structure of the carbinolhydrazine **1** is shown to contain a hydrogen-bonding scheme appropriate for a self-catalyzed dehydration in the solid state.
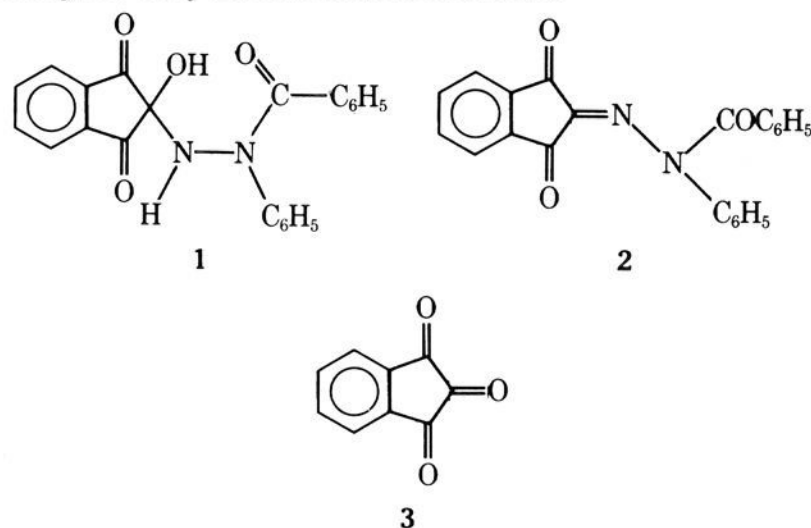
As a further point of interest, compounds with the carbinolhydrazine and related functional groups have been of particular importance in physical organic solution chemistry because of their role as intermediates in the reactions of carbonyl compounds with such reagents as hydroxylamine, semicarbazide, and arylhydrazines to give the correspond-

ing products containing a carbon–nitrogen double bond.[11] Carbinols, analogous to **1** (the intermediate in the reaction of indantrione (**3**) with *N*-benzoyl-*N*-phenylhydrazine), have seldom been isolated,[12] and **1** seems to be the first such example whose crystal structure has been determined.

Experimental Section

Spectra and other additional experimental detail are available in ref 1.

2-Hydroxy-2-(β-benzoyl-β-phenylhydrazyl)indan-1,3-dione (**1**). To a solution of 1.78 g (0.01 mol) of ninhydrin (the hydrate of **3**) dissolved in a minimum volume of warm methanol was added four drops of glacial acetic acid and the resulting solution cooled to −5°. A cold solution of 2.12 g (0.01 mol) of α-benzoyl-α-phenylhydrazine in methanol was added dropwise to the cold (<0°) ninhydrin solution. After 1 hr, colorless crystals began to precipitate. After n additional hour, the reaction mixture had become thick with white solid. The precipitate was filtered, washed thoroughly with several small portions of cold methanol, and then air-dried. Recrystallization from mixtures of diethyl ether and isooctane gave colorless crystals: mp 122–132° dec; ir (CHCl₃) 1630, 1723, and 1753 cm⁻¹; ir (Nujol) 1630, 1725, 1760, and 3300 cm⁻¹; NMR (CDCl₃) δ 6.2 (1 H, s), 6.4 (1 H, s, broad).

Anal. Calcd for $C_{22}H_{16}N_2O_4$: C, 70.93; H, 4.33; N, 7.56. Found: C, 70.73; H, 4.29; N, 7.77.

Attempts to purify the white solid **1** by recrystallization from acetone, benzene, or chloroform solution failed to give colorless crystals. Solutions of **1** in these solvents were observed to become red when allowed to stand for several days. Red crystals of the benzoylphenylhydrazone **2** were isolated from an attempted recrystallization of the white compound **1** from acetone. The only solvent which gave pure colorless single crystals of **1** was diethyl ether.

The interfacial angles of a crystal of **1** grown by slow evaporation of an ether–isooctane solution were measured with a Tecam two-circle optical goniometer. The crystals measured by optical goniometry and used for the x-ray structure determination were tablets elongated along *b* with {001} or {10$\bar{2}$} as the prominent faces: interfacial angles, ±1° (calcd) (001):($\bar{1}$02) 73° (73°), (001):(0$\bar{1}$0) 90° (90°), (001):(012) 47° (47°), ($\bar{1}$02):(0$\bar{1}$0) 90° (90°), ($\bar{1}$02):(012) 79° (79°).

