

Nucleophilic Reactivity

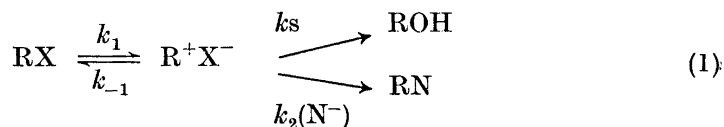
Part VI. An Ion-Pair Mechanism for Reactions of Methyl Benzenesulphonate With Nucleophiles in Water

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Rate constants and Arrhenius parameters were evaluated for reactions of methyl benzenesulphonate with several nucleophiles in water. The most simple interpretation of the results and previously reported data for nucleophilic reactions of methyl nitrate,¹ methyl perchlorate,² and methyl halides³ is that these reactions proceed by a mechanism that involves ionization of the substrate and subsequent reaction of the contact ion-pair with the nucleophile. The rate constant of the attack of the nucleophile on the methylum-anion ion-pair is independent of the anion of the ion-pair. The relative rate constants of reactions of two nucleophiles N^- and X^- in an ion-triplet $N^-CH_3^+X^-$ were evaluated. According to this mechanism, the linear free energy relationships proposed by Swain and Scott⁴ and by Edwards⁵ are applicable only to restricted groups of closely similar reactions. The values of the constant a in the equation $^2 \log k_N/k_{H_2O} = apK_a + b$ is equal (0.24) for the reactions of methyl benzenesulphonate, methyl nitrate, and methyl perchlorate with basic oxygen-containing nucleophiles with pK_a values of nucleophiles ranging over 11 units.

Sneen and Larsen^{6,7} postulated that the reaction between *p*-methoxybenzyl chloride and sodium azide in 70 vol. % aqueous acetone proceeds by a contact ion-pair mechanism. This mechanism involves ionization of the substrate to a contact ion-pair and subsequent reaction of the nucleophile with the carbonium ion of the contact ion-pair. Later, Scott³ provided evidence that nucleophilic reactions of methyl halides also occur by a contact ion-pair mechanism. Instead of a one-step substitution reaction, traditionally typical S_N2 reactions seem to occur by a two-step mechanism:

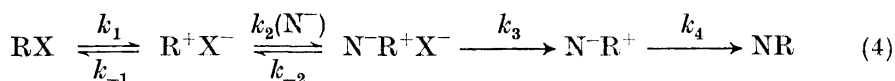


$$\text{If } k_{-1} \ll k_s + k_2(\text{N}^-), \text{ then } k_{\text{obs}} = k_1 \quad (2)$$

$$\text{If } k_{-1} \gg k_s + k_2(\text{N}^-), \text{ then } k_{\text{obs}} = Kk_s + Kk_2(\text{N}^-) \quad (3)$$

where $K = k_1/k_{-1}$. The reaction may be either of first, second, or intermediate order depending on the relative magnitudes of the three rate constants. The limiting case of the second-order reaction, eqn. 3, is kinetically indistinguishable from a one-step bimolecular substitution mechanism.

Considering the reverse of reaction 1, obviously the ion-pair R^+N^- should be included in the mechanism, and as an intermediate between the two contact ion-pairs N^-R^+ and R^+X^- , the ion-triplet $\text{N}^-\text{R}^+\text{X}^-$ can be postulated. The complete mechanism would then be written as:



Application of the stationary-state treatment gives a second-order rate constant, k_{obs} , in the limiting case $k_{-1}(k_3 + k_{-2}) \gg k_2k_3(\text{N}^-)$:

$$k_{\text{obs}} = \frac{k_1k_2k_3}{k_{-1}(k_3 + k_{-2})} \quad (5)$$

Two limiting cases are of interest. When the attacking nucleophile N^- is much stronger than the leaving group X^- ,

$$k_3 \gg k_{-2} \text{ and } k_{\text{obs}} = Kk_2 \quad (6)$$

where $K = k_1/k_{-1}$. On the other hand, when the attacking nucleophile N^- is much weaker than the leaving group X^- ,

$$k_3 \ll k_{-2} \text{ and } k_{\text{obs}} = \frac{k_1k_2k_3}{k_{-1}k_{-2}} \quad (7)$$

This extended ion-pair mechanism will be tested below by results obtained on studying rates of reactions of methyl benzenesulphonate with various nucleophiles in water.

