

continues beyond 1.6 *M* HClO<sub>4</sub> is obscured by the incursion of the two-proton process. A similar situation prevails in the hydrolysis of 2-dimethoxymethylquinoline. The initial decline in  $k_{\text{obsd}}$ , and hence in  $f_{\text{SH}^+}/f_{\text{tr}^+}$ , is somewhat steeper and persists into higher acid molarities. One can rationalize these decreases in  $f_{\text{SH}^+}/f_{\text{tr}^+}$  with increasing HClO<sub>4</sub> molarity in terms of stronger solvation of the transition state than the ground state through solvation by the oxygen atoms of water molecules (*cf.* ref. 2 and 3). However, the decline in  $f_{\text{SH}^+}/f_{\text{tr}^+}$  is not spectacular, especially when viewed on a logarithmic scale. In effect then, the assumption applied first by Hammett, that a ratio such as  $f_{\text{SH}^+}/f_{\text{tr}^+}$  suffers relatively little medium effect, is reasonably good in the instances of the hydrolyses of the dimethyl acetals of pyridine-2-aldehyde and quinoline-2-aldehyde.

It was expected that an 8-*t*-butyl substituent on the 2-dimethoxymethylquinoline would substantially alter matters. According to molecular models, the N-H proton of the nitrogen conjugate acid (*i.e.*, the ground state) is very effectively shielded from solvation. On the other hand, the main sites of developing charge in the transition state are only remotely shielded. On this basis two predictions are made: (1) In any particular medium,  $f_{\text{SH}^+}K_{\text{SH}^+}/f_{\text{tr}^+}K_{\text{SH}^{2+}}$  should be greater for the 8-*t*-butyl than the unsubstituted quinoline. (2) The quantity  $f_{\text{SH}^+}/f_{\text{tr}^+}$  for the *t*-butyl derivative should decrease more than the corresponding ratio for the unsubstituted compound as mineral acid molarity is increased. In other words, in the *t*-butyl compound, the ground state (*i.e.*, SH<sup>+</sup>) would have less to lose in free energy of solvation, relative to the transition state, as the activity of water is decreased. These predictions have been realized in full. Thus  $k_{\text{obsd}}$  is appreciably greater in any particular medium for the 8-*t*-butyl derivative (note that the rate results are at 40° for the *t*-butyl compound and at 60° for the unsubstituted one). Furthermore,  $k_{\text{obsd}}$ , and hence  $f_{\text{SH}^+}/f_{\text{tr}^+}$ , declines by a factor of about 12-fold between 0.6 and 6 *M* HClO<sub>4</sub>. It is of interest to note that a Hammett plot (somewhat scattered) has a slope of about 0.65 in this instance.

TABLE II  
RATE CONSTANTS FOR THE HYDROLYSIS OF  
2-DIMETHOXYMETHYLQUINOLINE (A) AND  
8-*t*-BUTYL-2-DIMETHOXYMETHYLQUINOLINE (B)

HClO <sub>4</sub> , <i>M</i>	$10^4 k_{\text{obsd}}$	
	Compd. A	Compd. B
0.10	4.67	<i>a</i>
0.58	3.72	12.41
0.95	3.51	10.01
1.27	...	9.13
1.60	3.32	7.36
1.96	3.21	...
2.33	3.19	5.25
2.71	3.21	4.80
3.11	3.33	4.11
3.54	3.74	3.44
3.99	4.36	3.20
4.60	5.74	1.91
5.09	9.13	1.60
5.72	18.0	1.36
6.51	46.5	1.11
7.60	...	2.03
9.42	...	106.8

<sup>a</sup> Compound insoluble.

For the 8-*t*-butyl compound the one-proton process predominates over a much wider range of perchloric acid strength; *i.e.*, the rate does not begin to turn up until about 7 *M* HClO<sub>4</sub>. This is to be expected since the two-proton hydrolysis should be less effected by the substituent, *i.e.*, solvation of the NH proton should be roughly equal in the ground state and transition state of the two-proton process.