Solid-State Thermal Dehydration of 2-Hydroxy-2-(β-benzoyl-β-phenylhydrazyl)indan-1,3-dione (**1**). A vial containing approximately 75 mg of small single crystals of the carbinolhydrazine **1** was heated at 65°. A good vacuum was maintained throughout the period of heating. During the reaction, the crystals of **1** became red. No evidence of melting was observed. After 3.5 weeks at 65° the crystals were nearly completely red in color. The visible spectrum of a freshly prepared acetonitrile solution of a sample of these red crystals exhibited an absorption characteristic of the benzoylphenylhydrazone **2**[13] in the 474-nm region. Calculations, based on the intensity of the 474-nm band, established that the dehydration product **2** was present in 23.8% yield. The microanalysis of the sample which was approximately one-fourth "dehydrated" still gave a correct analysis for the pure carbinolhydrazine **1**, indicating that in the early stages of the solid-state-dehydration, the water produced may not be escaping from the crystal lattice.

Anal. Calcd for $C_{22}H_{16}N_2O_4$: C, 70.9; H, 4.3; N, 7.6. Calcd for $C_{22}H_{15.52}N_2O_{3.76}$: C, 71.8; H, 4.3; N, 7.6. Found: C, 71.0; H, 4.8; N, 7.7.

The dehydration of single crystals of the compound **1** was observed on a microscope stage. At temperatures greater than 70°, the crystals of **1** eventually becamea red melt. At 65°, the solid-state thermal dehydration was observed over a period of approximately 3 weeks. Photomicrographs of the dehydration process run at 61° are shown in Figure 1. The dehydration of **1** showed anisotropic behavior. In a number of crystals studied, accumulation of the red product was first observed at the side face, (10$\bar{1}$) or ($\bar{1}$01), and spread in a direction parallel to the long morphological crystal axis (parallel to *b*). The advancement of a somewhat delineated red front proceeded slowly throughout the crystal in a direction parallel to the major face (001). After 17 days at 65°, the visible spectrum of the partially reacted crystals indicated that approximately 10% of the dehydration product **2** was present, and after nearly 4 weeks only 24% of **2** could be detected by spectral techniques.[14]

Table I. Final Atomic Coordinates in Fractions of the Unit Cell Edge for the Molecule 1[a]

	x	y	z
C(1)	0.6452 (3)	0.7885 (3)	0.3927 (1)
C(2)	0.5925 (2)	0.7386 (3)	0.3248 (1)
C(3)	0.7223 (3)	0.6272 (3)	0.3398 (1)
C(4)	0.8612 (3)	0.6572 (3)	0.4060 (1)
C(5)	1.0168 (3)	0.6039 (4)	0.4365 (1)
C(6)	1.1263 (4)	0.6521 (5)	0.4985 (2)
C(7)	1.0848 (4)	0.7452 (5)	0.5300 (2)
C(8)	0.9287 (4)	0.7969 (4)	0.5000 (1)
C(9)	0.8168 (3)	0.7504 (3)	0.4367 (1)
C(10)	0.5463 (3)	0.7917 (3)	0.1917 (1)
C(11)	0.5777 (3)	0.8088 (3)	0.1407 (1)
C(12)	0.5341 (4)	0.6986 (4)	0.0958 (1)
C(13)	0.5571 (5)	0.7167 (5)	0.0464 (2)
C(14)	0.6212 (5)	0.8423 (5)	0.0414 (2)
C(15)	0.6608 (4)	0.9529 (4)	0.0845 (1)
C(16)	0.6396 (3)	0.9360 (4)	0.1341 (1)
C(17)	0.8259 (3)	0.8638 (3)	0.2791 (1)
C(18)	0.9089 (3)	0.7631 (3)	0.2681 (1)
C(19)	1.0711 (4)	0.7867 (5)	0.2944 (2)
C(20)	1.1477 (4)	0.9052 (5)	0.3327 (2)
C(21)	1.0651 (4)	1.0025 (4)	0.3442 (1)
C(22)	0.9033 (3)	0.9832 (3)	0.3179 (1)
O(1)	0.5615 (2)	0.8466 (2)	0.4069 (1)
O(2)	0.7076 (2)	0.5326 (2)	0.3030 (1)
O(3)	0.4194 (2)	0.7383 (2)	0.1793 (1)
O(4)	0.4368 (2)	0.6824 (2)	0.2892 (1)
N(1)	0.6160 (2)	0.8671 (2)	0.2971 (1)
N(2)	0.6587 (2)	0.8425 (2)	0.2527 (1)
H(O)[b]	0.412 (4)	0.694 (4)	0.246 (2)
H(N)	0.530 (3)	0.927 (3)	0.278 (1)
H(5)	1.047 (4)	0.537 (4)	0.411 (2)
H(6)	1.239 (4)	0.616 (4)	0.523 (2)
H(7)	1.166 (5)	0.782 (4)	0.575 (2)
H(8)	0.887 (3)	0.863 (3)	0.518 (1)
H(12)	0.476 (3)	0.615 (3)	0.098 (1)
H(13)	0.523 (4)	0.644 (4)	0.016 (2)
H(14)	0.638 (4)	0.852 (4)	0.004 (2)
H(15)	0.710 (4)	1.045 (5)	0.080 (2)
H(16)	0.670 (3)	1.013 (3)	0.164 (1)
H(18)	0.852 (3)	0.681 (3)	0.244 (1)
H(19)	1.121 (4)	0.711 (4)	0.283 (2)
H(20)	1.264 (4)	0.921 (4)	0.350 (2)
H(21)	1.124 (4)	1.087 (4)	0.373 (2)
H(22)	0.843 (3)	1.053 (3)	0.327 (1)