EXPERIMENTAL

Materials. Methyl benzenesulphonate was prepared from benzenesulphonyl chloride and methanol and distilled under reduced pressure. All the other reagents were commercial products of highest purity.

Kinetic experiments. The rate measurements were performed as described earlier.^{1,2,8} Some of the rate constants published previously⁸ were redetermined.

DISCUSSION

The results are shown in Tables 1 and 2, which include previous results for nucleophilic reactions of methyl perchlorate² and methyl nitrate.¹ The ratios of the rate constants of the reactions of the three substrates methyl benzenesulphonate, methyl nitrate, and methyl perchlorate with a nucleophile are approximately constant (Table 2). In all these reactions, the attacking

Table 1. Second-order rate constants of reactions of nucleophiles N with methyl benzenesulphonate in water, calculated rate constants at 25°C, parameters *E* and *A* of the Arrhenius equation and p*K*_a values ^{9,10} of the nucleophiles at 25°C.

N	0°C	10 ⁵ <i>k</i> ₂ , l mol ⁻¹ sec ⁻¹		60°C	5 + log <i>k</i> ₂ 25°C	<i>E</i> kcal mol ⁻¹	log <i>A</i>	p <i>K</i> _a 25°C
		20°C	40°C					
PO ₄ ⁻³	2.60	259	1880	18200	2.69	19.50	11.99	12.38
CO ₃ ⁻²		55.1	589	3400	2.02	20.03	11.70	10.33
OH ⁻	3.54	87.8 ^a	502	3260	1.94	20.66	12.09	15.72
PhO ⁻	3.02	51.5	419		1.93	21.27	12.52	9.99
HPO ₄ ⁻²		8.95	128	821	1.26	21.98	12.37	7.20
AcO ⁻		2.18	29.0	152	0.64	20.66	10.78	4.76
HCO ₃ ⁻		1.74	17.7	148	0.50	21.55	11.30	3.76
SO ₄ ⁻²		0.78	8.49	93	0.16	23.16	12.14	1.99
NO ₃ ⁻		0.10	1.05	7.84	-0.73	21.17	9.78	-1.3
H ₂ O		0.0117	0.116	0.87	-1.69	21.07	8.77	-1.74
CN ⁻	29.4	238	1805		2.62	17.51	10.45	9.21
N ₃ ⁻		47.7 ^a	265	2500	1.66	22.36	13.05	4.70
NO ₂ ⁻		22.9	165	477	1.58	18.00	9.78	3.15
S ₂ O ₃ ⁻²	238	2050	4410 ^b		3.48	15.82	10.08	1.74
SO ₃ ⁻²	174	1310	9550		3.65	16.81	10.68	7.20
SCN ⁻		41	247	1590	1.81	17.72	9.80	
I ⁻		50.2 ^a	256	1880	1.70	20.47	11.68	
Br ⁻		7.50 ^a	37.2	244	0.88	19.63	10.27	
Cl ⁻		1.10	12.7	89.4	0.32	21.34	10.96	

^a At 25°C. ^b At 30°C.

Table 2. Second-order rate constants *k*_N of reactions of methyl benzenesulphonate, methyl nitrate,¹ and methyl perchlorate² with nucleophiles N divided by the second-order rate constants *k*_{H₂O} of their hydrolysis reactions, mean values of relative rate constants and relative rate constants of reactions of nucleophiles with methylum-anion ion-pairs.

N	log <i>k</i> _N / <i>k</i> _{H₂O}			Mean value	<i>k</i> _{2(I⁻)/2(N)}}
	25°C PhSO ₃ Me	90°C MeNO ₃	0°C MeClO ₄		
PO ₄ ⁻³	4.375	4.233	4.226	4.278	0.25
CO ₃ ⁻²	3.702	3.637	3.632	3.657	1.05
OH ⁻	3.630	3.570	3.563	3.588	1.26
PhO ⁻	3.616	3.476	3.469	3.520	1.47
HPO ₄ ⁻²	2.947	2.945	2.938	2.943	4.95
AcO ⁻	2.327	2.203	2.296	2.275	25.9
HCO ₃ ⁻	2.289		2.178	2.233	28.4
SO ₄ ⁻²	1.848			1.875	64.9
NO ₃ ⁻	0.954			0.998	489
CN ⁻	4.301		4.306	4.303	0.24
N ₃ ⁻	3.345	3.273	3.266	3.295	2.46
NO ₂ ⁻	3.271	3.227	3.093	3.197	3.09
S ₂ O ₃ ⁻²	5.165	5.140	5.233	5.179	0.032
SO ₃ ⁻²	5.335	4.744	4.737	5.335	0.045
SCN ⁻	3.500	3.819	3.683	3.591	1.25
I ⁻	3.383	3.690	3.683	3.687	1.00
Br ⁻	2.563	2.793	2.786	2.790	7.80
Cl ⁻	2.009	1.734	1.727	1.823	58.0
H ₂ O	0	0	0	0	4860

