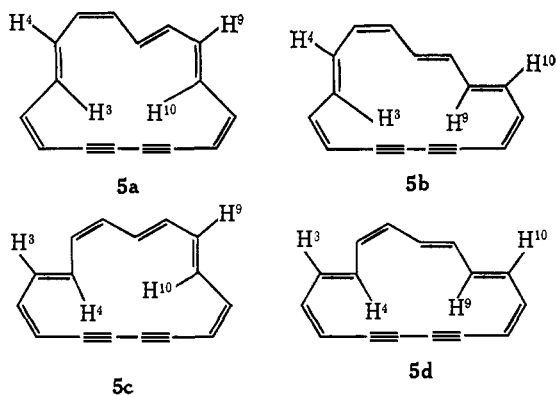


Figure 5. Nmr spectrum at 40° of compound C (1,3-bisdehydro-[16]annulene) (5), measured in carbon tetrachloride at 100 Mcps.

difference in environment of each of these protons in the conformers.

The four conformers of 5 are 5a-d,¹² only rotation about the H³,H⁴ and the H⁹,H¹⁰ *trans* double bonds being considered. The chemical shifts suggest that H³, H¹⁰ occupy an inner position about two-thirds of the



time, whereas H⁴, H⁹ occupy an inner position about one-third of the time. Cooling to lower temperatures

than -80° would presumably give information about the relative contribution of the various conformers.

On warming a carbon tetrachloride solution of 5, the chemical shifts of H³ and H¹⁰ become different from each other, as do those of H⁴ and H⁹. As a result, at 40° (Figure 5) the H³, H¹⁰ and H⁴, H⁹ bands each exhibit eight lines. The substance decomposed relatively quickly at 40°, and it was not possible to investigate the spectrum at higher temperatures.

Conclusion

The substances 4 and 5 are the first dehydroannulenes in which interconversion between *nonequivalent* conformers has been observed. Substance 4 is also the first example of a dehydroannulene in which the protons on a *trans* double bond adjacent to an acetylene are being transferred between internal and external positions.

The fact that the inner protons in all three compounds 1, 4, and 5 appear at considerably lower field than the outer protons provides evidence for the existence of a magnetically induced paramagnetic ring current. Each of the three substances has 16 out-of-plane π electrons, and this finding (which parallels that made with [16]annulene)⁷ is in accord with the predictions made for [4*n*]annulenes and dehydro[4*n*]annulenes.¹⁶

Acknowledgment. I. C. C. thanks the C.S.I.R.O. (Australia) for an Overseas Postgraduate Studentship. We are also grateful to Dr. C. W. Haigh (Swansea) for valuable discussions.

(16) J. A. Pople and K. G. Untch, *J. Amer. Chem. Soc.*, **88**, 4811 (1966); F. Baer, H. Kuhn, and W. Regel, *Z. Naturforsch.*, **22a**, 103 (1967); H. C. Longuet-Higgins, Special Publication No. 21, The Chemical Society, London, 1967, p 109.

The Mechanism of Hydrolysis of Methyl Pseudo-2-benzoylbenzoate in Aqueous Sulfuric Acid¹

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Contribution from the Department of Chemistry, Seton Hall University, South Orange, New Jersey 07079. Received February 28, 1968

Abstract: The hydrolysis of methyl pseudo-2-benzoylbenzoate (2) in 1 *M* aqueous sulfuric acid is characterized by a ΔS^\ddagger of -19.4 eu and a D₂O solvent isotope effect of $k_{H_2O}/k_{D_2O} = 0.50$. In 5 *M* sulfuric acid these values become -19.1 eu and 0.56, respectively. In moderately concentrated sulfuric acid a plot of $\log k_\psi$ vs. $-H_0$ is linear with a slope of 0.67. A plot of $\log k_\psi + H_0$ vs. $H_0 + \log [H^+]$ shows downward curvature. The slopes, ϕ , are 0.66 at 1 *M* and 0.41 at 5 *M*. In 90% aqueous acetonitrile containing sulfuric acid (-)-menthyl pseudo-(-)-2-benzoylbenzoate undergoes racemization much faster than hydrolysis. Thus, the evidence supports a mechanism which is bimolecular.

Several attractive mechanisms can be written for the acid-catalyzed hydrolysis of partial acylals, 1. Since these compounds are the esters of hemiacetals they could choose to react, as most simple esters do,³

(1) Presented, in part, at the 154th National Meeting of the American Chemical Society, Chicago, Ill., Sept 1967, Abstract S175.

