The Effect of Structure Change in Bases on their Reaction with 2,4-Dinitrophenyl Arylmethanesulphonate Esters in Water

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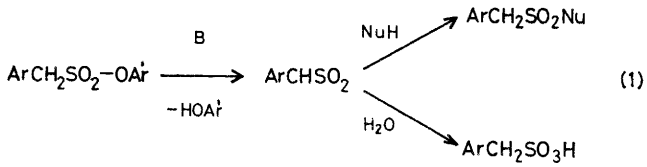
The reaction of bases with 2,4-dinitrophenyl arylmethanesulphonate in water has been measured over a wide range of base structure for aryl = 3,5-dinitrophenyl, phenyl, and 4-chloro-2-nitrophenyl. Reaction is shown to involve S–O bond cleavage to yield phenol and sulphonate derivative; no S_NAr mechanism is observed except to a minor extent for attack of hydroxide. The Brønsted β value for the reaction of bases with the sulphonate esters decreases with an increase in electron-withdrawing power of the substituents on the arylmethane group consistent with a transition state involving little S–O bond fission. The data are consistent with an unsymmetrical *E*2 mechanism where C–H and S–O cleavage are not equally advanced in the transition state.

A PREVIOUS study of the decomposition of aryl arylmethanesulphonates in aqueous buffers indicates that the



(1)

reaction is general base catalysed for leaving groups with basicity less than that of 4-nitrophenolate anion.[1] Amines and other nucleophilic species yield the corresponding sulphonic acid derivative by trapping the intermediate sulphene but the rate is limited by the base catalysed formation of the latter species [equation (1)].

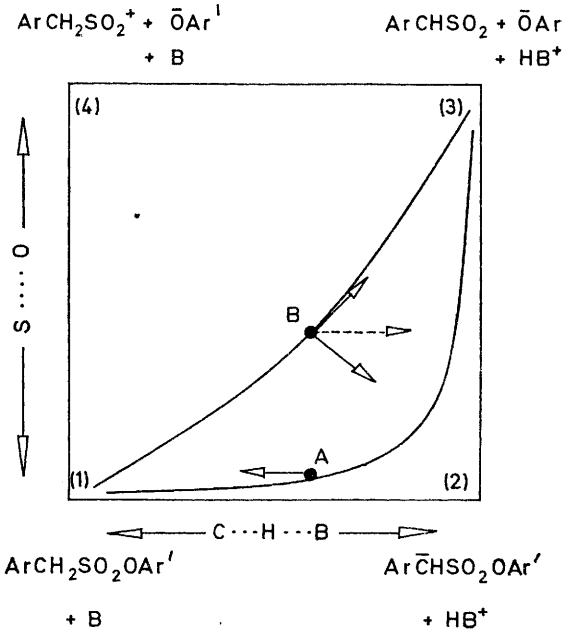
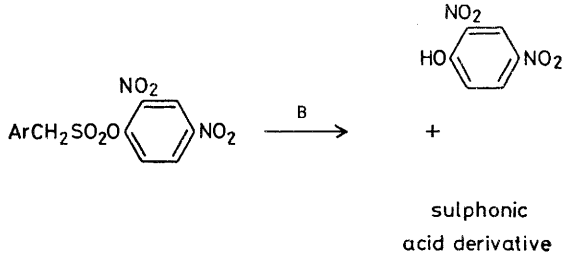


FIGURE 1 Three dimensional potential energy diagram for the elimination of phenol from an aryl arylmethanesulphonate. Energy contours are omitted for clarity; the filled circles A and B represent transition states on the unsymmetrical and symmetrical paths. The arrows represent the direction of movement of the transition states caused by an increase in energy of product (3) and cationic intermediate (4) and a decrease in energy of the carbanion (2) relative to reactants (1)

The mechanism of sulphene formation has been shown to progress from *E*1cB$_r$ through *E*1cB$_i$ to *E*2 as the basicity of the leaving group decreases and the latter mechanism holds for phenylmethanesulphonate esters of 2,4-dinitrophenol.[1] The transition state structure for the *E*2 mechanism is proposed to be unsymmetrical with C–H bond cleavage advanced over S–O fission (at point A in Figure 1).