While the situation just described is a contrived one it nevertheless allows the conclusion that the assumption that  $f_{\text{SH}^+}/f_{\text{tr}^+}$  for an A-1 process suffers little change with medium should be applied with care. Unfortunately, the results also demonstrate again that one cannot base mechanistic conclusions on merely the acidity dependence of a rate constant. They further saliently point out that considerably more must be learned about the effect of medium upon the free energies of the ground and transition states of reactions catalyzed in strong acids before the interpretation of the acidity dependence of rate constants can once again be considered to be firmly based.

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### The Possibility of a Cyclic Mechanism for Acid-Catalyzed Ester Hydrolysis

Sir:

The observation of Bell<sup>1</sup> that the rate of hydrolysis of ethyl acetate does not increase with acidity as rapidly as expected for a Hammett indicator<sup>2</sup> has raised questions about the  $pK_a$  of ethyl acetate<sup>3</sup> and the involvement of water in the reaction.<sup>4</sup> Recently Long has concluded that solvent deuterium isotope effects for ester hydrolysis are best fitted by five or more exchangeable hydrogens in the transition state,<sup>5</sup> whereas the accepted tetrahedral mechanism has only three such hydrogens.<sup>6</sup> We now wish to report evidence for a transition state involving protonated ester and two water molecules in a six-membered ring. This transition state has five exchangeable hydrogens, and quantitatively accounts for the water and acidity dependence that we observe.

We have studied the rate of hydrolysis of ethyl acetate at 25° in 11–79% sulfuric acid by the spectrophotometric and dilatometric techniques. The rate reaches a maximum at 50–60% acid and decreases rapidly at higher concentrations. To interpret this maximum, it is necessary to know the  $pK_a$  of ethyl acetate, but none has been reported for an aliphatic ester.<sup>7</sup>

The concentration of protonated ethyl acetate as a function of sulfuric acid concentration was determined

- (1) R. P. Bell, A. L. Dowding, and J. A. Noble, *J. Chem. Soc.*, 3106 (1955).
- (2) M. A. Paul and F. A. Long, *Chem. Rev.*, **57**, 1 (1957).
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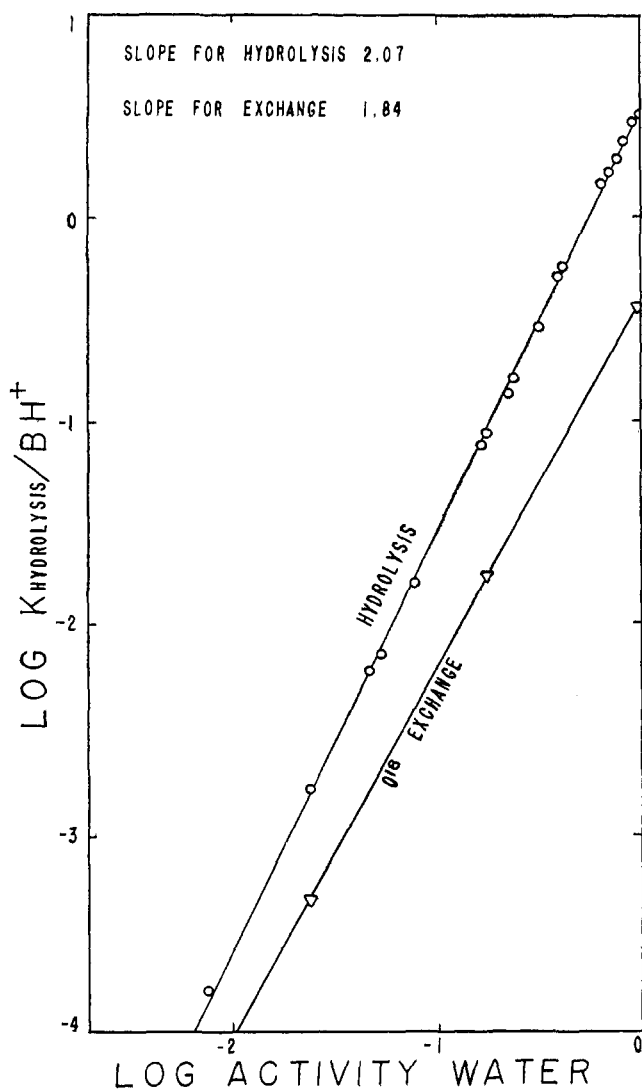