[a] Standard deviations are in parentheses. [b] Hydrogen atoms are given the number or symbol of the atom to which they are covalently bonded.

X-Ray Structure Determination of 2-Hydroxy-2-(β-benzoyl-β-phenylhydrazyl)indan-1,3-dione (1). Crystal Data. $C_{22}H_{16}N_2O_4$; M = 372; monoclinic; a = 10.069 (5), b = 9.205 (5), c = 24.913 (16) Å; β = 124.2 (1)°; V = 1913 Å^3; Z = 4; d_c = 1.29; $F(000)$ = 776; μ = 7.52 cm^{-1} (Cu Kα, λ 1.54178 Å); systematic absences, $h0l$ when $l = 2n + 1$ and $0k0$ when $k = 2n + 1$, led unambiguously to the space group $P2_1/c$.

Intensity data were collected at ambient temperatures on a crystal with approximate dimensions of 0.6 × 0.3 × 0.2 mm. All unique reflections in the 2 θ range of 2–130° were measured using a moving-crystal, moving-counter technique at a scan rate of 1° min^{-1}. Data collection procedures have been described previously.[15] Three standard reflections were measured every 50 reflections. There was no visual evidence for any red discoloration of the crystal during the period of data collection. The intensities for the three standards varied randomly ±3% throughout the period of data collection. A total of 2589 reflections out of the 3327 independent reflections was considered observed at the 2 σ level. No corrections for absorption or extinction were employed.

The structure was solved by the symbolic addition method, using the FAME, MAGIC-LINK-SYMPL,[16] series of programs. The least-squares refinement of the positional and anisotropic thermal parameters for all nonhydrogen atoms led to an R factor of 0.093. The 16 hydrogen atom positions were located from a difference map. With the introduction of hydrogen atoms, the molecule was

Table II. Final Thermal Parameters[a,b] in the Molecule 1[c]

	β_{11}	β_{22}	β_{33}	β_{12}	β_{13}	β_{23} (× 10^4)
N(1)	103 (3)	123 (3)	18.4 (4)	11 (2)	24 (1)	8 (1)
N(2)	96 (3)	125 (3)	15.5 (4)	−5 (2)	18 (1)	1 (1)
O(1)	202 (3)	236 (3)	32.9 (5)	56 (3)	57 (1)	19 (1)
O(2)	207 (3)	127 (3)	31.8 (5)	−10 (2)	37 (1)	−7 (1)
O(3)	115 (3)	198 (3)	21.9 (4)	−35 (2)	15 (1)	−3 (1)
O(4)	102 (3)	209 (3)	27.6 (5)	−44 (2)	18 (1)	15 (1)
C(1)	133 (4)	146 (4)	23 (1)	9 (3)	32 (1)	14 (1)
C(2)	94 (3)	137 (4)	18.3 (5)	−13 (3)	17 (1)	9 (1)
C(3)	138 (4)	113 (3)	22 (1)	−12 (3)	27 (6)	7 (1)
C(4)	111 (4)	139 (4)	21 (1)	6 (3)	20 (1)	12 (1)
C(5)	123 (5)	192 (6)	32 (1)	28 (4)	25 (2)	20 (2)
C(6)	132 (6)	289 (8)	35 (1)	23 (5)	18 (2)	23 (2)
C(7)	171 (6)	310 (8)	22 (1)	−41 (6)	4 (2)	6 (2)
C(8)	194 (6)	229 (6)	22 (1)	−5 (5)	28 (2)	2 (2)
C(9)	123 (4)	163 (4)	18 (1)	0 (3)	20 (1)	12 (1)
C(10)	110 (4)	123 (3)	17.9 (5)	5 (3)	14 (1)	3 (1)
C(11)	118 (4)	142 (4)	14.9 (5)	24 (3)	14 (1)	1 (1)
C(12)	185 (5)	154 (5)	24 (1)	24 (4)	23 (2)	−3 (2)
C(13)	257 (7)	222 (7)	22 (1)	73 (6)	34 (2)	−11 (2)
C(14)	276 (8)	250 (8)	28 (1)	88 (6)	55 (2)	14 (2)
C(15)	234 (6)	210 (6)	27 (1)	40 (5)	52 (2)	14 (2)
C(16)	175 (5)	157 (5)	21 (1)	13 (4)	36 (2)	1 (1)
C(17)	93 (3)	134 (4)	16.9 (6)	3 (3)	18 (1)	7 (1)
C(18)	135 (5)	149 (5)	28 (5)	17 (4)	32 (2)	4 (2)
C(19)	157 (5)	240 (7)	39 (1)	56 (5)	48 (2)	16 (2)
C(20)	117 (5)	259 (7)	40 (1)	−16 (5)	31 (2)	6 (2)
C(21)	137 (5)	216 (6)	35 (1)	−46 (5)	28 (2)	−10 (2)
C(22)	117 (4)	155 (4)	24 (1)	−19 (4)	24 (1)	−4 (1)