Using arguments discussed extensively by Jencks and Jencks [2] it is possible to confirm the position of the transition state on the three-dimensional potential energy diagram (Figure 1) by measuring the effect of substrate substituent on the Brønsted β value. Increasing the stability of the anion (bottom right corner of Figure 1) by substituting electron-withdrawing groups leads to a concomitant decrease in stability of the cation (top left corner of Figure 1); the stability of the sulphene



(2)

product is also decreased. The direction of movement of the transition-state caused by stability changes alters the Brønsted β in a defined manner; it is the purpose of this work to use the variation in β with substrate structure [equation (2)] to confirm the position of the transition-state as lying approximately mid-way along the C–H co-ordinate. Previous work on the general base reaction [1] is not extensive enough to give us confidence in the Brønsted slope and the present study is of a much larger series of bases.

EXPERIMENTAL

Materials.—The sulphonate esters were from previous studies [3] and amines and buffer reagents were either of analytical grade purity or were recrystallised or redistilled from bench grade materials.

Methods.—Kinetics were measured spectroscopically as

described in the accompanying paper.[3] All reactions were carried out using aqueous buffers at 25° and with ionic strength maintained at 1M with KCl; the wavelength employed in the kinetic studies was 400 nm.

The stoicheiometry of the reaction [equation (2)] was studied using the phenylmethanesulphonate in 1M-TRIS (trishydroxymethylaminomethane) buffer at pH 10.53 and assaying for 2,4-dinitrophenol using the absorbance at 400 nm [extinction coefficient at 400 nm (1.06×10^4) agrees well with that from other laboratories].[4] Routinely the absorbance change during the kinetics was used as a check on the products.

Reactions were carried out in buffers composed of either the base in question or with background buffers (pyridine, 2,6-lutidine, or TRIS). In the latter procedure two stock solutions were prepared containing background buffers at the same concentration; both solutions were adjusted to the same pH and one contained the base species at 1M total concentration. Dilution of the two stock solutions provided buffer at constant pH with varying base concentration; the pH, measured with a Radiometer PHM62, was essentially constant.

The hydrolysis of 2,4-dinitrophenyl phenylmethanesulphonate in ^{18}O-enriched water was carried out using the substrate (0.25 g) in 1,2-dimethoxyethane (5 ml). The stock solution of the substrate was added slowly with stirring to the enriched buffer (10 ml; pyridine buffer at 2M total concentration; fraction of base = 0.5; ionic strength 1M; 25°). The final buffer contained one-third v/v dimethoxyethane and the time of addition was at least 2 h; it was found impossible using control experiments with natural water to duplicate precisely the conditions of the kinetics while retaining a homogeneous solution. When the reaction had concluded the solution was acidified and extracted with chloroform. The product 2,4-dinitrophenol together with a sample of the water solvent and natural 2,4-dinitrophenol from a control experiment with natural water were submitted for mass spectral analysis by Dr. R. B. Turner on an AEI–MS 902 high resolution mass spectrograph.

RESULTS

Stoicheiometry Studies.—Release of 2,4-dinitrophenol from the phenyl methanesulphonate was found to be 97.4% of the theoretical value; a conservative estimate of the errors in this assay (±5%) indicates that <5% of the reaction flux yields product which involves modified phenol. The alternative product could be that from an S_NAr reaction of TRIS with the 2,4-dinitrophenyl nucleus. Routinely, the 2,4-dinitrophenol liberated during the kinetics was found to be always close to the theoretical yield.

