Nucleophilic Reactivity

Part III.* Kinetics of Reactions of Methyl Perchlorate with Amines in Water and Methanol

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Second-order rate constants of reactions of methyl perchlorate with various amines in water and methanol were measured at 0°C. The value 0.77 of the slope of the approximately linear plot of log k against the nucleophilicity constant n for the reactions is close to the value 0.83 of the slope of the corresponding plot for reactions of methyl perchlorate with basic anionic nucleophiles.[1] Values of nucleophilicity constants were calculated for the studied amines.

When log k values for reactions of methyl perchlorate with amines in water are plotted against the pK_a values of the amines and a straight line is drawn through the highest data points, the slope of the line has the value 0.20, which is close to the value of the slope 0.22 of a corresponding plot for reactions of methyl perchlorate with anionic nucleophiles containing nitrogen as the nucleophilic atom.[1] The low values of the rate constants of reactions of methyl perchlorate with many amines can be ascribed to steric effects, but the values for reactions of methyl perchlorate with ammonia and butylamine are exceptionally low. A rapid decrease in rate occurs when the pK_a value of the amine approaches zero. For *para*-substituted anilines, the value 0.62 was obtained for the slope of the log k *versus* pK_a plot. This change in reactivity of amines could be due to a change in reaction mechanism from S_N2 towards S_N1 because the hydrolysis of methyl perchlorate occurs mainly by a unimolecular S_N1 mechanism in the absence of amines.[1]

In Part II of this series [1] rate constants of reactions of methyl perchlorate with nucleophilic anions in water were reported. Separate, approximately linear relationships between the logarithms of the second-order rate contents and pK_a values of the nucleophiles were obtained for oxygen-, nitrogen-, and sulphur-containing nucleophiles. The slopes of the linear plots, about 0.23, are of the order of magnitude usually found for reactions occurring at tetrahedral carbon atoms,[4] whereas larger values of the slope, about 0.8, are usually obtained for nucleophilic reactions at carbonyl carbon atoms.[1]

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* For Part II, see Ref. 1.

Nucleophilic reactions in which the nucleophiles are small anions occur without any serious steric hindrance and statisfactory linear log k versus pK_a plots are obtained for such reactions. Nucleophilic reactions of amines give more scattered data [5-7] as steric effects are often important [8-20] alongside polar effects. Approximately linear relationships have been obtained [12] also when log k values of nucleophilic reactions of two substrates with various amines have been substituted in eqn. (1) proposed by Swain and Scott.[11]

$$\log k = s \cdot n + \text{constant} \qquad (1)$$

where n is the nucleophilicity constant of the amine.[11] The values of the slope s were found to have values from 0.6 to 1.2 for reactions at a tetrahedral carbon atom and values higher than 1.3 for reactions at a carbonyl carbon atom. [12] The Swain-Scott equation can be applied satistfactorily only to reactions of similar nucleophiles [1,11] such as amines, and even then when steric effects do not interfere. Instead of the two-parameter Swain-Scott equation, the four-parameter equation of Edwards has been applied [14,15] satisfactorily to reactions with a wide range of different nucleophiles. This work is an extension of previous work [12] on reactions of methyl perchlorate with different amines.

EXPERIMENTAL

Materials. In addition to reagents used in the previous work,[2] the following were employed. Pyrrolidone, 2,6-lutidine, 4-picoline, 2-picoline (purum, Fluka AG.), and morpholine, pyrrole (practical, Fluka AG.) were fractionally distilled and found to be free of impurities as revealed by gas chromatography. Quinoxaline (purum, Fluka AG.) was recrystallized. Imidazole, pyridazine, pyrazole, pyrimidine, pyrazine, urea, and acetamide (purum, Fluka AG.) were used as received.

Kinetic experiments. The kinetic experiments were performed and the rate constants calculated as described previously.[2] Samples removed from the reaction mixture at intervals were analysed for both methyl perchlorate and the perchloric acid produced in the reaction as described previously.[2] The rate constants reported previously [2] for reactions of methyl perchlorate with some bases in methanol were redetermined because the rate constants reported previously [2] for assumed simultaneous general base-catalysed methanolysis reactions in the presence of amines were due to experimental errors in analysing the reaction mixtures. When the reactions were reinvestigated using improved analytical methods, e.g. gas chromatography, no base-catalysed reaction was detected. The new values and second-order rate constants obtained for the reactions of methyl perchlorate with the above-mentioned bases in water and methanol at 0°C are shown in Table 1.

