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Kinetics of the Hydrolysis in 1:3 Water-Acetone of Aliphatic Esters having Substituents in the Alkyl Group, Catalysed by an Acid Resin or an **Acidic Solution**

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The efficiency of an acid resin for hydrolysis of esters substituted in the alkyl group, i.e., the ratio of the rate coefficient for hydrolysis with resin catalysts to the rate coefficient for hydrolysis in acidic solution, has been measured for a number of alkyl substituents. The efficiency has been shown to be related to the entropy of the substituent. Distribution coefficients have been measured for selected esters, and the results indicate that the variation in efficiency of the resin for esters containing cyclic and normal substituents is not due to differences in ester concentration in the vicinity of the resin matrix.

DAVIES and Thomas¹ have observed that the rate coefficients for hydrolysis of esters, in the presence of an acid catalyst, are different for an acid in solution and for a solution containing an insoluble acid resin. Though sulphonic acid resins may generally be considered to behave similarly to solutions of acids,² differences may arise due to diffusion effects, salting-in of reactants, etc. Many such phenomena can be ascribed to differences in solvent composition in the proximity of the resin matrix, compared to the composition in the bulk of the solution.³ More specific interactions between the reactants and the resin matrix or counter-ions may occur in certain systems.⁴ Bernhard and Hammett ⁵ proposed that the difference in rate coefficient for hydrolysis of esters in acidic solution, and in a solution containing a sulphonic acid resin, was due to interaction of the ester with the resin matrix. The efficiency of the resin catalyst, defined as the ratio of the rate coefficient for hydrolysis with an acid resin catalyst to the rate coefficient for hydrolysis in an acidic solution, was shown to be a function of the entropy of the ester. They proposed, therefore, that interaction with the resin matrix results in the ester being constrained, and that leads to a decrease in entropy. The decrease in entropy on formation of the transition state is greater in magnitude for reactions catalysed by an acidic resin than for acid-catalysis in solution. The magnitude of the decrease depends on the structure of the ester, e.g., esters

1962, p. 543.

containing cyclic substituents have less internal entropy than corresponding straight-chain compounds and therefore lose less entropy on interaction with the resin. A similar effect has been found with the acid-resincatalysed hydrolysis of amides.^{6,7}

No account was taken, however, of possible differences in distribution coefficients of cyclic and straight-chain compounds, between the bulk solution and the vicinity of the resin matrix. Helfferich suggests that the variation of distribution coefficient may be the prime cause of the relationship between the efficiency of the resin catalyst and the structure of the reactant.²

Hammett and his co-workers⁵ investigated the hydrolysis of esters substituted in the acyl group. There are scanty kinetic data available for the hydrolysis of esters substituted in the alkyl group. We therefore investigated the kinetics of hydrolysis of esters, substituted in the alkyl group, in the presence of acidic solutions, and in solutions containing insoluble acid resins. We also measured the distribution coefficients of the esters between the bulk of the solution and the solution within the interstices of the resin.

EXPERIMENTAL

Materials.—The acetates of methyl, ethyl, and n-butyl alcohol were available commercially. The remaining

¹ C. W. Davies and G. G. Thomas, J. Chem. Soc., 1952, 1607. ² F. Helfferich, J. Amer. Chem. Soc., 1954, **76**, 5567. ³ F. Helfferich, 'Ion Exchange,' McGraw-Hill, New York,

⁴ S. Affrossman and J. P. Murray, J. Chem. Soc. (B), 1966, 1015.

⁵ S. A. Bernhard and L. P. Hammett, J. Amer. Chem. Soc., ⁶ S. A. Dermand L. 1.
¹⁹⁵², **75**, 1798.
⁶ P. D. Bolton and T. Henshall, J. Chem. Soc., 1962, 1226.
⁷ P. D. Bolton and I. R. Wilson, Tetrahedron Letters, 1963, 847.

esters were prepared from acetic anhydride and the appropriate alcohol, by using pyridine as a catalyst. All the esters were treated with sodium hydrogen carbonate solution, washed, and dried over anhydrous magnesium sulphate. The esters were then fractionally distilled repeatedly, under dry nitrogen, until pure. The purity was checked by vapour-phase chromatography. A stationary phase of 10% Apiezon L on Celite was used, with a column temperature of 150°. The esters were considered pure when no impurities were detectable. The refractive indices of the esters were also measured. The boiling points and refractive indices are shown in Table 1, together with values from the literature. The esters were stored under dry nitrogen in a sealed vessel containing anhydrous magnesium sulphate.