The 2,4-dinitrophenol product from the fission of the ester in enriched water had an isotopic abundance identical with that (within experimental error) of a natural control sample [$(M + 2)/M$ respectively 0.012 93 and 0.012 53]; the abundance expected for full ^{18}O incorporation is 0.026 21 which is calculated from the abundance $^{18}O : {}^{16}O$ (0.015 72) found in the enriched water. 2,4-Dinitrophenol treated in the same way as the ester with enriched water did not incorporate ^{18}O.

The decomposition of the esters obeyed good pseudo-first-order kinetics over at least 90% of the total reaction. The rate constants are first order in buffer at low concentrations. At high concentrations of buffer (up to 1M) the rate constants are retarded below the linear dependence on concentration in some cases. This inhibition is discussed in ref. 5 and the

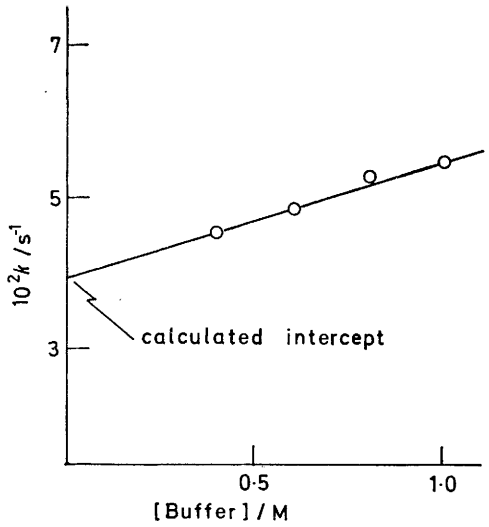


FIGURE 2 Reaction of acetamidine with 2,4-dinitrophenyl 3,5-dinitrophenylmethanesulphonate. Conditions: pH 8.97; 0.01M-TRIS; 1M ionic strength; 25 °C; the intercept agrees accurately with that calculated from the theoretical parameters for hydroxide ion and TRIS catalysis. The line is theoretical from parameters in Table 1

results analysed for equation (3) as in the previous work.

Kinetics carried out at different pH values with representative buffers (TRIS, guanidine, aminoacetonitrile, ethanolamine, ethylamine, and acetamidine with 2,4-dinitrophenyl phenylmethanesulphonate and pyridine with 2,4-dinitrophenyl 3,5-dinitrophenylmethanesulphonate) confirm that the reaction is with the basic form of the buffer.

$$k_{obs} = k^{max}[B]/(K + [BH]) \quad (3)$$

Experiments at pH values below the buffering range of the base species were carried out in the presence of added buffer; these bases were usually of such a high basicity that

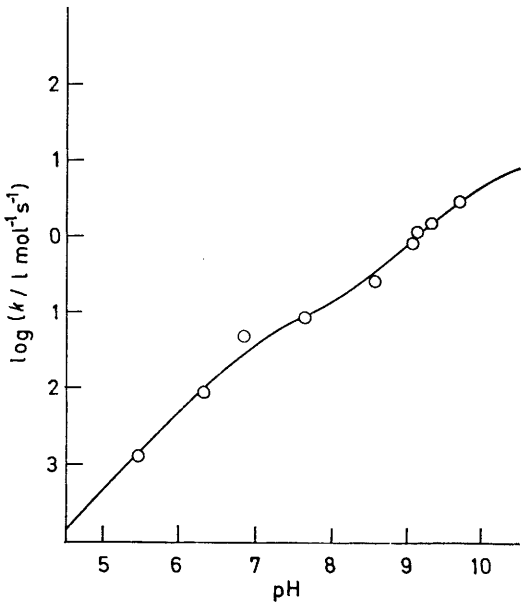


FIGURE 3 The dependence on pH of the reaction of ethylenediamine with 2,4-dinitrophenyl phenylmethanesulphonate. Conditions: 1M ionic strength, 25 °C; the line is theoretical calculated from parameters in Table 2

the background hydroxide rate constant at the buffering pH would be outside the range of the instruments used to measure the kinetics. An example is given for acetamidine (Figure 2) which should buffer normally at pH *ca.* 12. We are confident in the results because the intercepts at zero base concentration agree accurately with that calculated for the concentration of added background buffer and hydroxide ion (see Figure 2).

