

The General Acid-catalyzed Hydrolysis of Unsubstituted Ketene Acetals

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Proton transfer from different Brønsted acids to ketene di-2-methoxyethyl acetal in water and water-dioxane mixtures was studied. The catalytic coefficients of various acids were determined using buffer solutions. A linear free energy correlation was found between the logarithms of the rate coefficients of hydrolysis and the logarithms of the dissociation constants of the acids. Catalysis by deuterated Brønsted acids in deuterium oxide was also studied. The values of Brønsted α for the protonated and the deuterated acids, 0.56 ± 0.02 and 0.51 ± 0.06 , are almost equal. Thus, possible proton tunneling in the hydrolysis of the ketene acetal can be disregarded. The temperature dependence of the rate coefficients is also in accordance with this assumption. The solvent deuterium isotope effect, k_{DA}/k_{HA} , in the hydrolysis of ketene di-2-methoxyethyl acetal varied between 0.10 and 0.15 when different Brønsted acids were the catalysts.

Proton transfer from water to the ketene acetal was also studied. The change from light to heavy water as solvent led to a reduction of the rate of proton transfer by a factor of about ten. Also the water-catalyzed hydrolysis in dioxane-water mixtures was studied; a remarkable rate retardation was observed with increasing dioxane content of the solvent.

In a previous paper,¹ we discussed kinetic data for the fast hydrolytic decomposition of ketene diethyl acetal and 2-methylene-1,3-dioxolane and concluded that the proton transfer takes place in the rate-determining stage of the hydrolysis of ketene acetals similarly as in the hydrolysis of the structurally related vinyl ethers.^{2,3} Owing to their great susceptibility to hydrolytic decomposition, the hydrolysis of the ketene acetals could be studied only in solutions in which the hydronium ion concentration was less than 10^{-10} M. Gold and Waterman⁴ studied the hydrolysis of two substituted ketene acetals, cyanoketene dimethyl acetal and 2-dichloromethylene-1,3-dioxolane, the rates of which are relatively low due to the electronegative substituents attached to the carbon-carbon double bonds; the reactivities of these compounds are comparable to those of "normal" vinyl ethers, 1-alkoxyalkenes.^{2,3} The kinetic data for cyanoketene dimethyl acetal and 2-dichloromethylene-

1,3-dioxolane show features typical of vinyl ether hydrolysis. Recently, additional information on the hydrolysis of ketene acetals has been obtained in an extensive study of the hydrolysis of a number of substituted ketene acetals.⁵

The aim of this investigation was to study the hydrolytic decomposition of acetals of unsubstituted ketene in detail. As ketene diethyl acetal, the compound studied in the previous work,¹ is too reactive for extensive studies, we used as a model compound in the kinetic experiments ketene di-2-methoxyethyl acetal, the electronegative methoxy groups of which lower the reactivity compared to that of diethyl acetal. Consequently, general acid catalysis of its hydrolysis can be studied using Brønsted acids with greatly different pK_a values. With this model compound it is also possible to study deuterium solvent isotope effects and the temperature dependence of the rate coefficients in detail.

EXPERIMENTAL

Materials. Ketene di-2-methoxyethyl acetal (1,1-di(2-methoxyethyl)ethylene) was the preparation synthesized previously.⁶ The used deuterium oxide (99.8 % D_2O) was a product of Norsk Hydro. Dioxane was purified by the standard method.⁷