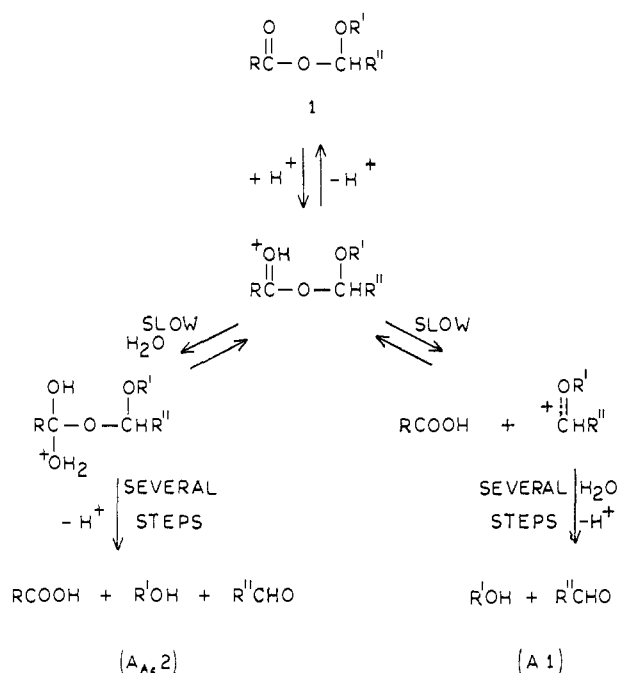
(2) Taken in part from the M.S. Theses submitted by A. G. (1966) and R. F. (1967) to Seton Hall University.

by the A_{Ac}2 mechanism shown in Scheme I. On the other hand 1 might prefer to react as most acetals do⁴ (A1 mechanism, Scheme I). Considering 1 as an ester the A1 mechanism would correspond to the A_{A1}1 mecha-

(3) C. K. Ingold, "Structure and Mechanism in Organic Chemistry," Cornell University Press, Ithaca, N. Y., 1953, p 767; M. L. Bender, *Chem. Rev.*, **60**, 53 (1960).

(4) F. A. Long and M. A. Paul, *ibid.*, **57**, 935 (1957).

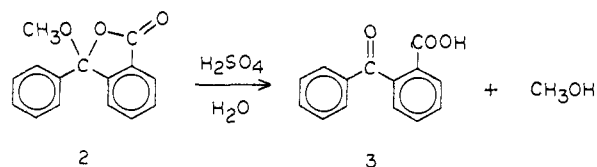
Scheme I



nism which has been demonstrated for such esters as *t*-butyl acetate.⁶ Several other mechanisms can be written and will be considered at the conclusion of this paper.

In a study of the mechanisms of hydrolysis of the partial acylals methoxymethyl acetate, ethoxymethyl acetate and methoxymethyl formate, Salomaa⁶ concluded that the two alkoxyethyl acetates were undergoing hydrolysis by the unimolecular process. The behavior of methoxymethyl formate indicated that although most of the reaction was unimolecular there was a small bimolecular component.⁶ More recently, Fife⁷ has reported that the hydrolysis of γ -ethoxy- γ -butyrolactone is unimolecular.

This paper reports our first efforts to investigate the reliability of the various criteria used to investigate the mechanisms of hydrolysis reactions. We wish to observe these criteria under conditions which are likely to test their credibility. The considerations above led us to believe that partial acylals would provide us with a rare opportunity to observe a change in mechanism over a narrow range of substrate structure. We could then observe the various criteria of mechanism as we swept through the region of changing mechanism. We have undertaken a study of the hydrolysis of methyl pseudo-2-benzoylbenzoate (**2**) in aqueous sulfuric acid. This compound provides a partial acylal, albeit cyclic, which is reasonably easy to prepare and purify. Further there is ample opportunity for subtle structural variation within the pseudo ester system.



(5) C. A. Bunton, A. E. Comyns, and J. L. Wood, *Research* (London), 6, 383 (1951).

(6) P. Salomaa, *Acta Chem. Scand.*, 11, 132, 141, 235 (1957).

(7) T. H. Fife, *J. Amer. Chem. Soc.*, 87, 271 (1965).

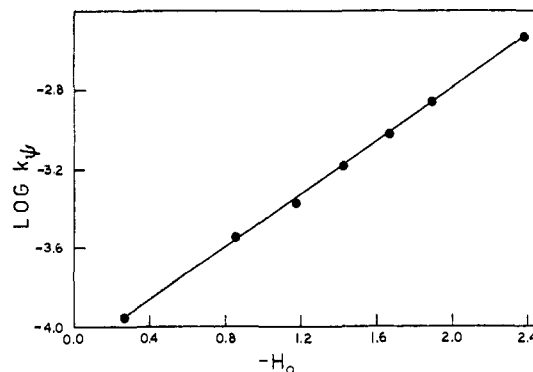


Figure 1. Hydrolysis of methyl pseudo-2-benzoylbenzoate in sulfuric acid solutions; plot of $\log k_\psi$ against $-H_0$. The slope is +0.67.

Results and Discussion

Methyl pseudo-2-benzoylbenzoate (**2**) reacts in aqueous sulfuric acid to form 2-benzoylbenzoic acid (**3**) and methanol. The reaction shows straightforward pseudo-first-order behavior. Rate constants under various conditions are shown in Table I.