The determination of k_B for the two forms of ethylenediamine and piperazine was made by measuring the rate constant for 2,4-dinitrophenol release from a solution of the ester in buffer at a constant concentration but with varying pH. The pK_a values of the species involved were determined titrimetically using the Radiometer set. The reactivity (k_B') of the weaker acid of the dibasic species was estimated from the rate constants in the lower pH range of the determination using the known pK_a and equation (4). The equation fitted the data well until the pH was such that

$$k_{obs} = \frac{k_B'\,[\text{total buffer}]}{1 + a_H/K_a' + K_a''/a_H} \qquad (4)$$

the neutral diamine existed in significant concentrations. The value of k_B' for the cationic diamine species was then substituted into equation (5) together with the two ionisation constants (k_a' and k_a'') in order to determine the

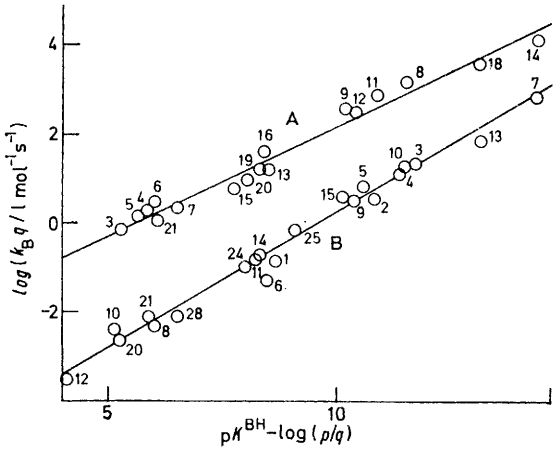


FIGURE 4 Brønsted plots of k_B for reaction of bases with 2,4-dinitrophenyl 3,5-dinitrophenylmethanesulphonate (A) and with 2,4-dinitrophenyl phenylmethanesulphonate (B). Lines are theoretical and obey equations: (A) $\log k_B = 0.61\,pK_a^{HB} - 5.54$ and (B) $\log k_B = 0.53\,pK_a^{HB} - 2.97$. Numbering is from Table 1 for A and Table 2 for B

reactivity (k_B'') of the neutral diamine from the data from the *higher* pH range. The degree of fit of the parameters k_B' and k_B'' to the data are illustrated in Figure 3 for ethylenediamine.

$$\frac{k_{obs}}{[\text{total amine}]} = \frac{k_B'}{1 + a_H/K_a' + K_a''/a_H} + \frac{k_B''}{(1 + a_H/K_a'' + a_H^2/K_a''K_a')} \qquad (5)$$

The values of k_B for the bases concerned are recorded in Tables 1—3 for the 3,5-dinitrophenylmethane-, phenylmethane-, and 4-chloro-2-nitrophenylmethane-sulphonates respectively and Brønsted plots for k_B *versus* pK_a^{HB} corrected statistically [6] are illustrated in Figure 4.

There are too few points for the 4-chloro-2-nitrophenylmethanesulphonate ester to provide a reliable estimate of β; the correlation coefficient for this ester is much less than that for the other two (r 0.910 compared with 0.990 and 0.978) and we have therefore not illustrated this correlation.