Kinetic measurements. The rate coefficients of the hydrolysis of the ketene acetal were measured in buffer solutions, the lyonium ion concentrations of which were less than 10^{-8} M. Both light and heavy water were used as solvents. The water-catalyzed reaction was studied also in water-dioxane mixtures that were 0.01 M in sodium hydroxide to suppress the hydronium ion-catalyzed reaction. The ratio of the concentration of the acid to that of the base was usually 1/1 in the buffer solutions, but 1/14 in the hydrogen tellurite-tellurite buffers and 1/9 in the arsenic acid-hydrogen arsenite ion buffers. The concentrations of the more acidic components of the buffer solutions varied as follows: hydrogen tellurite ion $4 \times 10^{-5} - 2 \times 10^{-4}$ M, hydrogen selenite ion $5 \times 10^{-4} - 1.5 \times 10^{-3}$ M, hydrogen carbonate ion $3.3 \times 10^{-3} - 10^{-2}$ M, hydrogen arsenate ion $3 \times 10^{-3} - 10^{-1}$ M, hydrogen phosphate ion $2 \times 10^{-2} - 10^{-1}$ M, arsenic acid $6.6 \times 10^{-4} - 2 \times 10^{-3}$ M, and trifluoroethanol $10^{-2} - 5 \times 10^{-2}$ M. The ionic strengths of all the reaction mixtures were adjusted to 0.1 M by adding sodium chloride.

The progress of the hydrolysis of the ketene acetal was followed by measuring the absorbance of the carbon-carbon double bond at 230-237 nm with a Unicam SP. 800 spectrophotometer, the cell housing of which was held at the desired temperature with water circulated from a Lauda electronically controlled thermostat.

RESULTS AND DISCUSSION

General acid catalysis. The first-order rate coefficients of the hydrolysis of ketene di-2-methoxyethyl acetal in different buffer solutions can be expressed by

$$k_{\text{obs}} = k_{\text{HA}}(\text{HA}) + k_{\text{H}_3\text{O}^+}(\text{H}_3\text{O}^+) + k_{\text{H}_2\text{O}}(\text{H}_2\text{O}) \quad (1)$$

where k_{HA} is the rate coefficient of the reaction catalyzed by the undissociated Brønsted acid and $k_{\text{H}_3\text{O}^+}$ and $k_{\text{H}_2\text{O}}$ are the catalytic coefficients of hydronium ion and water, respectively. When the first-order rate coefficients are plotted against the concentration of the undissociated Brønsted acid, a straight line should result as the hydronium ion concentration remains constant in buffer solutions of constant ratio $(\text{HA})/(\text{A}^-)$ when the amount of the undissociated acid is varied. To determine whether this is the case in the hydrolysis

of the studied ketene acetal, the rate coefficients for the reaction in bicarbonate – carbonate buffer solutions in heavy water were plotted against the concentration of bicarbonate ion (Fig. 1). Similar linear relationships were obtained for the reaction in the other buffer solutions. The slopes and intercepts of the plots were calculated by the method of least squares. The linearity of the plots is satisfactory as the relative standard errors of the k_{HA} values collected in Table 1 are in all cases less than 5 %. The data collected in Table 1

Table 1. Kinetic data for the general acid-catalyzed hydrolysis of ketene di-2-methoxyethyl acetal in buffer solutions in light and heavy water. LA is the more acidic component of the buffer solution. The ionic strength was adjusted to 0.1 with sodium chloride.