Table I. Methyl Pseudo-2-benzoylbenzoate Hydrolysis in Aqueous Sulfuric Acid

No.	$10^4[\text{substrate}]$, <i>M</i>	$[\text{H}_2\text{SO}_4]$, <i>M</i>	Temp, $^\circ\text{C}$	10^4k_ψ , ^a sec^{-1}
1	5.0	1.01	29.8	1.11 ± 0.03
2	5.0	2.03	29.8	2.88 ± 0.05
3	5.0	2.59	29.8	4.27 ± 0.03
4	5.0	3.08	29.8	6.64 ± 0.13
5	5.0	3.61	29.8	9.65 ± 0.05
6	5.0	4.12	29.8	13.8 ± 0.13
7	5.0	5.19	29.8	29.6 ± 0.05
8	5.0	1.01	40.0	2.94 ± 0.05
9	5.0	1.01	50.6	7.24 ± 0.03
10	4.6	5.12	25.8	23.7 ± 0.50
11	8.8	5.12	25.8	23.6 ± 1.8
12	4.6	5.12	34.0	47.8 ± 1.0
13	8.8	5.12	34.0	48.0 ± 0.90
14	4.6	5.12	45.1	137 ± 13

^a Average of at least two runs. Confidence intervals are based on a 95% confidence level.

Criteria Based on Acidity Functions. When the logarithm of the pseudo-first-order rate constant ($\log k_\psi$) for hydrolysis of **2** is plotted against the Hammett acidity function ($-H_0$)⁸ the data show good linearity (Figure 1). The Zucker-Hammett hypothesis^{4,9} predicts a linear correlation for a reaction in which no water is involved in the transition state of the rate-determining step, *i.e.*, A1. The behavior of this reaction is far from ideal, however, because the Zucker-Hammett hypothesis requires a slope of unity. Small deviations from the ideal slope are usually tolerated but the observation of a slope of 0.67 in this work makes a useful application of the Zucker-Hammett hypothesis of doubtful value. Plotting $\log k_\psi$ against $\log [\text{H}^+]$, which should result in linearity if a molecule of water

(8) L. P. Hammett and A. J. Deyrup, *ibid.*, 54, 2721 (1932); M. A. Paul and F. A. Long, *Chem. Rev.*, 57, 1 (1957).

(9) L. Zucker and L. P. Hammett, *J. Amer. Chem. Soc.*, 61, 2791 (1939); L. P. Hammett, "Physical Organic Chemistry," McGraw-Hill Book Co., Inc., New York, N. Y., 1940, pp 273-277.

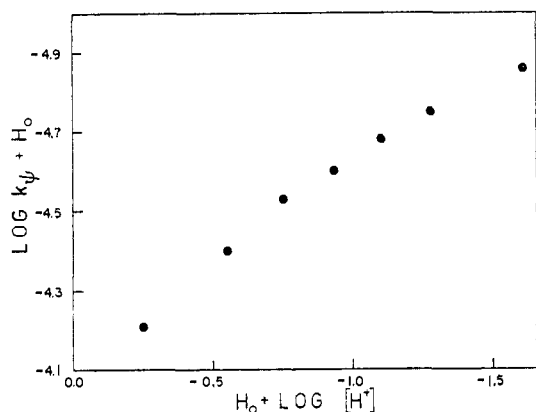


Figure 2. Hydrolysis of methyl pseudo-2-benzoylbenzoate in sulfuric acid solutions; plot of $(\log k_{\psi} + H_0)$ against $(H_0 + \log [H^+])$. The slopes, ϕ , are $+0.66$ ($1 M$) and $+0.41$ ($5 M$).

is involved in the transition state, gives severe curvature. Clearly, the reaction does not fit either of the Zucker-Hammett categories.

Bunnett¹⁰ and Bunnett and Olsen¹¹ have suggested alternative methods for treating these data. The more recent of these is the ϕ parameter.¹¹ Using these ϕ values Bunnett has assigned a large number of organic reactions occurring in moderately concentrated mineral acid to mechanistic categories with remarkable success, although he cautions against the too literal interpretation of ϕ values in terms of mechanism. The appropriate treatment of our data is shown in Figure 2. The data show significant curvature. This was disappointing since the ϕ treatment usually results in "arrow straight" correlations even in cases where the older w plots¹⁰ were badly curved.

It is interesting to note that ϕ for the hydrolysis of **2** lies intermediate between those values resulting from substrates known to hydrolyze *via* an A2 mechanism and those from substrates undergoing A1-type mechanisms. Data collected by Bunnett¹¹ allow a wide choice of model compounds. These are presented in Table II to show all of the structural features of methyl pseudo-2-benzoylbenzoate. Compound **10** is of special interest. Salomaa⁶ has postulated that this compound undergoes hydrolysis largely *via* an A1 mechanism but with an observable A2 component. He supported this with some elegant work in aqueous methanol solution. The ϕ value for **10** is noticeably more positive than those for **8** and **9**. This indicates that ϕ is a sensitive probe for changes in reaction mechanism.