RESULTS AND DISCUSSION

The log k values in water at 0°C (Table 1) were plotted against the nucleophilicity constants n of the amines for which values of n are known.[2] The fitted approximate linear equation is

$$\log k = 0.77 \, n - 5.34 \pm 0.13 \qquad (2)$$

The fit is not as good as that obtained for reactions of methyl perchlorate with nucleophilic anions in water (± 0.05 log k units).[1] The value of the slope 0.77 is close to the value 0.83 found for reactions of methyl perchlorate with basic nucleophilic anions [1] and of the order, 0.6 to 1.2, usually obtained for nucleophilic reactions at a tetrahedral carbon atom.[12] This eqn. (2) was used to

Table 1. Second-order rate constants of reactions of methyl perchlorate with amines in water and methanol at 0°C and pK_a values [3] of the amines in water at 25°C. Nucleophilicity constants n for reactions in water at 0°C were calculated using eqn. (2).

No.	Amine	pK_a	$10^4 k_2$ l·mole^{-1}sec^{-1}		$4+\log k_2$		$\Delta\log k_2$	n
			H$_2$O	MeOH	H$_2$O	MeOH		
1	Pyrrolidine	11.1	1042	1135	3.019	3.055	−0.03	5.67
2	Triethylamine	10.70	107	265	2.030	2.440	−0.42	3.98
3	Butylamine	10.63	406	690	2.609	2.838	−0.23	5.13
4	Ammonia	9.25	72.4	115	1.860	2.060	−0.20	4.16
5	Morpholine	8.35	410	265	2.613	2.423	0.19	5.13
6	2,4,6-Collidine	7.45	2.0	1.4	0.30	0.15	0.15	2.13
7	Imidazole	7.10	26.6	41.8	1.425	1.621	−0.20	3.58
8	2,6-Lutidine	6.72	1.7	1.3	0.23	0.10	0.13	2.04
9	4-Picoline	6.05	123	70.2	2.090	1.847	0.24	4.45
10	2-Picoline	5.99	29.0	14.6	1.463	1.164	0.30	3.64
11	Pyridine	5.20	90.0	57.1	1.954	1.757	0.20	4.27
12	N,N-Dimethyl-aniline	5.11		41.8		1.621		
13	N-Methylaniline	4.85		83.2		1.920		
14	Aniline	4.61	103	86.0	2.013	1.934	0.07	4.35
15	p-Methylaniline	4.42	136	184	2.134	2.265	−0.12	4.52
16	p-Chloroaniline	3.99		33.7		1.528		
17	m-Nitroaniline	2.47		3.84		0.584		
18	Pyrazole	2.53	6.62	6.73	0.822	0.828	0.00	2.81
19	Pyridazine	2.24	52.0	51.5	1.716	1.712	0.00	3.98
20	Pyrimidine	1.30	15.9	10.6	1.201	1.025	0.18	3.30
21	p-Nitroaniline	1.00		0.1		−1.0		
22	Diphenylamine	0.78		−0.2^a				
23	Pyrazine	0.60	21.4	7.85	1.330	0.895	0.43	3.47
24	Quinoxaline	0.56	24.51	1.25	0.655	0.10	0.55	2.60
25	Urea	0.15	0.21	0.22	−0.68	−0.66	−0.02	0.86
26	Acetamide	−0.44	0.08	0.1	−1.1	−1.0	0.10	0.31
27	Pyrrole	−3.8		−0.2^a				

^{a} The solvolysis is retarded by the amine.

calculate the values of unknown nucleophilicity constants of the amines used in this work (Table 1).

When the log k values are plotted against the pK_a values of the amines, a small positive slope is observed although the points are scattered (Fig. 1).
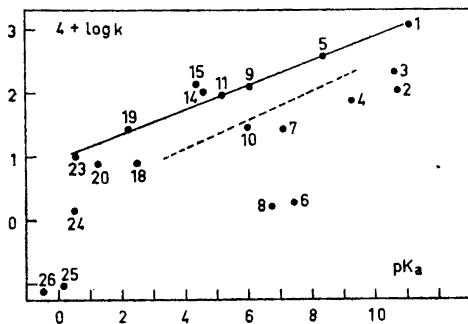

Fig. 1. Plot of the logarithms of the second-order rate constants of reactions of methyl perchlorate with amines in water at 0°C against the pK_a values of the amines in water at 25°C.

A straight line was drawn arbitrarily through the highest log k values. The broken line is the log k versus pK_a plot given in part II [1] for reactions of methyl perchlorate with basic nucleophiles (CN^-, N_3^- and NO_2^- containing nitrogen as the nucleophilic atom. The slopes of these lines, 0.20 and 0.22, respectively, are approximately equal. The neutral amines, however, are about 0.5 log k units more reactive than the anionic bases. Reactions involving reactants of different charge type give separate linear free energy relationships mainly due to electrostatic solvent effects.