LA	pK_{LA}^{25}	Solvent	Temp. °C	Number of runs	k_{HA} ($\text{M}^{-1}\text{s}^{-1}$)	$10^2 k_0$ (s^{-1})
$\text{TeO}_2(\text{OH})^-$ $\text{SeO}_2(\text{OH})^-$ $\text{As}(\text{OH})_3$	7.70 8.30 9.28	H_2O	15.8	16	152 ± 6	0.74 ± 0.08
			15.8	13	96.7 ± 1.2	1.47 ± 0.12
			6.3	5	10.0 ± 1.0	
			10.7	7	14.9 ± 0.6	
			15.8	10	15.7 ± 1.0	1.22 ± 0.14
$\text{CO}_2(\text{OH})^-$	10.36	H_2O	20.5	7	25.6 ± 0.7	
			6.3	9	3.51 ± 0.05	
			10.7	9	4.65 ± 0.08	
			15.8	15	5.77 ± 0.10	0.62 ± 0.07
			20.5	8	6.93 ± 0.05	
$\text{AsO}_3(\text{OH})^{2-}$	11.60	H_2O	6.3	7	1.03 ± 0.07	
			10.7	10	1.48 ± 0.10	
			15.8	13	2.29 ± 0.05	0.51 ± 0.18
			20.5	8	2.69 ± 0.06	
			15.8	15	0.587 ± 0.011	0.50 ± 0.08
$\text{PO}_3(\text{OH})^{2-}$ $\text{F}_3\text{CCH}_2\text{OH}$ H_2O	12.32 12.37 15.74	H_2O	15.8	10	0.167 ± 0.008	0.56 ± 0.03
			15.8	3		0.401 ± 0.002
			20.3	2		0.545 ± 0.012
			25.5	3		1.03 ± 0.01
			30.4	2		1.26 ± 0.02
$\text{SeO}_2(\text{OD})^-$ $\text{As}(\text{OD})_3$	8.79 9.80	D_2O	35.2	3		1.90 ± 0.02
			15.7	6	13.4 ± 0.2	0.16 ± 0.03
			6.4	4	0.803 ± 0.069	
			11.1	6	1.22 ± 0.06	
			15.7	6	1.63 ± 0.09	0.17 ± 0.01
$\text{CO}_2(\text{OD})^-$	10.97	D_2O	20.4	6	2.23 ± 0.14	
			6.2	5	0.330 ± 0.022	
			10.9	5	0.449 ± 0.032	
			15.7	5	0.579 ± 0.016	0.09 ± 0.01
			20.4	7	0.732 ± 0.035	
$\text{AsO}_3(\text{OD})^{2-}$	12.35	D_2O	6.4	6	0.179 ± 0.024	
			10.9	5	0.247 ± 0.011	
			15.7	6	0.354 ± 0.007	-0.31 ± 0.05
			20.4	7	0.427 ± 0.018	
			15.7	6	0.0736 ± 0.0022	0.003 ± 0.016
$\text{PO}_3(\text{OD})^{2-}$ D_2O	12.99	D_2O	15.7	2		0.0544 ± 0.0035
			20.3	2		0.0725 ± 0.0026
			25.5	2		0.136 ± 0.001
			30.4	2		0.192 ± 0.001
			35.2	2		0.286 ± 0.009

show that the k_0 values measured in most of the used buffer solutions are equal within the limits of experimental error and of the magnitude expected for the water-catalyzed reaction although the hydronium ion concentrations of the buffer solutions differed by several powers of ten. Thus we can conclude that the intercepts of the plots represent only the rate coefficients of the water-catalyzed reaction, although it is possible that there is a small contribution

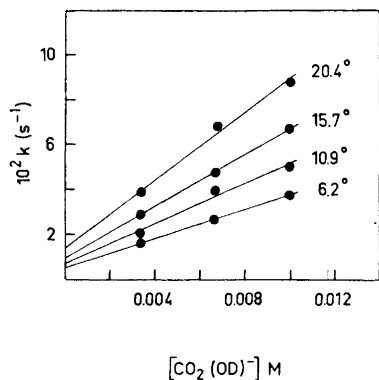


Fig. 1. The first-order rate coefficients of the hydrolysis of ketene di-2-methoxyethyl acetal in bicarbonate-carbonate buffer solutions in heavy water as a function of the concentration of the more acidic component of the buffer solution. The ionic strength was adjusted to 0.1 with sodium chloride.