	B_θ, Å^2		B_θ, Å^2		B_θ, Å^2
H(5)	8.6 (1.0)	H(14)	11.0 (1.2)	H(21)	8.0 (0.9)
H(6)	9.6 (1.0)	H(15)	10.6 (1.2)	H(22)	5.6 (0.7)
H(7)	10.7 (1.1)	H(16)	5.5 (0.7)	H(N)	5.2 (0.6)
H(8)	6.7 (0.8)	H(18)	6.0 (0.7)	H(O)	11.1 (1.1)
H(12)	5.9 (0.7)	H(19)	9.8 (1.1)		
H(13)	8.0 (0.9)	H(20)	9.1 (0.9)		

[a] Anisotropic thermal parameters expressed as $\exp[-(\beta_{11}h^2 + \beta_{22}k^2 + \beta_{33}l^2 + 2\beta_{12}hk + 2\beta_{13}hl + 2\beta_{23}kl)]$. [b] Isotropic thermal parameters expressed as $\exp[-B_\theta \sin^2 \theta/\lambda^2]$. [c] Standard deviations are in parentheses.

divided into two groups for further refinement. The first group consisted of N(1), O(4), C(4–9), C(11–22) and attached hydrogen atoms, while the second group consisted of N(1–2), C(1–3), C(10), and O(1–4) and attached hydrogen atoms. Positional and anisotropic thermal parameters were refined for the nonhydrogen atoms; positional and isotropic thermal parameters were refined for the hydrogen atoms. The final R factor was 0.058, and the weighted R factor, R_2, was 0.062 on all observed data (see Supplementary Material). A final difference map had no peaks greater than 0.15 electron/Å^3. During the final cycle of least-squares refinement, no parameter shifted by more than 0.2 times its standard deviation. The final atomic coordinates and thermal parameters are listed in Tables I and II, respectively. The atomic scattering curves for C, N, and O were taken from the compilation by Cromer and Mann,[17] while the curve calculated by Stewart et al. was used for hydrogen.[18]

Results and Discussion

The Molecular Structure of 1. A stereoscopic view of the molecule is shown in Figure 2. Bond lengths and angles are listed in Table III.

The lengths of the C(2)–N(1) and N(1)–N(2) bonds, 1.454 (3) and 1.413 (3) Å, indicate single bonds. The N(2)–C(10) amide bond is 1.370 (4) Å and is considerably shorter than the amide C–N bonds found in the indantrione 2-(N-benzoyl-N-phenylhydrazone) series that had a range of 1.410 to 1.457 Å.[13,19] This shorter value suggests that there is significantly more double bond character for the C–N amide bond of **1** than for the corresponding bond in any of the structurally related analogues.[13] The C(11–16) phenyl ring makes an angle of 42° with the plane through
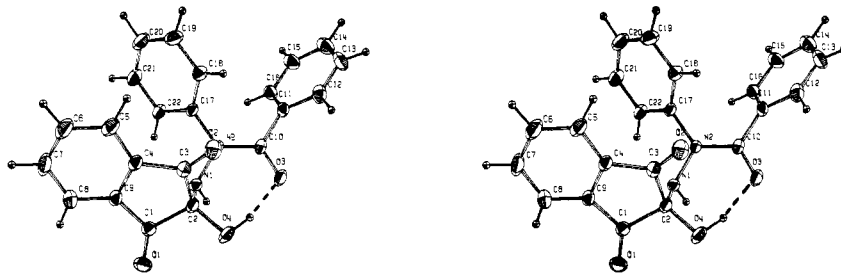
Figure 2. A stereoscopic view of the single molecule of **1**. The intramolecular hydrogen bond (O(4)—H· · ·O(3)) is shown by a discontinuous line.