We have considered two interpretations of these data. Initially, we believed that the fact that ϕ for the hydrolysis of **2** lay intermediate between those values expected for the A1 and A2 mechanisms indicated that the reaction was proceeding *via* a mixture of unimolecular and bimolecular pathways. Curvature of the ϕ plot indicated that the proportion of molecules undergoing hydrolysis by the two pathways changed as the concentration of mineral acid changed. That is, at sulfuric acid concentrations of about $1 M$ a large number of molecules hydrolyzed *via* the bimolecular pathway but at about $5 M$ sulfuric acid the A1 pathway had

(10) J. F. Bunnett, *J. Amer. Chem. Soc.*, **83**, 4956, 4968, 4973, 4978 (1961).

(11) J. F. Bunnett and F. P. Olsen, *Can. J. Chem.*, **44**, 1899, 1917 (1966).

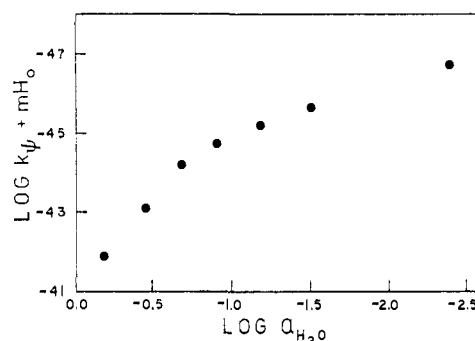


Figure 3. Hydrolysis of methyl pseudo-2-benzoylbenzoate in sulfuric acid solutions; plot of $(\log k_{\psi} + mH_0)$ against $\log a_{H_2O}$; $m = 0.90$. $\log a_{H_2O}$ values taken from ref 10.

become more important. An alternative interpretation would be that **2** suffers an hydrolysis reaction *via* a bimolecular mechanism which does not obey the acidity function criteria.

Table II. Bunnett ϕ Values for Methyl Pseudo-2-benzoylbenzoate, Selected Esters and Selected Acetals

No.	Compound	ϕ^a	Slope of $\log k_{\psi}$ vs. $-H_0$	Mechanism
2	Methyl pseudo-2-benzoylbenzoate	0.66 ($1 M H_2SO_4$) ^b 0.41 ($5 M H_2SO_4$) ^b	0.67 ^b	
4	Methyl benzoate	0.98 ($HClO_4$)		A2
5	α -Glycerol mono-benzoate	0.99 ($HClO_4$)		A2
6	Ethyl acetate	0.84 (H_2SO_4)		A2
7	γ -Butyrolactone	0.87 (HCl)		A2
8	Methoxymethyl acetate	-0.06 (H_2SO_4)	1.15 ^c	A1
9	Ethoxymethyl acetate	-0.44 (HCl)	1.15 ^c	A1
10	Methoxymethyl formate	0.15 (HCl)	1.00 ^c	A1 (A2)
11	Methylal	-0.005 (H_2SO_4)		A1
12	<i>t</i> -Butyl acetate	-0.21 (HCl)		A1
13	Methyl mesitoate	-0.25 (H_2SO_4)		A1

^a Reference 11. ^b Present work. ^c Reference 6.

Yates¹² has suggested a modification of the Bunnett hydration parameter, w .¹⁰ The modification involves using an acidity function which is appropriate to the type of substrate being investigated. The Yates treatment eliminates the well-known deficiencies¹³ associated with the use of H_0 but requires the tedious process of obtaining indicator slopes for each type of substrate. Yates and his coworkers have had striking success in correlating rate with acidity and water activity for amides¹² and acetate esters.¹⁴

Figure 3 shows our data for the hydrolysis of **2** plotted according to Yates's method where we have taken $m = 0.90$.¹⁵ The positive dependence on water activity

(12) K. Yates and J. C. Stevens, *Can. J. Chem.*, **43**, 529 (1965); K. Yates and J. C. Riordan, *ibid.*, **43**, 2328 (1965).

(13) E. M. Arnett in "Progress in Physical Organic Chemistry," Vol. 1, S. G. Cohen, A. Streitwieser, Jr., and R. W. Taft, Ed., Interscience Publishers, Inc., New York, N. Y., 1963, p 223 ff.

(14) K. Yates and R. A. McClelland, *J. Amer. Chem. Soc.*, **89**, 2686 (1967).

(15) We thank Professor Yates for suggesting this value for the indicator slope for benzoate esters based on preliminary work on methyl benzoate. The rapid hydrolysis of **2** has made it impossible for us to determine m .

and the severe curvature can be interpreted as in the case of the ϕ parameter. The Bunnett w treatment (not shown) yields qualitatively the same result. Yates's work on acetate ester hydrolysis over a wide range of acidity¹⁴ showed nonlinear behavior over regions of changing mechanism although the change was more abrupt than in our work.