nucleophile N is a stronger nucleophile than the leaving group, the benzenesulphonate ion, the nitrate ion, or the perchlorate ion. If the ion-triplet mechanism is assumed to be valid for these reactions then $k_{\text{obs}} = Kk_2$ (eqn. 6). The ratio of two observed rate constants should be equal to the ratio of the rate constants k_2 of the reactions of the two nucleophiles with a methylium-anion contact ion-pair. From the constancy of the ratios of rate constants it follows that the rates of reactions of nucleophiles with methylium-anion contact ion-pair are independent of the anion of the ion-pair. If, however, the mechanism were a one-step S_N2 mechanism, the constancy of the values of $k_N/k_{\text{H}_2\text{O}}$ for the nucleophilic reactions of these three substances would be obvious.

Large differences between the values of k_{obs} for reactions of the three substances with the same nucleophile are due to differences in the values of the ionization constants K of the substances. For example, the relative second-order rate constants are 1, 250, and 13 000 of the nucleophilic reactions of methyl nitrate,¹ methyl benzenesulphonate, and methyl perchlorate,² respectively, with hydroxide ion in water at 25°C.

The rate constants of the reactions of methyl benzenesulphonate, methyl nitrate, and methyl perchlorate were measured at 25°, 90°, and 0°C, respectively. The effect of temperature on the relative rate constants $k_N/k_{\text{H}_2\text{O}}$ is, however, small,¹ as the values of the activation energy do not vary greatly for reactions with different nucleophiles (Table 1).

The ratios of the rate constants $k_N/k_{\text{H}_2\text{O}}$ for the reactions of methyl iodide, methyl bromide, and methyl chloride with nucleophiles are not constant. They also differ greatly from the ratios for the rate constants of nucleophilic reactions of methyl benzenesulphonate, methyl nitrate, and methyl perchlorate (Table 3). In these cases, however, the leaving nucleophiles, the iodide, bromide, and chloride ions are approximately equally strong nucleophiles as the

Table 3. Logarithms of second-order rate constants³ of reactions of methyl halides with nucleophiles k_N divided by the second-order rate constants $k_{\text{H}_2\text{O}}$ of hydrolysis reactions of the methyl halides in water at 25°C, mean values of logarithms of relative rate constants from Table 2 and relative second-order rate constants of reactions of nucleophiles N with halide ions, $X = \text{Cl}^-$, Br^- , or I^- , in contact ion-triplets $\text{N}^-\text{CH}_3^+\text{X}^-$. Values in brackets were obtained by linear interpolation.³

N	MeCl	$\log k_N/k_{\text{H}_2\text{O}}$ MeBr	MeI	Mean value	Cl^-	$k_{-2}(\text{X})/k_3(\text{N})$ Br^-	I^-
$\text{S}_2\text{O}_3^{2-}$	6.35	6.64	7.44	5.18	0	0	0
I^-	4.61	4.91	5.63	3.69	0.7	0.7	1.0
Br^-	3.09	(4.45)	4.48	2.79	3.6	(0.6)	2.7
Cl^-	(2.69)	2.83	3.36	1.82	(1.0)	1.8	4.2
F^-	1.55	1.67	1.71				
OH^-	4.14	4.27	4.69	3.59	3.2	4.9	13
CN^-	(5.20)	(5.45)	5.65	4.30	(0.8)	(1.0)	7
SCN^-	(4.65)	(4.87)	5.42	3.59	(0.29)	(0.5)	1.7
SO_3^{2-}			7.49	5.33			0
N_3^-		4.00		3.30		2.0	
H_2O	0	0	0	0	14	28	180

attacking nucleophiles. Only the thiosulphate ion is a much stronger nucleophile than the halide ions. Eqn. 6 is then applicable to reactions of thiosulphate ion with methyl halides but eqn. 5 to the other reactions whose rate constants are given in Table 3. The ratio of the rate constants of the reactions of a methyl halide with thiosulphate ion and a nucleophile N is obtained from eqns. 5 and 6:

$$\frac{k_{\text{obs}(\text{S}_2\text{O}_3^{-2})}}{k_{\text{obs}(\text{N})}} = \frac{k_{2(\text{S}_2\text{O}_3^{-2})} (k_3 + k_{-2})}{k_{2(\text{N})} k_3} \quad (8)$$