Table III. Bond Lengths (Å)^a and Angles (deg) for
2-Hydroxy-2-(β-benzoyl-β-phenylhydrazyl)indan-1,3-dione (1)

C(1)–C(2)	1.531 (4)	C(2)–C(1)–C(9)	106.3 (3)
C(2)–C(3)	1.533 (4)	C(2)–C(1)–O(1)	126.2 (2)
C(3)–C(4)	1.470 (4)	C(9)–C(1)–O(1)	127.3 (2)
C(4)–C(5)	1.391 (4)	C(1)–C(2)–C(3)	102.2 (3)
C(5)–C(6)	1.372 (5)	C(1)–C(2)–O(4)	112.4 (2)
C(6)–C(7)	1.377 (6)	C(1)–C(2)–N(1)	103.3 (3)
C(7)–C(8)	1.391 (5)	C(3)–C(2)–O(4)	114.0 (2)
C(8)–C(9)	1.393 (4)	C(3)–C(2)–N(1)	108.4 (3)
C(9)–C(4)	1.380 (3)	O(4)–C(2)–N(1)	115.1 (2)
C(9)–C(1)	1.477 (4)	C(2)–C(3)–C(4)	106.9 (2)
C(10)–C(11)	1.480 (4)	C(2)–C(3)–O(2)	124.9 (2)
C(11)–C(12)	1.386 (4)	C(4)–C(3)–O(2)	128.2 (3)
C(12)–C(13)	1.384 (5)	C(3)–C(4)–C(5)	128.0 (3)
C(13)–C(14)	1.363 (6)	C(3)–C(4)–C(9)	109.9 (2)
C(14)–C(15)	1.366 (7)	C(5)–C(4)–C(9)	122.2 (2)
C(15)–C(16)	1.376 (6)	C(4)–C(5)–C(6)	116.5 (3)
C(16)–C(11)	1.380 (5)	C(5)–C(6)–C(7)	122.2 (4)
C(17)–C(18)	1.374 (4)	C(6)–C(7)–C(8)	121.3 (4)
C(18)–C(19)	1.393 (5)	C(7)–C(8)–C(9)	116.9 (3)
C(19)–C(20)	1.366 (6)	C(1)–C(9)–C(4)	110.3 (2)
C(20)–C(21)	1.358 (5)	C(1)–C(9)–C(8)	129.2 (3)
C(21)–C(22)	1.383 (5)	C(4)–C(9)–C(8)	120.6 (2)
C(22)–C(17)	1.379 (4)	C(11)–C(10) –O(3)	121.2 (3)
C(1)–O(1)	1.207 (3)	C(11)–C(10)–N(2)	118.4 (3)
C(3)–O(2)	1.212 (3)	O(3)–C(10)–N(2)	120.5 (4)
C(10)–O(3)	1.235 (4)	C(10)–C(11)–C(12)	119.4 (3)
C(2)–O(4)	1.396 (3)	C(10)–C(11)–C(16)	121.4 (3)
C(2)–N(1)	1.454 (3)	C(12)–C(11)–C(16)	118.9 (2)
C(10)–N(2)	1.370 (4)	C(11)–C(12)–C(13)	119.6 (3)
C(17)–N(2)	1.436 (3)	C(12)–C(13)–C(14)	120.5 (4)
N(1)–N(2)	1.413 (3)	C(13)–C(14)–C(15)	120.2 (4)
N(1)–H(N)	0.90 (4)	C(14)–C(15)–C(16)	119.8 (3)
O(4)–H(O)	0.96 (6)	C(11)–C(16)–C(15)	120.7 (2)
		C(18)–C(17)–C(22)	120.6 (2)
		C(18)–C(17)–N(2)	120.2 (2)
		C(22)–C(17)–N(2)	119.0 (2)
		C(17)–C(18)–C(19)	118.9 (2)
		C(18)–C(19)–C(20)	120.3 (3)
		C(19)–C(20)–C(21)	120.0 (4)
		C(20)–C(21)–C(22)	120.8 (3)
		C(17)–C(22)–C(21)	119.1 (2)
		C(2)–N(1)–N(2)	116.3 (2)
		C(10)–N(2)–C(17)	125.5 (3)
		C(10)–N(2)–N(1)	119.9 (2)
		C(17)–N(2)–N(1)	114.5 (2)
		C(2)–O(4)–H(O)	99 (2)
		C(2)–N(1)–H(N)	113 (2)
		N(2)–N(1)–H(N)	107 (2)
		O(3)–H(O)· · ·O(4)	164 (4)

^{a} The C–H lengths range from 0.92 (5) to 1.04 (4) Å.