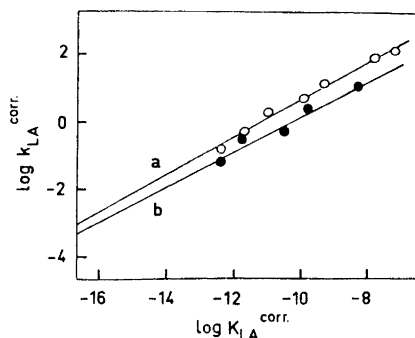


Fig. 2. Plot of the logarithms of the rate coefficients of the general acid-catalyzed hydrolysis of ketene di-2-methoxyethyl acetal versus the logarithms of the dissociation constants of the acids used as catalysts. Light water (open circles) and heavy water (filled circles) were used as solvents.

of the hydronium ion-catalyzed reaction in the most acidic buffer solutions. Most of the dissociation constants were taken from the Handbook of Chemistry.⁸ The pK value taken for water is that reported by Laughton and Robertson.⁹ For trifluoroethanol, we used the value determined by Ballinger and Long.¹⁰

The logarithms of the catalytic coefficients of different Brønsted acids at 15.8°C are plotted against the logarithms of the dissociation constants of the acids in Fig. 2. Statistical corrections were applied to the kinetic and equilibrium data.¹¹ For the reaction catalyzed by arsenic acid, corrections were not applied due to the uncertainty in the actual scheme of dissociation of the acid. Plot a in Fig. 2 shows an excellent Brønsted relationship with slope α equal to 0.56 ± 0.02 . It should be noted that this value is based on kinetic data obtained with oxyacids of widely varying strength as catalysts. Gold and Waterman⁴ obtained the value 0.63 for the hydrolysis of a substituted ketene acetal, cyanoketene diethyl acetal, and the value 0.49 for the hydrolysis of 2-dichloromethylene-1,3-dioxolane. Their values of α were based on kinetic data for the reactions in carboxylic acid buffers. Straub⁵ recently obtained values between 0.36 and 0.42 for the hydrolysis of substituted ketene acetals

in carboxylic acid buffer solutions. He also observed that the values of the Brønsted α are dependent on the acids used as catalysts.

Solvent deuterium isotope effects. In addition to the rate coefficients in light water, Table 1 contains rate coefficients of hydrolysis of the ketene acetals in deuterium oxide. The relative standard errors of these rate coefficients are seen to be less than 5 %. The pK_{DA} values in Table 1 were calculated with the aid of the relative acidity constants in light and heavy water reported by Salomaa *et al.*^{12,13} As these values are based on measurements with glass electrodes, they may be subject to errors due to liquid junction potentials.¹⁴ However, the effect of these possible errors on the Brønsted plot cannot be material, as only relative pK values are required. The dissociation constant of hydrogen arsenate ion in deuterium oxide was estimated on the basis of the equilibrium data for phosphoric acids in light and heavy water.^{12,13}

The Brønsted relationship in the case of the deuterated acids is shown in Fig. 2. Curve b plotting the logarithms of the rate coefficients (at 15.7°C) against the logarithms of the dissociation constants has a slope of 0.51 ± 0.06 . This value of the Brønsted α is equal within the limits of experimental error to that for the reaction in protium oxide. If proton tunneling were substantial in the studied reaction, the values of α for the reaction in light and heavy water should differ.^{4,15} Definite conclusions cannot, however, be drawn because of the limited kinetic data.

Table 2. Solvent deuterium isotope effects in the hydrolysis of unsubstituted ketene acetals in water. The rate coefficients at 25°C were calculated from the Arrhenius equations.

Compound	Acid HA	Temp.	k_{DA}/k_{HA}	Ref.
Ketene diethyl acetal	L ₂ O	10.0	0.16	1
2-Methylene-1,3-dioxolane	L ₂ O	10.0	0.12	1
Ketene di-2-methoxyethyl acetal	L ₂ O	25.0	0.139	This work
	PO ₃ (OL) ²⁻	15.8	0.125	This work
	AsO ₃ (OL) ²⁻	25.0	0.152	This work
	CO ₂ (OL) ⁻	25.0	0.109	This work
	As(OL) ₃	25.0	0.100	This work
	SeO ₂ (OL) ⁻	15.8	0.139	This work