If the rate constant k_2 of the reaction of nucleophile N^- with the methyl carbonium ion of the ion-pair is independent of the anion as was found to be approximately true for the three reactions discussed above, values of $k_{2(\text{S}_2\text{O}_3^{-2})}/k_{2(\text{N})}$ can be calculated from the rate constants of nucleophilic reactions of CH_3X , where the leaving group X^- is a weak nucleophile. It is then possible to calculate values of k_{-2}/k_3 , *i.e.* values of the relative reactivities of two nucleophiles N^- and X^- in a contact ion-triplet $\text{N}^-\text{CH}_3^+\text{X}^-$. Such values are shown in Table 3.

It is interesting to note that when N^- and X^- are identical, the value of k_{-2}/k_3 is close to 1 as would be expected. When the attacking nucleophile N^- is the same and the leaving group X^- is varied (Cl^- , Br^- , or I^-) or when X^- is the same and N^- is varied (Cl^- , Br^- , or I^-), the values of the relative rate constants k_{-2}/k_3 vary approximately as 1:2:4 for Cl^- , Br^- , and I^- . There are admittedly some inconsistencies which may be due to experimental errors. These results indicate that the ion-triplet mechanism affords a simple interpretation of the observed differences in the rate constants of a large number of nucleophilic reactions.

Relative reactivities $k_{2(\text{I}^-)}/k_{3(\text{N})}$ of nucleophiles with methylum-anion contact ion-pair (Table 2) vary more than the relative reactivities $k_{-2(\text{X}^-)}/k_{3(\text{N})}$ of the nucleophiles in a contact ion-triplet $\text{N}^-\text{CH}_3^+\text{X}^-$ (Table 3). Similar effects are also observed when rates of nucleophilic reactions in protic and aprotic solvents are compared,¹¹ the solvation of the nucleophiles being weaker and differences in their reactivities being smaller in aprotic solvents.

Various linear free energy relationships proposed for nucleophilic reactions have been only partly successful. Swain and Scott⁴ proposed the equation:

$$\log k_{\text{N}}/k_{\text{H}_2\text{O}} = s n \quad (9)$$

where $k_{\text{H}_2\text{O}}$ is the rate constant of a hydrolysis reaction and k_{N} the rate constant of a reaction of the same substrate with a nucleophile N, s is a constant and $n = \log k_{\text{N}}/k_{\text{H}_2\text{O}}$, a value characteristic for the nucleophile and determined with the aid of a reference reaction. According to the ion-pair mechanism, the Swain-Scott linear free energy equation can be expected to be valid only for reactions of the same type, *e.g.* when both the reference reaction and the reactions under study involve substrates with weak leaving groups that are attacked by stronger nucleophiles. Swain and Scott chose reactions of methyl bromide with nucleophiles as reference reactions, and eqn. (9) cannot then be expected to be generally applicable to nucleophilic reactions (Fig. 1).

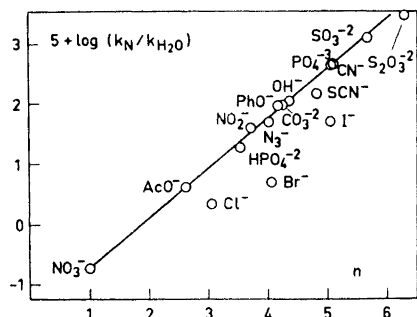


Fig. 1. Logarithms of the ratios of second-order rate constants of reactions of methyl benzenesulphonate with nucleophiles and water in water at 25°C plotted against the values of the Swain-Scott⁴ nucleophilicity constant.