Table	1
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		n_D^{20}		B.p.
Acetate	n_D^{20}	in lit.ª	В.р.	in lit.ª
Methyl	1.3619	1.3617	57.0°	57.0°
Ethyl	1.3700	1.3701	77.0	77.06
n-Butyl	1.3966	1.3970	126.5	126.5
Cyclopentyl	1.4102	1.4131	154.1	155.0
Pent-2-yl	1.3952	1.3960	135.0	133.5
n-Pentyl	1.4035	1.4031	150.1	149.25
Cyclohexyl	1.4386	1.4401	174.0	174.5
n-Hexyl	1.4101	1.4119	170.0	169.2
n-Octyl	1.4222	1.4261	208.1	210.0

^a All values were taken from 'Handbook of Chemistry and Physics,' 46th edn., Chemical Rubber Publishing Co., Cleveland, 1966, except the b.p. of cyclopentyl acetate and the refractive indices of cyclopentyl, n-hexyl, and n-octyl acetate which were obtained from Beilstein's 'Handbook of Organic Chemistry,' Springer-Verlag, Berlin, 1958.

Resin Pretreatment.—Amberlite I.R. 120 (B.D.H.), a polystyrene sulphonic acid resin, was treated with alcoholic hydrochloric acid to remove metal ions, and acetone and methanol to remove traces of soluble organic material, and then subjected to numerous cycles of 2N-hydrochloric acid, 2N-sodium hydroxide, and demineralised water. The resin was finally stored in the sodium ion form after prolonged washing with demineralised water.

Resin Capacity.—The number of ionogenic groups per unit weight of resin was determined as follows. About fifty samples of the resin, in the sodium form, were weighed out in as short a time as possible (to reduce variations in moisture content). A random selection of ten samples was chosen for capacity determinations and the remainder were kept for reactions. The samples were converted into the hydrogen-ion form by batch equilibration with hydrochloric acid. The hydrogen counter-ion of the resin was then exchanged by repeated batch equilibration with an excess of 1.0M-sodium chloride. The hydrogen ion content of the sample was then estimated by titrating the combined decanted solutions with standard sodium hydroxide.

Kinetic Procedure.—25% v/v aqueous acetone was prepared by adding AnalaR acetone to 250 ml. of demineralized water to make 1 l.

The hydrolysis with acid in solution was carried out with ester concentrations of 0.1—0.4M in 0.0240N-hydrochloric acid. The acetic acid formed during the hydrolysis was estimated by titration with 0.1N-sodium hydroxide. The first-order rate equation,

$$kt = 1/[\mathrm{H}^+] \ln a/(a - x)$$

where a is the initial ester concentration and (a - x) is the ester concentration after time t, was used to calculate k in

l. mole⁻¹ sec.⁻¹. The reactions were carried out at 35°. (Repeat runs were carried out at each temperature.) Table 2 shows the rate coefficients and steric substituent constant, $E_{\rm s} = \log k/k_0$, as defined by Taft.⁸

TABLE 2						
	$10^{5}k$			$10^{5}k$	Effi-	
	(acid		E_{s} in	(acid	ciency,	
Acetate	soln.)	E_s	lit.ª	resin)	q	
Methyl	13.0	0.00	0.00	6.45	0.49	
Ethyl	12.0	-0.03	0.09	3.34	0.28	
n-Butyl	9.65	-0.13	0·34 b	1.12	0.12	
Cyclopentyl	4.35	-0.48		0.612	0.14	
Pent-2-yl	3.59	-0.56		0.308	0.086	
n-Pentyl	8.78	-0.17		0.663	0.076	
Cyclohexyl	3.79	-0.54		0.478	0.13	
n-Hexyl	7.60	-0.23		0.420	0.056	
n-Octyl	6.65	-0.29		0.083	0.013	

The values of k are consistent to $\pm 2.5\%$ or better for acidic solution catalysts, and $\pm 3.5\%$ or better for acid resin catalysts. The rate coefficient for hydrolysis of methyl acetate may be compared with the value of 13.2×10^{-5} l. mole⁻¹ sec.⁻¹ calculated from the results of P. N. Rylander and D. S. Tarbell (J. Amer. Chem. Soc., 1950, 72, 3021) in a similar solvent.