C(11), N(2), and O(3), apparently a result of steric overcrowding of the bulky phenyl groups C(11-16) and C(17-22) about the C(10)-N(2) amide bond. The crowded orientation of these two phenyl groups seems to arise from an intramolecular O(4)—H···O(3) hydrogen bond which effectively locks the molecule into a conformation which has the phenyl groups in a syn orientation about the C–N (amide) bond. The O···O, H···O distances are 2.692 (4) and 1.75 (5) Å and the C—O···O and O—H···O angles are 89.0 (1) and
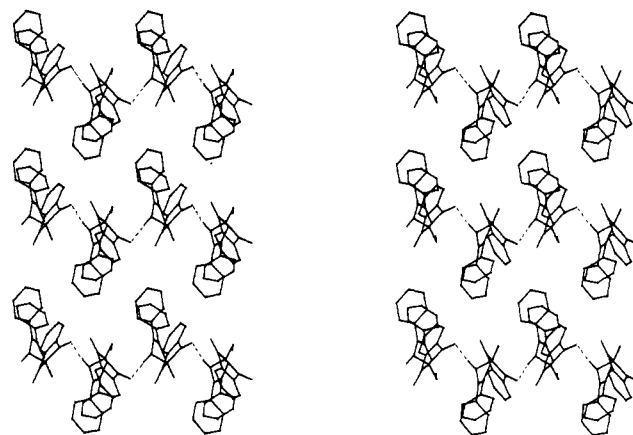
preferred direction for reaction

Figure 3. A stereoscopic packing diagram for 2-hydroxy-2-(β-benzoyl-β-phenylhydrazyl)-1,3-indandione (**1**) looking onto the (001) layer plane.

164 (4)°. The amide nitrogen atom lies only 0.035 Å from the plane defined by its three bonded neighbors, N(1), C(10), C(17). This near-coplanarity of the four atoms is in marked contrast to the case of the analogous benzoylphenylhydrazones which show pyramidal distortions of the amide nitrogen atoms ranging from 0.13 to 0.24 Å.[13,19]

The C(2)-O(4)H bond is 1.396 (3) Å. In the structure of the coumarin derivative warfarin,[20] which has a hemiketal structure, the exocyclic C-O(H) bond is 1.385 (2), while the endocyclic (ketal) C-O distance has the significantly long value of 1.483 (2) Å. In **1**, the C(2)-N(1) distance is 1.454 (3) Å, a value which corresponds to a normal C-N single bond length.

An intermolecular hydrogen bond involving the atoms N(1)—H(N)···O(2) links molecules in a chainlike fashion along the twofold screw (b) axis (9.025 Å). The distance between N(1) and O(2) at 1 − x, ½ + y, ½ − z is 3.166 (3) Å and is slightly longer than the corresponding interatomic distances found in other similar examples which involve N—H···O hydrogen bonding; the H(N)···O(2) distance is 2.33 (4) Å and the N(1)—H(N)···O(2) angle is 159 (2)°. For example, in the structures of acetanilide[21] and the 1:1 molecular complex between benzophenone and diphenylamine,[22] hydrogen bonded N···O distances of 2.943 (3) and 2.91 Å, respectively, were reported. Two different hydrogen bonds with N···O distances of 2.933 (3) and 2.907 (3) Å and H···O distances of 2.01 (3) and 2.05 (3) Å were reported in the crystal structure of benzamide.[23] The two polymorphic modifications of N-(p-methoxyphenyl-3-propyl)-
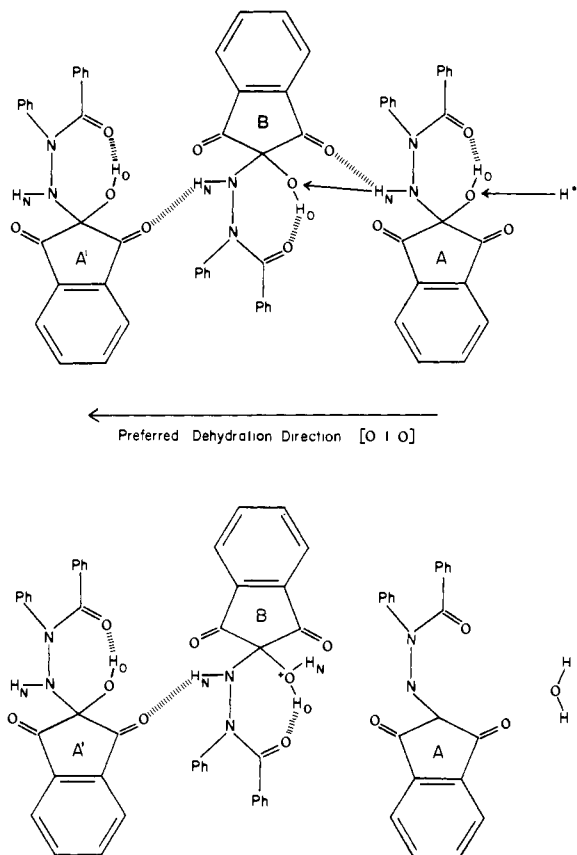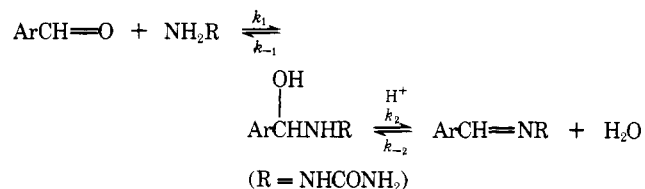
Figure 4. A possible mechanism for the dehydration reaction.