Entropy of Activation. The use of the entropy of activation (ΔS^*) as a criterion of mechanism in the investigation of aqueous hydrolysis reactions is based on the expectation that ΔS^* will be larger for unimolecular cleavage reactions than for bimolecular reactions.¹⁶ This is borne out by experimental observation. A number of aqueous hydrolysis reactions which are known to occur *via* an A1 mechanism have entropies of activation in the neighborhood of zero or slightly positive¹⁷⁻²¹ while those proceeding by an A2 process have ΔS^* in the region of -15 to -30 eu.^{10, 22}

A plot of $\log k_{\psi}$ against $1/T$ is linear for methyl pseudo-2-benzoylbenzoate hydrolysis. Activation parameters are listed in Table III. The ΔS^* of -19.4

Table III. Activation Parameters for the Hydrolysis of Partial Acylals

Compd	[HA], <i>M</i>	Temp, °C	ΔH^* , ^a kcal mol ⁻¹	ΔS^* , ^a eu
2	1.01 (H ₂ SO ₄)	30.0	17.0 ± 0.5	-19.4 ± 1.0
2	5.12 (H ₂ SO ₄)	30.0	16.6 ± 1.0 ^b	-19.1 ± 3.0 ^b
8	0.10 (HCl)	25.0	22.0	+3.4
9	0.10 (HCl)	25.0	21.5	+4.5
10 (<i>k</i> ₁)	0.10 (HCl)	25.0	21.2	+2.7
10 (<i>k</i> ₂)	0.10 (HCl)	25.0	13.4	-26.0

^a The errors reported were calculated from the maximum confidence interval based on a confidence level of 95%. ^b Calculated from the slope of a straight line obtained by plotting $\log k_{\psi}/[\text{HA}]$ against $1/T$.

eu at 1 *M* sulfuric acid is consistent with our belief that the hydrolysis of 2 is largely bimolecular and clearly inconsistent with a well-behaved unimolecular process.

The determination of ΔS^* provided a test for our initial interpretation of curvature of the ϕ plot. Thus, if the A1 mechanism were coming increasingly into play at higher mineral acid concentrations the value of ΔS^* would become more positive. However, as shown in Table III, ΔS^* remains essentially unchanged as the acidity of the medium is increased.

Finally, Salomaa²³ has provided us with data which allow a striking demonstration of the sensitivity of ΔS^* to mechanism. He found that the hydrolysis rates of alkoxymethyl acetates were linear with $1/T$. We have calculated ΔS^* from his data. The values (Table III) are quite consistent with an A1 process. The rate of hydrolysis of methoxymethyl formate was sufficiently nonlinear with $1/T$ that Salomaa was able to dissect the data into the unimolecular and bimolecular

(16) R. W. Taft, Jr., *J. Amer. Chem. Soc.*, **74**, 5372 (1952); R. W. Taft, Jr., E. L. Purlee, P. Riesz, and C. A. DeFazio, *ibid.*, **77**, 1584 (1955).

(17) M. L. Bender, H. Ladenheim, and M. Chem, *ibid.*, **83**, 123 (1961).

(18) A. M. Wenthe and E. H. Cordes, *ibid.*, **87**, 3173 (1965).

(19) J. G. Fullington and E. H. Cordes, *J. Org. Chem.*, **29**, 970 (1964).

(20) R. H. DeWolfe and J. L. Jensen, *J. Amer. Chem. Soc.*, **85**, 3264 (1963).

(21) M. Fuller and W. Schubert, *ibid.*, **85**, 108 (1963).

(22) A. Lamble and W. C. Lewis, *Trans. Chem. Soc.*, 2330 (1914).

(23) P. Salomaa, *Acta Chem. Scand.*, **11**, 239 (1957).

rate constants. Upon calculation of the entropy of activation from these data we have found values (Table III) which fall in the regions expected for the two processes. The rate of hydrolysis of 2 is linear with $1/T$; this fact is opposed to the idea of a mixed mechanism.

Deuterium Oxide Solvent Isotope Effect. The ratio of rate constants for an hydrolysis reaction in water and in deuterium oxide at equal acidities ($k_{\text{H}_2\text{O}}/k_{\text{D}_2\text{O}}$) has been proposed as a criterion of mechanism.²⁴ For weakly basic substrates typical values of $k_{\text{H}_2\text{O}}/k_{\text{D}_2\text{O}}$ for unimolecular reactions are 0.33-0.45^{7, 19, 20, 25, 26} and for bimolecular reactions, 0.70-0.85.²⁴ Appropriate rate data for the hydrolysis of 2 are listed in Table IV. At about 1 *M* acid $k_{\text{H}_2\text{O}}/k_{\text{D}_2\text{O}}$ lies between the values one would expect for the two types of mechanism.

Table IV. Methyl Pseudo-2-benzoylbenzoate Hydrolysis in Aqueous Sulfuric Acid. Determination of Deuterium Oxide Solvent Isotope Effect

No.	10 ⁵ [sub- strate], <i>M</i>	[Acid], <i>M</i>	Temp, °C	k_{ψ} , ^a sec ⁻¹	$k_{\text{H}_2\text{O}}/$ $k_{\text{D}_2\text{O}}$
1	4.6	0.987 (H ₂ SO ₄)	29.9	9.50 × 10 ⁻⁵	0.50
2	4.6	0.987 (D ₂ SO ₄)	29.9	19.1 × 10 ⁻⁵	
3	4.6	5.10 (H ₂ SO ₄)	30.7	3.97 × 10 ⁻³	0.56
4	4.6	5.12 (D ₂ SO ₄)	30.8	6.89 × 10 ⁻³	

^a Average of two runs.