^a The Taft parameters, E_s , are taken from C. K. Hancock, E. A. Meyers, and B. J. Yager, J. Amer. Chem. Soc., 1961, 83, 4211. ^b There are no experimental details concerning the value for n-butyl acetate. We note, however, that the results of Rylander and Tarbell give $E_s = -0.23$ for isobutyl acetate.

Hydrolysis with Resin Acid.—The reaction order for hydrolysis with the acid resin as catalyst was checked with respect both to ester and resin. n-Butyl acetate was selected for the determination of the reaction orders. The results are shown in Table 3. The extent of hydrolysis is indicated by the titration value of sodium hydroxide required to neutralise the acetic acid formed. The reaction is therefore first-order with respect to both ester and resin concentration.

TABLE 3

Resin weight (g.) Titre	$0.10 \\ 0.91$	$0.20 \\ 1.81$	$0.50 \\ 4.42$	$0.75 \\ 6.70$	$1.00 \\ 8.89$	
Ester concentration (M) Titre	$0.10 \\ 2.21$	$0.15 \\ 3.42$	$0.20 \\ 4.40$	$0.25 \\ 5.48$	$0.30 \\ 6.55$	$0.40 \\ 8.78$
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All reactions were carried out to less than $1^{\circ}_{,o}$ completion. The titration figures shown are therefore a measure of the 'initial' rates, and hence are proportional to the rate coefficients.

The resin-catalysed hydrolysis was carried out with 0.500 g. of resin in 50.0 ml. of 25% aqueous acetone containing 0.1—0.4 mole 1.⁻¹ of ester. The resin was batchequilibrated with 25% aqueous acetone before use. To estimate the extent of hydrolysis the reactant solution was decanted off and then the resin was washed three times with 25% aqueous acetone to remove sorbed reactants. The combined decanted solutions were titrated with standard sodium hydroxide. Repeat reactions were carried out at 35°. Table 2 shows the rate coefficients in 1. mole⁻¹ sec.⁻¹, and the efficiency, q = rate coefficient with resin catalyst/rate coefficient with acid in solution.

Distribution Coefficients.—The concentration of reactants in the vicinity of the resin matrix may differ from that in the bulk solution. Determination of the concentration at the matrix is subject to error due to the hydrolysis of the ester during equilibration. The method adopted, however,

⁸ R. W. Taft, 'Steric Effects in Organic Chemistry,' ed. M. S. Newman, ch. 13, Wiley, New York, 1956.

utilised the hydrolysis of the ester by the resin to measure the concentration of ester.

A sample of resin in the hydrogen-ion form was dried in air. Spherical resin beads were then obtained by placing the sample at one end of a tray, which was then tilted. The spherical beads rolled to the other end of the tray. A portion of the beads was used to determine the ion-exchange capacity. The remainder was transferred to a stainless steel wire-mesh basket with a Teflon cap, and immersed in aqueous acetone to equilibrate. The basket was then immersed in an aqueous acetate solution containing 0.1 mole 1.⁻¹ of ester. The basket was shaken in the ester solution until completely equilibrated. A large excess of ester solution was used to ensure that no appreciable concentration change occurred due to hydrolysis. After equilibration the basket was shaken vigorously in aqueous acetone for 10 sec. to remove ester solution adhering to the surface of the beads and basket. The basket was then placed in a stoppered flask and left for 7 days. The ester within the beads was completely hydrolysed in this time. The acetic acid was then eluted and estimated. Table 4 shows the results for n-pentyl, cyclopentyl, n-hexyl, and cyclohexyl acetate. The relative concentrations of the normal and cyclic esters are also given.

TABLE 4

Acetate	Ester concn. within resin bead (mole ester/ mequiv. H ⁺ of resin)	Relative concentration (normal/cyclic)
n-Pentvl	0.284	
	0.291	
	0.286	1.28/1.00
Cyclopentyl	0.232	
	0.223	
	0.212	
n-Hexvl	0.248	
2	0.244	
	0.260	1.13/1.00
Cyclohexyl	0.222	
5 5	0.255	
	0.218	

DISCUSSION

The effect of substituents on the rate coefficients for ester hydrolysis has been carefully examined by Chapman et al.⁹ and Ritchie.¹⁰ The former workers conclude that the separation of polar and steric effects by the method of Taft,¹¹ is unlikely to be valid owing to solvation effects. Ritchie also questions the application of the Taft analysis, and concludes that polar effects for all alkyl groups are zero. Hancock 12 has incorporated parameters to allow for hyperconjugation, and the number of atoms in the sixth position from the carbonyl oxygen atom (Newman's rule 13).