In Table 2 are collected values of the solvent deuterium isotope effect (k_{DA}/k_{HA}) in the hydrolysis of several unsubstituted ketene acetals. Although the pK values of the used catalysts differ markedly, the isotope effects are of the same magnitude and vary between 0.10 and 0.15. As we previously reported,¹ isotope effects of this magnitude are to be expected for rate-determining proton transfers from weak Brønsted acids to ketene acetals. In a kinetic study of the hydrolysis of substituted ketene acetals, Gold and Waterman⁴ obtained k_{DA}/k_{HA} values of about 0.2, which are only slightly higher than those in Table 2. The solvent deuterium isotope effects for the hydronium ion-

catalyzed hydrolysis of substituted ketene acetals have been observed to be almost equal to those in the hydrolysis of vinyl ethers.⁵

Temperature dependence of the rate coefficients. The rates of the reactions catalyzed by hydrogen carbonate ion, hydrogen arsenate ion, and arsenic acid in light and heavy water were measured at several temperatures between 5 and 20°C. Owing to the high rates of the reactions, only these relatively low temperatures could be employed. The logarithms of the rate coefficients are plotted against reciprocal temperature in Fig. 3. The parameters of the Arrhenius equation were calculated from the data by the method of least squares (Table 3). Owing to the relatively narrow temperature range used in the

Table 3. The temperature dependence of the rate coefficients in the general acid-catalyzed hydrolysis of ketene di-2-methoxyethyl acetal in light and heavy water.

Catalyst	Solvent	A	E (kcal/mol)	ΔS^\ddagger (e.u.)
AsO ₃ (OH) ²⁻	H ₂ O	9.82×10^8	11.5	-19.4 ± 4.5
AsO ₃ (OD) ²⁻	D ₂ O	2.35×10^7	10.4	-26.8 ± 3.0
CO ₂ (OH) ⁻	H ₂ O	4.16×10^8	7.75	-30.2 ± 2.0
CO ₂ (OD) ⁻	D ₂ O	4.60×10^8	9.12	-30.0 ± 1.1
As(OH) ₃	H ₂ O	4.62×10^8	9.79	-20.9 ± 7.4
As(OD) ₃	D ₂ O	1.14×10^9	11.7	-19.1 ± 2.3
H ₂ O ^a	H ₂ O	2.30×10^8	14.2	-21.9 ± 2.0
D ₂ O ^a	D ₂ O	2.70×10^8	15.5	-22.3 ± 1.8

^a The parameters of Arrhenius' equation were calculated from the experimental first-order rate coefficients.

measurements, the effect of temperature on the dissociation constants of the catalysts can be omitted. The activation entropies of the hydrolysis vary between -20 and -30 e.u. and the activation energies between 8 and 12 kcal/mol. When the activation parameters for the reactions catalyzed by protonated and deuterated acids are compared, only small differences are found. For instance, the activation entropies for the reactions catalyzed by the protium carbonate ion and the deuterium carbonate ion are -30.2 ± 2.0 and -30.0 ± 1.1 e.u., respectively. The uncertainty in the entropy values is, however, relatively large owing to the limited temperature range where the rates were measured. The possible differences are not marked. The transition state theory predicts that the ratio A_H/A_D should vary from 0.5 to 1.0 in proton transfer reactions.¹⁵ The data in Table 3 reveal that this is the case for the hydrolysis catalyzed by hydrogen carbonate ion and arsenic acid. The ratio A_H/A_D for the reaction catalyzed by hydrogen arsenate ion is greater than unity. Bell¹⁶ has concluded that A_H/A_D values less than 0.5 provide evidence of proton tunneling. As the measured ratios in all cases exceed 0.5, the contribution of proton tunneling cannot be substantial.