We applied a test similar to that involving ΔS^* and expected to observe a decrease in $k_{\text{H}_2\text{O}}/k_{\text{D}_2\text{O}}$ at higher acidity if a mixed mechanism were at play. At about 5 *M* acid the value increased slightly. There is some basis for believing that the natural consequence of higher acidity of the medium, in the absence of a change in mechanism, would be an increase in $k_{\text{H}_2\text{O}}/k_{\text{D}_2\text{O}}$.²⁷ Thus, neither the entropy of activation nor the solvent isotope effect support our initial interpretation of the ϕ plot.

General Acid vs. Specific Hydronium Ion Catalysis. Employing a series of phosphate buffer solutions of constant pH and ionic strength but differing absolute buffer concentration we have been unable to observe general acid-base catalysis. The data in Table V

Table V. Methyl Pseudo-2-benzoylbenzoate Hydrolysis in Buffer Solutions

No.	[H ₃ PO ₄] = [KH ₂ PO ₄], <i>M</i>	[LiClO ₄], <i>M</i>	10 ⁵ k_{ψ} , ^a sec ⁻¹
1	0.20	0.00	2.42
2	0.18	0.02	2.37
3	0.16	0.04	2.34
4	0.14	0.06	2.37
5	0.12	0.08	2.30
6	0.10	0.10	2.33

^a Average of two runs. The substrate concentration was 5.0 × 10⁻⁵ *M*. The temperature was 61.2°. The pH of all solutions was 2.00 ± 0.01.

(24) K. Wiberg, *Chem. Rev.*, **55**, 719 (1955).

(25) M. L. Bender and M. S. Silver, *J. Amer. Chem. Soc.*, **85**, 3006 (1963).

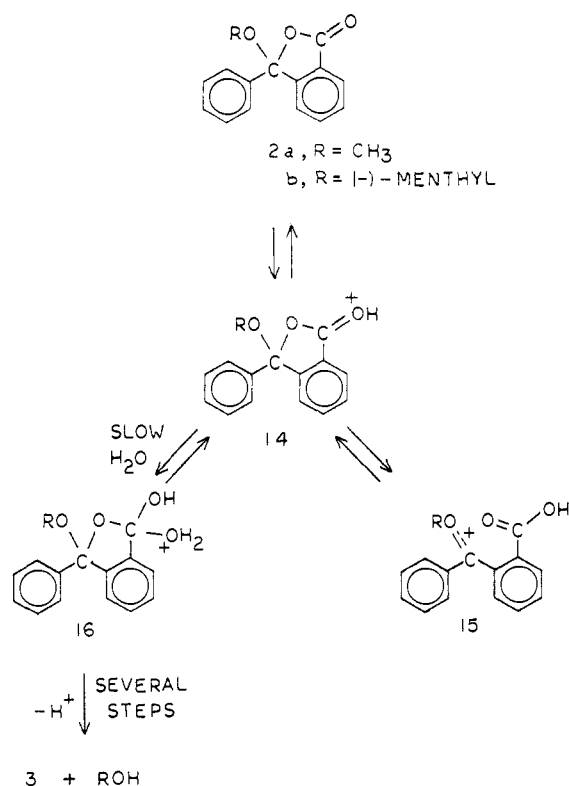
(26) M. Kilpatrick, *ibid.*, **85**, 1036 (1963).

(27) Reference 25, p 721.

clearly show no significant trend in the rate constant with changing buffer concentration. The observation of general acid-base catalysis would have indicated clearly a bimolecular mechanism, however, failure to observe such catalysis is not inconsistent with the A2 process. These data are disappointing but, in fact, not surprising. The unequivocal demonstration of *intermolecular* general acid-base catalysis of ester hydrolysis is rare and usually observed with compounds having some unusual structural features.²⁷⁻³⁰

Experiments on (-)-Menthyl Pseudo(-)-2-Benzoylbenzoate. The conclusion that **2** suffers hydrolysis by a process which is partly bimolecular is a surprising one.³¹ One would have thought intuitively that an A1 mechanism proceeding through the oxocarbenium ion, **15** (Scheme II), would be especially favorable in

Scheme II



view of the expected stability that **15** would possess from extensive delocalization of the positive charge. A reason for the unusual behavior of **2** might be that once **15** is formed the reaction with water is unable to compete with the cyclization back to the protonated substrate, **14**. Since the A1 pathway for hydrolysis is blocked the compound eventually suffers hydrolysis *via* the slower, but available, A2 route.

An interesting test is available for this hypothesis. In **2** the carbon atom which will become the carbonium ion center in **15** is asymmetric. One could test our hypothesis by comparing the rate of racemization with the rate of hydrolysis of the resolved pseudo ester. The

(28) E. J. Fuller, *J. Amer. Chem. Soc.*, **85**, 1777 (1963).

(29) J. F. Kirsch and W. P. Jencks, *ibid.*, **86**, 833 (1964).