The amines giving data points in the upper parts of Fig. 1 are, with the exception of aniline, cyclic secondary or tertiary amines. Steric hindrance is therefore expected to be small for all these amines. When methyl substituents are introduced in the 2 and 6 positions of pyridine, marked decreases in reactivity are observed. 2-Methylpyridine is about 0.65 and 2,4,6-trimethyl-pyridine and 2,6-dimethylpyridine about 2.0 log k units less reactive because of steric hindrance. The effects are of the order of magnitude usually obtained for nucleophilic reactions.[1,8,10,15] The low values of log k for N,N-dimethyl-aniline and triethylamine may also be mainly due to steric effects. The values obtained for ammonia and butylamine are exceptionally low as no large steric effects would be expected with these amines. Similar results have been obtained for other nucleophilic reactions also.[7,12] The low values of the rate constants obtained for imidazole and quinoxaline can be explained qualita-tively by assuming that resonance stabilisation of the conjugated acids of these amines results in high pK_a values. No such resonance is expected when the transition state is formed in the nucleophilic reactions and therefore lower values of pK_a should be used which would bring the points closer to the straight line.

A straight line is obtained when log k values for reactions of methyl perchlo-rate with para-substituted anilines are plotted against the pK_a values of the anilines. The value of the slope 0.62 is much higher as the value 0.20 obtained for the other amines. An abrupt decrease in reactivity occurs when pK_a approaches zero, as indicated by the low values of the rate constants of the reactions with urea, acetamide, and pyrrole. In the reaction with a weakly basic nucleophilic, only a weak bond is formed in the transition state and the mechanism changes gradually towards the S_N1 mechanism, by which the hydrolysis of methyl perchlorate takes place.[1]

Table 1 includes also rate contants of reactions between methyl perchlorate and amines in methanol at 0°C. The differences in the log k values of the reac-tions in water and methanol are usually small and vary between -0.4 and 0.6 (Table 1), about -0.27 for aliphatic acyclic amines, about 0.1 for cyclic amines, about 0 for anilines, and about 0.21 for tertiary aromatic amines. These differences are smaller by about 1.0 log k unit than those obtained for the reactions of methyl perchlorate with anionic nucleophiles in water and methanol. Generally [16,17] the reactivities of neutral amine nucleophiles are less sensitive to solvent effects than the reactivities of anionic nucleophiles.[17] The log k values obtaines for the reactions in methanol are not plotted in Fig. 1 as neither the rate constants nor the values of pK_a differ much from those in water.

REFERENCES

1. Koskikallio, J. *Acta Chem Scand.* **23** (1969) 1477.
2. Koskikallio, J. *Suomen Kemistilehti* **B 40** (1967) 199.
3. Perrin, D. D. *Dissociation Constants of Organic Bases in Aqueous Solutions*, Butterworths, London 1965.
4. Hudson, R. F. and Green, M. *J. Chem. Soc.* **1962** 1055, 1062, 1068.
5. Jencs, W. P. and Carriulo, J. *J. Chem. Soc.* **82** (1960) 1778.
6. Bruice, T. C. and Lapinski, R. *J. Am. Chem. Soc.* **80** (1958) 2265.
7. Pearson, R. G., Sobel, H. and Søngstad, J. *J. Am. Chem. Soc.* **90** (1968) 319.
8. Evans, D. P. *J. Chem. Soc.* **1944** 422.
9. Okamoto, K., Fukui, S., Nitta, I. and Shingu, H. *Bull. Chem. Soc. Japan* **40** (1967) 2350, 2354.
10. Brown, H. C. *J. Chem. Soc.* **1950** 1248.
11. Swain, C. G. and Scott, C. B. *J. Am. Chem. Soc.* **75** (1953) 141.
12. Hall, H. K. *J. Org. Chem.* **29** (1964) 1590.
13. Edwards, J. E. *J. Am. Chem. Soc.* **76** (1954) 1590.
14. Klopman, G. *J. Am. Chem. Soc.* **90** (1968) 223.
15. Gold, V. and Jefferson, E. G. *J. Am. Chem. Soc.* **1953** 1409.
16. Cook, D., Evan, I. P., Ko, E. F. C. and Parker, A. J. *J. Chem. Soc.* **B 1966** 1911.
17. Torkura, N. and Kondo, Y. *Bull. Chem. Soc. Japan* **37** (1964) 133.