The reactions catalyzed by light and heavy water were also studied at different temperatures. The parameters of the Arrhenius equation were calculated from the observed first-order rate coefficients (Table 2). The fre-

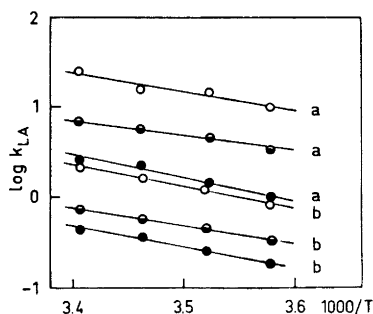


Fig. 3. The logarithms of the second-order rate coefficients of the hydrolysis of ketene di-2-methoxyethyl acetal at different temperatures versus reciprocal temperature (K). The measurements were performed in light (a) and heavy (b) water. The catalysts were arsenic acid (open circles), hydrogen carbonate ion (half-filled circles), and hydrogen arsenate ion (filled circles).

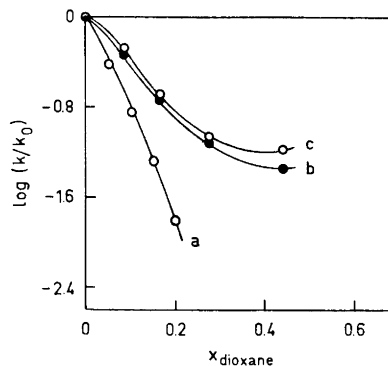
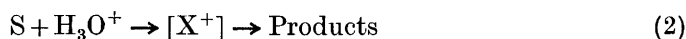


Fig. 4. Solvent effects in rate-determining proton transfer reactions in water – dioxane mixtures. The water – catalyzed hydrolysis of ketene di-2-methoxyethyl acetal (plot a), the hydronium ion-catalyzed hydrolysis of 2-methyl-4-methylene-1,3-dioxolane (plot b) and the hydronium ion-catalyzed hydrolysis of tri-2-chloroethyl orthoformate (plot c).

quency factors for the reactions in light and heavy water were found to be equal within the limits of experimental error. This observation gives additional evidence for the absence of proton tunneling in the hydrolysis of ketene acetals. Apparent second-order rate coefficients for the water-catalyzed reaction can be obtained by dividing the first-order rate coefficients by the concentration of water, 55.5 M. The use of these rate coefficients would lower the ΔS^\ddagger values of the water-catalyzed reactions in Table 2 by about 8 e.u.

Solvent effects. To study the effect of solvent on the rate coefficients of the hydrolysis of ketene acetals, especially on the water-catalyzed reaction, some additional experiments were performed with water–dioxane mixtures to which sodium hydroxide had been added to suppress the hydronium ion-catalyzed reaction.

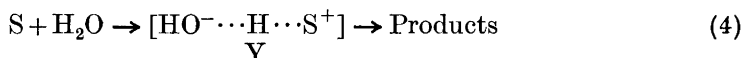
A remarkable reduction of the rate of the water-catalyzed reaction occurs with increasing mol fraction of dioxane, as can be seen from plot a in Fig. 4. To compare this solvent effect with that of the corresponding hydronium ion-catalyzed reactions, the logarithms of the rate coefficients of the hydrolysis of 2-methylene-1,3-dioxolane¹⁷ and tri-2-chloroethyl orthoformate¹⁸ were plotted against the mol fraction of dioxane (Fig. 4). The solvent effects are seen to be more significant in the water-catalyzed reaction than in reactions in which the proton is transferred from hydronium ion. This is easily understood from the solvent effects on the initial and the transition states. The second-order rate coefficients of the hydronium ion-catalyzed $A-S_E2$



reaction (2) can be expressed in the form

$$k_2 = k_0 \frac{y_{\text{H}_2\text{O}^+} y_s}{y_{\text{X}^+}} \quad (3)$$

where k_0 is the standard rate coefficient and the y 's are the molar activity coefficients of the different species referred to dilute solutions in water. Similarly, for the hydrolysis reaction in which the proton is transferred from water to the substrate in the rate-determining stage (eqn. (4)),