chloroform, even during attempted recrystallization, to give the benzoylhydrazone **2**.

An elegant dissection of the steps involved in the formation in aqueous ethanol at 25° of semicarbazones from semicarbazide and a series of meta- and para-substituted benzaldehydes was made by Anderson and Jencks.[11c] They thus

$$ArCH{=\!=}O \ + \ NH_2R \ \underset{k_{-1}}{\overset{k_1}{\rightleftharpoons}}$$

$$\underset{ArCHNHR}{\overset{OH}{\mid}} \ \underset{k_{-2}}{\overset{k_2}{\rightleftharpoons}} \ ArCH{=\!=}NR \ + \ H_2O$$

$$(R = NHCONH_2)$$

obtained information about the dehydration step (indicated here by the rate constant k_2). In neutral solution the "acid catalyzed" dehydration was rate determining with a ρ of -1.74 (with a better fit with σ than σ^+). In the pH range 9-12 there was a base-catalyzed elimination leading to the same semicarbazone product.

It was of interest to discover if an analogous dehydration could be achieved in the solid state. The thermal behavior of **1** has been described in some detail in the Experimental Section. It may be summarized as follows. Reaction proceeds very slowly at 65°, the highest temperature accessible without danger of partial melting. It appears to be initiated at nucleation sites and to spread in the long direction of the crystal, but there is no well-defined frontal migration. The probable sequence of events in a reaction of this kind (nucleation, reaction with solid solution formation, nucleation of product phase, and separation of product phase) has been summarized.[3] The behavior of **1** can now be discussed in the context of the crystal packing. In Figure 3 is shown a stereopair drawing of the structure. Each hydroxyl group, O(4)-H(O), is intramolecularly hydrogen bonded to the O(3) carbonyl oxygen atom and does not participate in any additional hydrogen bonding. A second intermolecular hydrogen bond occurs along the b axis of the crystal and involves chains of molecules related by the screw axis symmetry operation. In Figure 4 is shown a schematic drawing of three molecules of a hydrogen-bonded chain. If a proton from any source removes a hydroxyl group from molecule A, the proton H(N) is available at the other side of the molecule to remove a hydroxyl group from the adjacent molecule (B). Although, the proton is not hydrogen bonded to the correct hydroxyl oxygen but rather to a carbonyl group
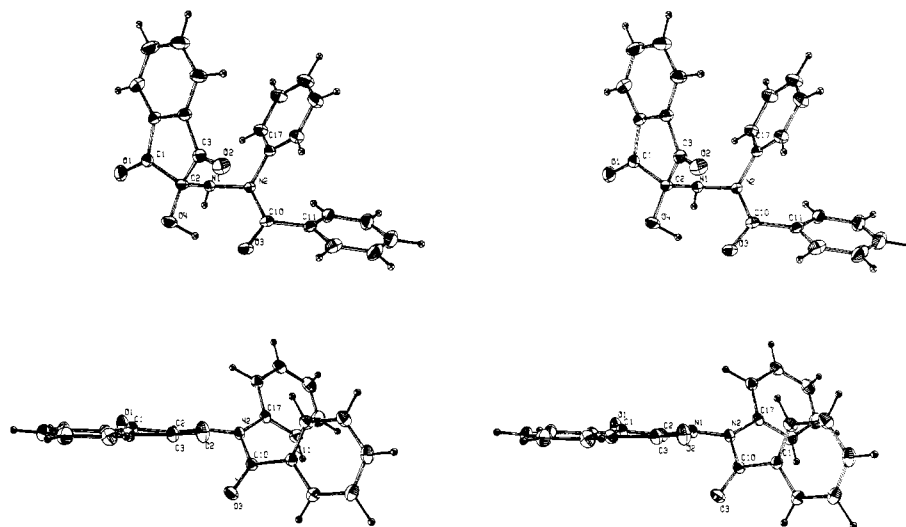
p-bromobenzamide have somewhat longer N⋯O distances of 2.988 (11) and 3.026 (14) Å[24] and are more in accord with that observed for **1**.