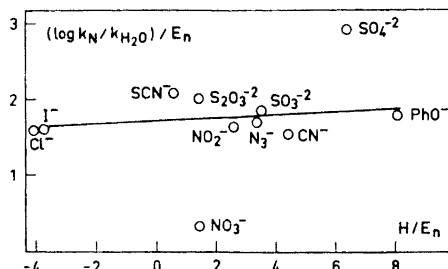


Fig. 2. A plot of Edwards⁵ linear free energy eqn. 10 for reactions of methyl benzenesulphonate with nucleophiles in water at 25°C.

Unsatisfactory results are also obtained when the equation proposed by Edwards⁵ is used:

$$\log k_N/k_{H_2O} = \alpha E_n + \beta H \quad (10)$$

where α and β are constants, $H = pK_a + 1.74$, $E_n = E^\circ + 2.60$ and E° the normal oxidation potential of the nucleophile. According to eqn. 10, a linear relationship is expected when values of $(\log k_N/k_{H_2O})/E_n$ are plotted against values of H/E_n but again the results are unsatisfactory (Fig. 2).

A somewhat different linear free energy relationship that has been proposed earlier² is:

$$\log k_N/k_{H_2O} = a pK_a + b \quad (11)$$

where K_a is the acid constant of the conjugate acid of the nucleophile N, and a and b are constants. This equation is valid for restricted groups of reactions, *e.g.* reactions of methyl benzenesulphonate, methyl nitrate,¹ and methyl perchlorate² with basic nucleophiles containing an oxygen atom as the attacking nucleophilic centre (Fig. 3). The only exceptions are reactions

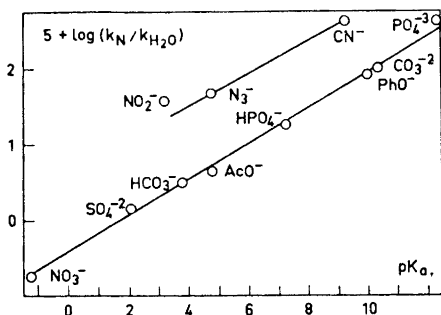


Fig. 3. Logarithms of the ratios of second-order rate constants of reactions of methyl benzenesulphonate with nucleophiles and water in water at 25°C plotted against the pK_a values of the nucleophiles in water at 25°C.

Table 4. Values of constants a and b of equation $\log k_N/k_{H_2O} = a \text{ p}K_a + b$ for reactions of methyl perchlorate, methyl benzenesulphonate, and methyl nitrate with basic oxygen-containing nucleophiles, correlation coefficient r of linear regression, and differences between values of b for reactions with nitrogen and oxygen containing basic nucleophiles.

Substrate	$T^\circ\text{C}$	a	b	r	$b_N - b_O$
MeClO_4	0°	0.235	1.277	0.996	0.96
PhSO_3Me	25°	0.236	1.295	0.999	1.09
MeNO_3	90°	0.228	1.402	0.997	0.87

where hydroxide ion and water are nucleophiles. The role of water in a hydrolysis reaction is twofold, for it acts as a reacting nucleophile and takes part in the solvation process. Therefore, a disagreement is not unexpected.

Values of constants a and b for the nucleophilic reactions of methyl benzenesulphonate, methyl nitrate, and methyl perchlorate are given in Table 4. The values of a are almost independent of temperature. If the rate constants of the nucleophilic reactions of methyl benzenesulphonate at 20° , 40° , and 60°C are plotted against the $\text{p}K_a$ values of the nucleophiles at 25°C , values of a of 0.25, 0.24, and 0.24, respectively, are obtained. The values of a for the reactions of methyl benzenesulphonate, methyl nitrate, and methyl perchlorate with nucleophiles would be expected to be constant also if the rates were measured at the same temperature. The values of b for these three reactions (Table 4) differ slightly and they decrease as the temperature increases. The changes could be due to a temperature effect.

A plot of the rate constants of the reactions of methyl benzenesulphonate with basic nitrogen-containing nucleophiles (Fig. 3) is somewhat less satisfactory as the point for the nitrite ion deviates from the plot. The equation is thus valid only for reactions with closely similar nucleophiles. Compared with oxygen-containing nucleophiles of equal basicity, these nitrogen-containing nucleophiles are about 10 times more reactive. Nucleophiles containing a sulphur atom as the attacking nucleophilic centre are even more reactive than nitrogen-containing nucleophiles of equal basicity, but at present too few values of rate constants are available to permit a quantitative estimate of the relative reactivities of these two groups of nucleophiles.

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