the second-order rate coefficient is

$$k_2 = k_0 \frac{f_{\text{H}_2\text{O}} y_s}{y_{\text{Y}}} \quad (5)$$

Here the activity of water is given on the rational (mol fraction) scale with activity coefficient $f_{\text{H}_2\text{O}}$ equal to unity in pure liquid water. The effect of solvent on the ratio $y_{\text{H}_2\text{O}^+}/y_{\text{X}^+}$ for the hydronium ion-catalyzed reaction is relatively weak as both hydronium ion and the transition state of the hydrolysis are of the same charge type. In addition, the effect of solvent on the activity coefficient of an uncharged substrate cannot be very significant and the rate retardation does not hardly exceed one power of ten. The situation is quite different in the water-catalyzed reaction, where the effect of solvent on the ratio $f_{\text{H}_2\text{O}}/y_{\text{Y}}$ can be expected to be very material. For instance, when we go from water to the water-dioxane mixture in which the mol fraction of dioxane is 0.4, the mol fraction activity coefficient $f_{\text{H}_2\text{O}}$ increases only about 13 %, ^{17,19} but the effect of solvent on y_{Y} must be very pronounced as the positive and negative charges are separated in the transition state of the hydrolysis (see eqn. (3)). On the basis of the value 0.56 ± 0.02 of Brønsted α for the hydrolysis of ketene di-2-methoxyethyl acetal, it can be interferred that the extent of proton transfer, and hence the separation of opposite charges, is substantial in the transition state. As this charge separation is strongly favored in polar solvents like water, the remarkable rate decrease in water-dioxane mixture is understandable.

REFERENCES

1. Kankaanperä, A. and Tuominen, H. *Suomen Kemistilehti* **B 40** (1967) 271.
2. Salomaa, P., Kankaanperä, A. and Lajunen, M. *Acta Chem. Scand.* **20** (1966) 1790.
3. Kresge, A. J. and Chiang, J. *J. Chem. Soc.* **B 1967** 58.
4. Gold, V. and Waterman, D. C. A. *J. Chem. Soc.* **B 1968** 839, 849.
5. Straub, T. S., Ph.D. Thesis, Illinois Institute of Technology, Chicago 1970.
6. Kankaanperä, A. and Aaltonen, R. *Suomen Kemistilehti* **B 43** (1970) 183.
7. Vogel, A. I. *Practical Organic Chemistry*, 3rd Ed., Longmans, London 1956, p. 177.
8. *Handbook of Chemistry*, The Chemical Rubber Co., Cleveland 1964, D78.
9. Loughton, P. M. and Robertson, R. E. In Coetzee, J. F. and Ritchie, C. D., Eds., *Solute-Solvent Interactions*, Marcel Dekker, New York 1969, p. 412.
10. Ballinger, P. and Long, F. A. *J. Am. Chem. Soc.* **81** (1959) 1050.
11. Benson, S. W. *J. Am. Chem. Soc.* **80** (1958) 5151.
12. Salomaa, P., Schaleger, L. L. and Long, F. A. *J. Am. Chem. Soc.* **86** (1964) 1.
13. Salomaa, P., Hakala, R., Vesala, S. and Aalto, T. *Acta Chem. Scand.* **23** (1969) 2116.
14. Salomaa, P. *Personal communication*.

15. Bell, R. P. *Proc. Roy. Soc. A* **154** (1936) 414.
16. Bell, R. P. *The Proton in Chemistry*, Methuen, London 1959, pp. 197, 210–214.
17. Kankaanperä, A. and Merilahti, M. *Acta Chem. Scand.* **26** (1972) 685.
18. Kankaanperä, A., Lahti, M. and Merilahti, M. *Acta Chem. Scand.* **24** (1970) 360.
19. Kenttämää, J. and Lindberg, J. J. *Suomen Kemistilehti B* **33** (1960) 32, 98; Cox, B. and McTigue, P. *Aust. J. Chem.* **20** 1819.

Received September 28, 1971.