(30) S. L. Johnson, *ibid.*, **86**, 3819 (1964).

(31) Our confidence in our data has been strengthened by unpublished work by Mr. George Zuurick and Mr. William Suggs, a National Science Foundation undergraduate research participant, on pseudo esters in the 8-aryol-1-naphthoic acid system. The various criteria indicate that the hydrolyses of these compounds are well-behaved examples of an A1 mechanism.

rapid and reversible formation of **15** should make the rate of racemization faster than the rate of hydrolysis.

Several experimental difficulties presented themselves. The resolution of **2** proved to be beyond us. However, the work of Schafgen, Verhoek, and Newman³² provided us with the resolved pseudo ester, (-)-menthyl pseudo(-)-2-benzoylbenzoate (**2b**). Another difficulty, for which there is no entirely satisfactory solution, is that in order to follow the racemization it is necessary to work at fairly high substrate concentrations. In order to get enough pseudo ester into solution to enable us to follow the loss of optical activity polarimetrically it was necessary to use a medium of high organic solvent content (90% aqueous acetonitrile). This, in turn, casts doubt on any extrapolation of our observations in a highly organic medium to the question of the mechanism of hydrolysis in purely aqueous solution.

The first-order rate constant for the racemization of **2b** at 0.125 M sulfuric acid is $7.33 \times 10^{-6} \text{ sec}^{-1}$ (Table VI). The rate of hydrolysis under identical conditions is too slow to measure. Despite the reservations that one must have about the quantitative significance of these data as applied to the aqueous hydrolysis mechanism of **2a** the large difference in rate indicates that the oxocarbenium ion, **15b**, does have difficulty reacting with water (water is present, even in this solution, in 100-fold excess). The dependence of the rate of racemization on temperature was measured. The results appear in Table VI. The entropy of activation was +9.9 eu. Therefore, the racemization is probably a unimolecular process.

Table VI. Sulfuric Acid Catalyzed Racemization of (-)-Menthyl Pseudo(-)-2-benzoylbenzoate in Acetonitrile-Water

No.	Temp, °C	$10^6 k_{\psi}$, ^a sec ⁻¹
1	29.5	7.33
2	39.5	29.8
3	50.2	126

^a Average of three runs. The concentration of sulfuric acid was 0.125 M. The substrate concentration was 5.8×10^{-3} M. The enthalpy of activation calculated from these data was 26.5 ± 1.0 kcal mol⁻¹. The entropy of activation at 30° was $+9.9 \pm 2.0$ eu.

Conclusions

Our observations on the hydrolysis of **2** are not consistent with a well-behaved A1 mechanism. The transition state for the rate-determining step almost certainly involves at least one molecule of water. The A2 mechanism which we favor (Scheme II) is similar to that suggested by Newman and Courduvelis³³ for the isomerization of **2** to the normal methyl ester in methanolic HCl.

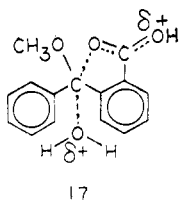
There are several other mechanisms which would satisfy the requirement for a bimolecular transition state. The transition states for two of these are shown as **17** and **18**. Transition state **17** corresponds to a bimolecular acetal hydrolysis and has precedent in work recently reported by Fife.³⁴ Transition state **18** is a concerted process in which the tetrahedral inter-

(32) J. R. Schafgen, F. H. Verhoek, and M. S. Newman, *J. Amer. Chem. Soc.*, **67**, 253 (1945).

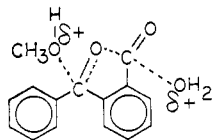
(33) M. S. Newman and C. Courduvelis, *J. Org. Chem.*, **30**, 1795 (1965).

(34) T. H. Fife, *J. Amer. Chem. Soc.*, **89**, 3228 (1967).

mediate is bypassed. These possibilities are receiving our attention.



17



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Experimental Section

Materials. Methyl pseudo-2-benzoylbenzoate (**2**) was prepared by the method of Newman and McCleary.³⁵ Urea was used instead of pyridine to neutralize the HCl produced.³⁶ The compound was recrystallized several times from a methylene chloride-hexane mixture to give a sample for kinetics studies, mp 82–83° (lit.³⁵ mp 81.4–82.4°).

Anal. Calcd for C₁₅H₁₃O₃: C, 74.98; H, 5.04. Found: C, 75.01; H, 5.10.

Methyl 2-benzoylbenzoate was prepared by the method of Newman and McCleary,³⁵ mp 49.5–51.5° (lit.³⁵ mp 51–51.8°).

Anal. Calcd for C₁₅H₁₃O₃: C, 74.98; H, 5.04. Found: C, 74.85; H, 5.02.

(–)-Menthyl pseudo-(–)-2-benzoylbenzoate (**2b**) was prepared by the method of Schafgen, Verhoek, and Newman:³² mp 115–117°; [α]_D²⁵ –184.7° (lit.³² mp 116–117°, [α]_D –186°).