Fig. 1.—Rate of hydrolysis of protonated ethyl acetate from pH 0.33 to 78.8% sulfuric acid. The  $pK_a$  of ethyl acetate is at  $-1.96$  log activity water.

by changes in the zero-time extinction coefficient at  $1900 \text{ \AA}$ . and the chemical shift of the acetyl protons. The equation  $\log BH^+/B = 0.645(-6.93 - H_0)$  gives a very satisfactory fit of the data,<sup>8</sup> where  $BH^+$  is the concentration of protonated ethyl acetate and  $B$  the concentration of unprotonated ester. The half-protonation concentration is 77% sulfuric acid, exactly the value predicted by Arnett.<sup>7</sup>

The study of the hydrolysis of protonated ester has crucial advantages over that of unprotonated ester. The effect of water solvation on the protonation equilibrium<sup>9</sup> is no longer a concern, the use of model indicators to approximate the activity coefficient behavior of ester in sulfuric acid solutions is not necessary,<sup>10</sup> and speculation about the extent of protonation<sup>3</sup> is no longer necessary. The dependence of the hydrolysis of protonated ester<sup>11</sup> on water activity<sup>12</sup> may be obtained by

(8) Slopes of 0.645 are not unusual for carboxylic derivatives. For instance, the slopes of eleven amides are 0.38 to 1.00: J. T. Edward and I. C. Wang, *Can. J. Chem.*, **40**, 966 (1962); A. R. Katritzky and A. J. Waring, *Tetrahedron*, **19**, 465 (1963).

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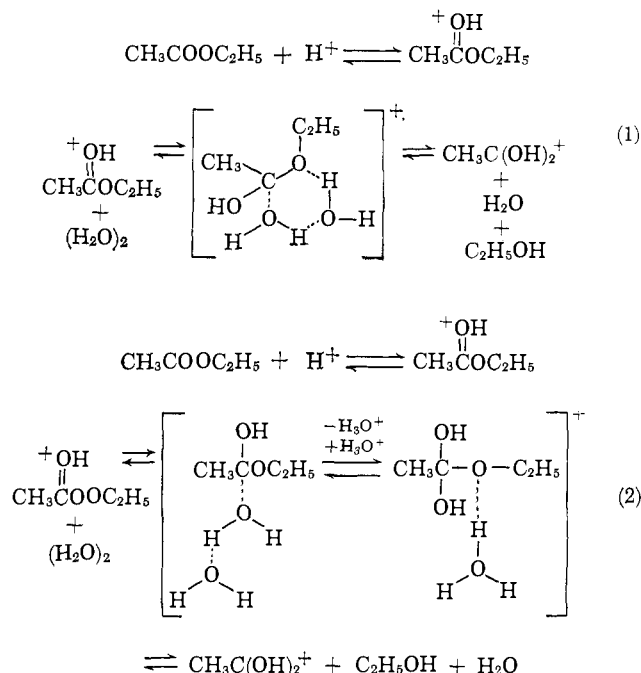
(10) F. A. Long and M. A. Paul, *Chem. Rev.*, **57**, 935 (1957).

(11) The observed rate of hydrolysis multiplied by  $(1 + BH^+/B)/(BH^+/B)$  is the rate of hydrolysis of protonated ester. This simplifies to  $k_{\text{hydrolysis}}/BH^+$  when the total ethyl acetate concentration is set equal to 1.

(12) W. F. Giaque, E. W. Hornung, J. E. Kungler, and T. R. Rubin, *J. Am. Chem. Soc.*, **82**, 62 (1960);

plotting  $\log k_{\text{hydrolysis}}/BH^+$  vs.  $\log a_{H_2O}$  as in Fig. 1. The slope is equal to the order in water, which is apparently two. We have also determined the rate of exchange of the carbonyl oxygen in three concentrations of sulfuric acid. This rate also shows a maximum and nearly parallels the hydrolysis data in Fig. 1.