TABLE 1

Reaction of bases with 2,4-dinitrophenyl 3,5-dinitrophenylmethanesulphonate

	Base	pK_a	N [b]	pH	k_B/l mol^{-1} s^{-1}
1	Hydroxide	16.5 [c]			2.9 × 10^5 [d]
2	Acetate [a]	4.51	9	5.12	0.049
3	Pyridine [a]	5.30	39	4.63— 5.76	0.70
4	2-Picoline [a]	5.87	7	5.27	1.9
5	3-Picoline [a]	5.66	5	5.06	1.3
6	4-Picoline [a]	6.01	8	5.41	3.0
7	2,6-Lutidine [a]	6.53	8	5.93	2.3
8	Ethylamine	10.98	6	6.00	1 700
9	Glycine	9.84	9	6.00	410
10	Piperidine	11.40	9	6.00	7800
11	β-Alanine	10.3	9	8.00	860
12	Ethanolamine	9.88	9	6.00	342
13	Triethanolamine	8.50	8	6.00	15
14	Guanidine	13.6	6	6.00	10 400
15	Ethyl glycinate	7.30	6	6.00	6.5
16	TRIS	8.38	7	6.00	42
17	Morpholine	8.48	8	6.00	120
18	Acetamidine	12.48	7	6.00	4 400
19	Hydrazine	8.15	8	6.00	35
20	Ethylenediamine	7.56	8	6.00	9.7
21	Aminoacetonitrile [a]	5.59	7	5.60	1.1

[a] These bases were used as buffers; other bases were studied using 2,6-lutidine buffers at 0.01M. [b] Number of data points. [c] Footnote *f* of Table 3. [d] Ref. 3.

DISCUSSION

Previous work [1] has shown that reaction of 2,4-dinitrophenyl phenylmethanesulphonate in 0.1M-NaOH results

TABLE 2

Reaction of bases with 2,4-dinitrophenyl phenylmethanesulphonate

	Base	pK_a	pH	N [d]	k_B/l mol^{-1} s^{-1}
1	TRIS	8.38	7.57—8.74	25	0.14 [a]
2	β-Alanine	10.3	8.29	5	3.9
3	Diethylamine	11.7	8.26	5	22
4	Methylamine	10.94	8.29	5	13
5	Diethanolamine	10.3	8.26	5	6.6
6	Triethanolamine	8.50	8.30	5	0.048
7	Guanidine	13.6	8.43—9.28	16	730
8	Aminoacetonitrile	5.59	5.02, 5.57	11	0.0050
9	Ethanolamine	9.88	8.50—9.37	27	3.6
10	Ethylamine	10.98	8.45—9.20	19	17 [a]
11	Hydrazine	8.15	8.42	5	0.30
12	Semicarbazide	3.65	7.16	3	3.1 × 10^{-4}
13	Acetamidine	12.48	8.39, 9.00	7	69
14	Ethylenediamine	7.56	4.5—10.0	9	0.18
15	Ethylenediamine	9.97			8.5
16	Piperazine	6.04	5.00—9.54	13	5.6 × 10^{-3}
17	Piperazine	10.37			55
18	Hydroxide	16.5 [c]			4.2 × 10^3 [e]
19	Aniline	4.7			0.004 [b]
20	Pyridine	5.30			0.0023 [b]
21	4-Picoline	6.01			0.008 [b]
22	Phosphate dianion	6.68			0.0049 [b]
23	Imidazole	7.06			0.13 [b]
24	Methyl glycinate	7.58			0.11 [b]
25	Ethyl β-alaninate	8.64			0.66 [b]
26	Piperidine	11.40			121 [b]
27	Morpholine	8.48			3.1 [b]
28	2,6-Lutidine	6.53			7.5 × 10^{-3} [b]

[a] Error is noted in Table IV of ref. 1. [b] Data from ref. 1. [c] Footnote *f* of Table 3. [d] Number of data points. [e] Ref. 3.

in 8% attack *via* an S_NAr process. Although the result was judged to have considerable error this represents a significant proportion of the total reaction flux. We are able to estimate the relative proportions of aromatic *versus* sulphonyl attack in the reaction with amines because the S–O cleavage yields 2,4-dinitrophenol