Anal. Calcd for C₂₄H₂₈O₃: C, 79.09; H, 7.74. Found: C, 79.43; H, 7.88.

Deuteriosulfuric acid solutions were prepared by diluting sulfuric acid-*d*₂ (99%) with deuterium oxide (99.8%), both deuterated reagents being obtained from Stohler Isotope Chemicals. Sulfuric acid and deuteriosulfuric acid solutions were individually standardized against standard sodium hydroxide solutions. Phosphate buffers were prepared by mixing the appropriate amounts of standardized phosphoric acid (Baker reagent) solutions with stock solutions of K₂H₂PO₄ (Baker reagent) and LiClO₄ (G. F. Smith). Methanol was distilled from magnesium methoxide just before use. Acetonitrile (Matheson Coleman and Bell Spectroquality) was distilled just before use.

Rate Determinations. The hydrolysis of **2** was followed in the ultraviolet spectrum at 248 mμ where there is a substantial difference in the absorbance of the starting material, **2** (ε 3100), and the product, **3** (ε 13,200). Both compounds obeyed Beer's law. A full spectrum of the hydrolysis run after ten half-lives was superimposable on a spectrum of **3** at the same concentration. An isobestic point in the spectra of **2** and **3** occurred at 232 mμ. The absorbance at 232 mμ remained unchanged over a period of ten half-

lives which tends to rule out the possibility of an intermediate's being built up in appreciable concentration during the hydrolysis.

A stock solution containing the appropriate amount of **2** in methanol was prepared. A run was started by adding a small amount of this solution to the reaction solution which has been equilibrated at bath temperature. The final concentration of methanol was always 1%. For slow reactions the solutions were prepared in 100-ml volumetric flasks and the absorbance of an aliquot was measured at appropriate times on a Beckman DU spectrophotometer. For reactions of moderate rate the solutions were prepared directly in the uv cell which was placed in a constant-temperature cell compartment and the absorbance was measured at appropriate times. A Beckman DK-2 spectrophotometer equipped with a constant-temperature cell compartment and a time-drive attachment was used for fast reactions. Temperature control was ±0.05° or better in all cases.

Pseudo-first-order rate constants were obtained by plotting log (*A*_∞ – *A*_{*t*}) against time (seconds) where *k*_{*ψ*} = slope × 2.303. In most cases the mathematical and graphical manipulations were carried out by computer.³⁷ Correlation coefficients were 0.999 in all cases. All reactions were followed over at least two half-lives. The rate constant was independent of the initial concentration of substrate.

The possibility that this reaction occurs *via* the rapid conversion of the pseudo ester, **2**, to the normal ester, methyl 2-benzoylbenzoate, and then a slow hydrolysis to 2-benzoylbenzoic acid (**3**) is ruled out by the observation that the uv spectrum of the normal ester is virtually identical with that of **3**.

The racemization of (–)-menthyl pseudo-(–)-2-benzoylbenzoate (**2b**) was followed polarimetrically. Solutions which were 0.058 *M* in substrate and 0.125 *M* in sulfuric acid were prepared in 90:10 (v/v) acetonitrile-water and placed in a 1-dm jacketed polarimeter tube. Water at a constant temperature was circulated through the jacket. Rate constants were obtained from plot of log (α_{*t*} – α_∞)/(α_{*t*} – α_∞) against time (seconds). The observed rotation after ten half-lives was that which would be expected from a 0.058 *M* solution of (–)-menthol.

Product Analysis. Hydrolysis of Methyl Pseudo-2-benzoylbenzoate (**2**). **2** (2 g) was dissolved in a small amount of methanol which was added to 150 ml of 1 *M* sulfuric acid. The solution was refluxed for 1 hr. Work-up and purification yielded 1.2 g (63.8%) of a material which was identical in all respects with a genuine sample of 2-benzoylbenzoic acid.

Racemization of (–)-Menthyl Pseudo-(–)-2-benzoylbenzoate (2b**).** The reaction mixture from one of the rate determinations was worked up after 24 hr to yield 92 mg (73%) of a oil whose infrared spectrum was identical with a genuine sample of racemic **2b**. Examination of the ultraviolet spectrum of the product failed to reveal the presence of 2-benzoylbenzoic acid.

Hydrolysis of (–)-Menthyl Pseudo-(–)-2-benzoylbenzoate (2b**).** **2b** (126 mg) was dissolved in 5.4 ml of acetonitrile and 0.6 ml of 12 *M* sulfuric acid was added. After standing for 5 days at 40° the mixture was extracted with sodium bicarbonate solution to yield 12 mg (9.5%) of 2-benzoylbenzoic acid.

(35) M. S. Newman and C. D. McCleary, *J. Amer. Chem. Soc.*, **63**, 1537 (1941).

(36) M. S. Newman and L. K. Lala, *Tetrahedron Lett.*, 3267 (1967). We are grateful to Professor Newman for recommending this procedure prior to its publication and for providing us with a sample of **2** for comparison.

(37) We are grateful to Mrs. Judith Heyman of the Seton Hall Computer Center for preparing a program especially for these operations.