Two mechanisms satisfying a rate law including ester, hydrogen ion, and two water molecules are



The essential difference between the two mechanisms is in the function of the second water molecule. In the first mechanism, this water transfers a proton to the alkoxy group in much the same manner that proton mobility is explained.<sup>13</sup> In the second mechanism, a water molecule is required to remove a proton from the water attacking the ester. Both mechanisms readily account for carbonyl oxygen exchange: the first by including the carbonyl oxygen in the six-membered ring, the second by formation of a symmetrical tetrahedral intermediate.

The second mechanism must predict that the rate of proton transfer decreases in concentrated acid; otherwise, the maximum in rate of hydrolysis cannot be explained. The rate of proton transfer from methyl-oxonium ion is known to be very rapid in dilute acid solutions.<sup>14</sup> We find that even in 70%  $\text{H}_2\text{SO}_4$  at  $-20^\circ$  the n.m.r. spectrum shows only a narrow singlet for the methyl protons.<sup>15</sup> It should be pointed out that since this result is not quantitative, it is a factor against mechanism 2, but does not rule it out.

In conclusion, we think that the questions raised in the first paragraph have been satisfactorily answered by this work and that the cyclic mechanism is the best

(13) W. J. Moore, "Physical Chemistry," Prentice-Hall, Inc., Englewood Cliffs, N. J., 1962, p. 338.

(14) E. Grunwald, C. F. Jumper, and S. Meiboom, *J. Am. Chem. Soc.*, **84**, 4664 (1962).

(15) The rate of proton transfer from ammonium ions is much slower and we observe a well-resolved triplet for dimethylammonium ion in 73.5% sulfuric acid, in accordance with the results of A. Lowenstein and S. Meiboom, *J. Chem. Phys.*, **27**, 1067 (1957). Thus, the second mechanism may very well apply in the aminolysis of esters where second order dependence on amine has been interpreted by such a mechanism. For leading references see T. C. Bruice and S. J. Benkovic, *J. Am. Chem. Soc.*, **86**, 418 (1964).

explanation of our observations and those of other workers.<sup>6,16</sup>

**Acknowledgment.**—We are grateful to Professor A. Burlingame and to Sherri Firth for the oxygen-18 determinations, and to Dr. M. J. Jorgenson for many helpful and stimulating discussions.

(16) The transfer of a proton from the hydroxyl to the carbonyl group of benzoic acid in methanol is dependent on the square of methanol concentration. This has been interpreted in terms of a cyclic transition state where the proton transfer occurs through two hydrogen-bonded methanol molecules: E. Grunwald, C. F. Jumper, and S. Meiboom, *J. Am. Chem. Soc.*, **85**, 522 (1963).

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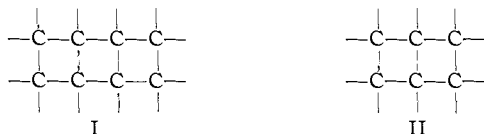
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### The Configuration of $C_8F_{12}$ , a Saturated Dimer of Hexafluorobutadiene

Sir:

The synthesis of a fully saturated dimer of hexafluorobutadiene was reported some years ago.<sup>1</sup> A two-step thermal reaction beginning with hexafluorobutadiene resulted in a volatile solid which melted at 40° and boiled at 80°. The related fluorocarbons  $C_8Cl_4F_8$  and  $C_8H_{10}$  were also synthesized by Miller.<sup>2</sup> It was suggested on the basis of the conditions of the syntheses that the carbon skeletons for these compounds may be