TABLE 3

Reaction of bases with 2,4-dinitrophenyl 4-chloro-2-nitrophenylmethanesulphonate [b]

Base	pK_a	N [a]	k_B/l mol^{-1} s^{-1}
Pyridine [c,d]	5.30		5.4
Acetate [c,g]	4.51		3.7×10^{-2}
Dimethylaminoacetonitrile [c]	4.62	8	0.12
Propargylmorpholine [c]	5.80	9	0.84
Cacodylate [c,g]	6.15		1.25
N-Chloroethylmorpholine [a]	6.46	9	0.30
N-Methylmorpholine [a]	8.02	8	42
Dimethylbenzylamine [a]	8.47	9	107
Triethylamine [a]	10.91	9	1 105
Hydroxide ion [d]	16.5 [f]		26.6×10^4

[a] Carried out with pyridine buffers at 0.01M. [b] Brønsted correlation (statistically corrected): $k_B = 0.60\ pK_a^{HB} - 3.44$ (r 0.910). [c] Curvature observed in the rate constant–buffer concentration plot for these species. [d] From ref. 3. [e] Number of data points. [f] C. K. Sauers, W. P. Jencks, and G. Groh, *J. Am. Chem. Soc.*, 1975, **97**, 5546. [g] From ref. 5.

whereas the S_NAr process gives an aniline. The relatively high reactivity of the bases compared with the known low efficiency of sulphonates to nucleophilic attack (except by hydroxide) [7] rules out direct nucleophilic displacement of the phenolate ion as do the studies carried out using ^{18}O-enriched water. The mechanism involving abstraction of the α-proton by base is consistent with the absence of large steric requirements (Figure 4) and of a primary deuterium isotope effect.[1] Figure 4 indicates minor deviations from a perfect Brønsted correlation. The cyclic secondary amines morpholine, piperazine, and piperidine are enhanced except for the monocationic piperazinium base which shows a retardation. Oxyanion bases, *e.g.* acetate, phosphate, and hydroxide, seem to be poorer catalysts than the correlation suggests. The origin of the deviations is not obvious and they are certainly outside experimental error. Highly hindered species such as TRIS and triethanolamine are apparently acting without steric constraint. Secondary amines such as piperidine are well known to be more reactive than primary amines and the explanation for this may involve solvation. The proton transfer reaction is susceptible to substitution in the *ortho*-position of the phenylmethanesulphonate.[3]

In order to compare the Brønsted selectivities we have omitted the cyclic six-membered secondary amines and the oxyanions from the calculations because these probably deviate due to non-electronic reasons. The Brønsted selectivities show a small (β 0.61—0.50) but significant decrease as the reactivity of the ester increase (Figure 4) from the phenylmethane sulphonate to the 3,5-dinitrophenylmethanesulphonate. The reactivity increase of approximately two powers of ten for a base of pK_a *ca.* 10 represents a relatively small energy change and only a small variation in β would be expected.

The decrease of β from 0.61 to 0.50 units is barely outside the error limits which are normally placed on measurements of β. Certainly Figure 4 indicates a definite trend to lower selectivity. The exclusion of points from the Brønsted correlation is necessary because we are looking for changes in electronic requirements; deviant points arising from solvation or steric effects are therefore legitimately left out of the correlations. A concerted process with symmetrical timing has a transition state close to B in Figure 1. The effect of stabilising the carbanion and destabilising the cation should be seen as a movement of B towards the anion perpendicular to the reaction co-ordinate. A further motion of B along the reaction co-ordinate towards the sulphene product is also expected because the latter will be destabilised by electron-withdrawing substituents. The net effect is a movement of B to *increase* the Brønsted β value as measured by the position of B on the C · · · H · · · B axis (Figure 1). A transition state close to A will not be affected by energy changes in cation or product; a stabilisation of anion will cause A to move towards reactant thereby decreasing the Brønsted selectivity β. The present results are in accord with the unsymmetrical concerted pathway.

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