Most of the investigations of ester hydrolysis have concerned esters substituted in the acyl group. We note that, for esters substituted in the alkyl group, any resonance effect is not transmitted to the reaction Further, if Ritchie's theory is correct, alkyl site. substituents have no polar effect.

Therefore, the rate of hydrolysis of esters substituted in the alkyl group by alkyl substituents should be mainly a function of steric effects. This should apply to both acid and base catalysis.

In acidic solutions the ester is first protonated on carbonyl oxygen, and then the transition state is formed by attack of a water molecule on carbonyl carbon. The two steps are influenced in opposite directions by polar effects. Polar effects are therefore usually taken to be small in acid hydrolysis. The proton transfer will not be greatly affected by steric effects. The attack of the water molecule in the carbonyl carbon will therefore reflect the influence of substituents. The steric effect of substituents can affect the rate coefficient of the reaction by inhibition of solvation, steric hindrance to motion, or an increase in nonbonded interactions on formation of the transition



The efficiency of the acid resin catalyst as a function of the entropy of RH in CH₃·CO₂R

Acetates: 1, methyl; 2, ethyl; 3, cyclopentyl; 4, cyclohexyl; 5, n-butyl; 6, pent-2-yl; 7, n-pentyl; 8, n-hexyl; 9, n-octyl

The values for the entropies were obtained from ' Handbook of Chemistry and Physics,' 46th ed., Chemical Rubber Publishing Co., Cleveland, 1966. Inspection of values for isomers suggests that the entropy of pent-2-yl acetate should be approximately 2 cal. mole⁻¹ deg.⁻¹ less than that of n-pentyl acetate

state. In aqueous acetone the transition state may be expected to be strongly solvated. Inhibition of solvation would only be predominant therefore with very bulky substituents.¹⁴ The reaction site, in the case of esters substituted in the alkyl group, is removed by one oxygen atom from the steric influence of the substituents. Steric inhibition of solvation is unlikely therefore to be a major factor.

We therefore conclude that the steric effect of the alkyl substituents in the alkyl group of the ester is mainly due to non-bonded interactions. The cyclic substituents

12 C. K. Hancock, B. J. Yager, C. P. Falls, and J. O. Schreck, J. Amer. Chem. Soc., 1963, 85, 1297.
 ¹³ M. S. Newman, J. Amer. Chem. Soc., 1950, 72, 4783.
 ¹⁴ K. Bowden, N. B. Chapman, and J. Shorter, J. Chem. Soc.,

⁹ N. B. Chapman, J. Shorter, and J. H. P. Utley, J. Chem. Soc., 1963, 1291.

 ¹⁹⁵⁰, 1291.
 ¹⁰ C. D. Ritchie, J. Phys. Chem., 1961, 65, 2091; C. D. Ritchie and W. F. Sager, Progr. Phys. Org. Chem., 1964, 2, 323.
 ¹¹ R. W. Taft, J. Amer. Chem. Soc., 1952, 74, 3120.

^{1964, 3370.}

J. Chem. Soc. (B), 1968

have a greater effect than the corresponding normal substituents owing to the increased probability of nonbonded interactions on rotation of the substituent about the alkyl-oxygen-substituent axis. The steric effect of the pent-2-yl group is greater than that of the cyclopentyl group. By analogy with Newman's rule, nonbonded interactions involving the 4- or 5-position carbon atoms of the pent-2-yl substituent, may account for the increase in steric effect.

Resin-catalysed Hydrolysis.—The order of rate coefficients differs for acid catalysts in solution and acid resin catalysts. The efficiency of the resin catalyst, q, however, parallels the entropy of the parent hydrocarbon, RH, of the substituent. A plot of the logarithm of qagainst the entropy of RH is approximately linear (see Figure). The alkyl-substituted aliphatic esters show the same effect, therefore, as the acyl-substituted esters.⁵ According to Helfferich, the difference between acid catalysts in solution and acid-resin catalysts may be a result of the dependence of the distribution coefficient on the structure of the ester. Table 4 shows, however, that esters with cyclic substituents are sorbed to a smaller extent than esters with normal substituents of the same number of carbon atoms. The greater efficiency of the resin for esters with cyclic substituents is not therefore due to an increase in the ester concentration in the vicinity of the resin matrix. It appears, therefore, that Hammett's theory is correct, and sorption of the reactant at the resin matrix causes an additional decrease in entropy of the transition state.

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