Solid-State Thermal Dehydration of 2-Hydroxy-2-(β-benzoyl-β-phenylhydrazyl)indan-1,3-dione (1). The carbinolhydrazine **1** is a member of a family of compounds of interest as intermediates in the formation of hydrazones and related derivatives from aldehydes and ketones.[11] In general, these intermediates have not been sufficiently stable to permit isolation. The indandione derivative **1** certainly has enhanced stability due to the two carbonyl groups bracketing the carbinolhydrazine group. Nevertheless, **1** is readily dehydrated in most solvents such as acetone, benzene, and

Figure 5. Stereoscopic views of the molecules of **1** and **2** oriented similarly with respect to the C-N bond that undergoes the covalency change.

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of the B molecule, its distance from the hydroxyl oxygen is only 3.01 Å. The very slow rate of reaction observed may be due in part to the difficulty of redirecting the hydrogen bond from the carbonyl to the hydroxyl oxygen even though the distance appears short. An experiment in which initiation of the reaction was assisted by a little finely ground *p*-toluenesulfonic acid hydrate placed next to one of the end faces of the crystal of **1** did indeed accelerate the beginning of reaction, but the acceleration decreased as the reaction front moved away from the region of the crystal near the external acid.

In Figure 5 is shown the structural relationship between the starting material **1** and product **2** in the conformations found in their respective crystal structures. It will be noted that the conformation of **1** is not far removed from that required for a syn elimination about the N(1)–C(2) bond, insofar as the positions of C(1), C(3), and N(1) are concerned. The H*O*–C(2)–N(1)–*H*(N) dihedral angle is 36°. A major change in molecular shape is required during the elimination reaction because the indandione skeleton has to move into the plane of the C(2)=N(1) double bond.

Since no other studies of this type are available for comparison, the analysis of factors controlling rates of such reaction must await further experimental results. It appears that, with the present state of advance of x-ray crystallography and physical organic chemistry, this kind of study may open up a new area of solid-state organic chemistry.

Supplementary Material Available: a listing of the observed and calculated structure factors (19 pp). Ordering information is given on any current masthead page.

References and Notes

(1) Taken from the Ph.D. thesis of Sherrill A. Puckett, submitted to the University of Illinois, 1975, available from University Microfilms, Ann Arbor, Mich. Part of the work has been presented at the Eighth Jerusalem Symposium on "Environmental Effects on Molecular Structure and Properties", April 1975, Jerusalem, Israel, and at the Fourth International Symposium on the Organic Solid State, July 1975, Bordeaux, France.
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Proton Exchange in Benzyl Alcohols. Acid, Base, Intramolecular, and Bifunctional Catalyses

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Abstract: Acid, base, intramolecular, and bifunctional catalysis of OH proton exchange of benzyl alcohols in Me$_2$SO and benzene have been detected by DNMR methods. Base-catalyzed exchange in Me$_2$SO involves displacement of a solvation molecule from the alcohol followed by formation of ionic intermediates. Strong bases with respect to full proton removal are good catalysts, whereas strong hydrogen-bonding bases impede exchange. *n*-Butylamine in benzene appears to be able to exchange via a proton removal-delivery mechanism within an ion pair. Imidazole (but not 1-methylimidazole) catalyzes exchange by means of a process which is second order in amine. Phenols also catalyze exchange. The ortho hydroxy group of *o*-hydroxybenzyl alcohol is a powerful intramolecular catalyst for base-catalyzed (but not acid-catalyzed) exchange of the benzylic hydroxyl proton. By far the most effective intermolecular catalyst discovered was a combination of amine and amine salt. Thus, the monoperchlorate salt of *N,N,N',N'*-tetramethylethylenediamine is a 10^4 better catalyst than the free diamine. The efficiency of the monosalt probably stems from a concerted acid-base mechanism which averts charge formation.

Bioorganic mechanisms have progressed to a stage where they possess an awesome (and perhaps uncomely) complexity.[2,3] These mechanisms incorporate detailed descriptions of proton transfers from complicated intermediates of fleeting existence and uncertain structure. This is not to detract from the ingenuity of much bioorganic thought; considering the inherent limitations of chemical kinetics, the progress made with multistep processes has been remarkable. The present paper departs from current format. Rather than speculating about a catalyzed proton transfer from the hy-