X-Ray diffraction photographs of  $C_8Cl_4F_8$  and  $C_8F_{10}$  were very suggestive of considerable disorder in these crystals.<sup>3</sup> The intensities of Bragg reflections fell off extremely rapidly with increasing angle of scattering. On the other hand, a full sphere of X-ray data using Cu  $K\alpha$  radiation was obtained for  $C_8F_{12}$ . The material crystallizes in the triclinic system with unit cell dimensions  $a = 6.02$ ,  $b = 6.29$ ,  $c = 7.27$  Å.,  $\alpha = 103.6^\circ$ ,  $\beta = 107.9^\circ$ ,  $\gamma = 106.4^\circ$  and contains one molecule per unit cell. The density is computed to be 2.29 g./cm.<sup>3</sup>. Statistical tests on the X-ray data strongly indicated a centrosymmetric cell. Phases determined by the symbolic addition procedure<sup>4</sup> led to an electron density map which could be satisfied only by a disordered structure. A satisfactory least-squares refinement was obtained with an acentric molecule which may reverse direction at random from cell to cell, giving rise to an approximate centrosymmetric average cell. The  $R$ -factor is 17.7% and the bond lengths and angles are reasonable. A complete description of the structure determination of  $C_8F_{12}$  will be published elsewhere.

The carbon skeleton of the  $C_8F_{12}$  molecule is not in the form of the three-ring system shown in I, but rather has two bridge bonds to form four-membered and five-membered rings (tricyclo[3.3.0.0<sup>2,6</sup>]octane). The sym-

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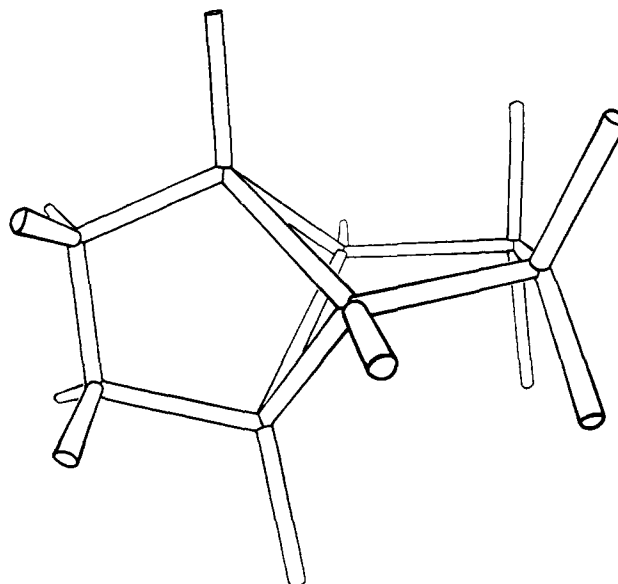
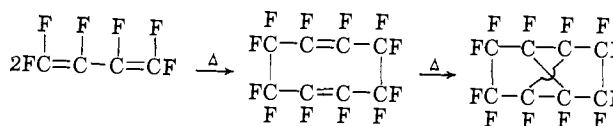


Fig. 1.—Model for the bonding pattern in  $C_8F_{12}$  shown in perspective. The principal axis of the molecule, a fourfold axis of rotary reflection (or rotary inversion), runs from left to right in the diagram.

metry of the molecule is  $D_{2d}$ . The stereochemical nature of the bonding pattern is displayed in the perspective drawing of Fig. 1.

The  $C_8F_{12}$  molecule is very compact and ellipsoidal in shape which accounts for its very high density. Its high volatility can be associated with its low surface area. Both the configuration and physical properties can be compared with those of adamantane<sup>5</sup> and twistane.<sup>6</sup> In  $C_8F_{12}$  it is interesting to note that the average C–F bond length for one fluorine atom attached to a carbon atom is 1.367 Å. as compared to 1.326 Å. for the average C–F when two fluorine atoms are attached to a carbon atom. This is in agreement with results obtained from electron diffraction studies of the vapors of fluorocarbons, where monofluorides have an average value of 1.38 Å. for the C–F whereas the average value for C–F in polyfluorides is 1.33 Å.<sup>7</sup>

In view of the configuration (Fig. 1), the chemical reactions which led to the synthesis of  $C_8F_{12}$  may perhaps be



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