# The Kinetics and Mechanism of the Reactions of Aromatic Sulphonyl Chlorides with Anilines in Methanol; Brønsted and Hammett Correlations

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The rate of reaction of substituted benzenesulphonyl chlorides with various substituted anilines has been measured in methanol. Substituent effects in sulphonyl chloride and aniline are correlated by Brønsted and Hammett equations, respectively. The results are interpreted in terms of a direct bimolecular nucleophilic displacement mechanism. The sensitivity parameters, β and ρ, obtained from the free-energy relations, are inter-related and are themselves sensitive to the reactivity of the system. Thus  $\beta$  varies from 0.65 for p-methoxybenzenesulphonyl chloride to 0.96 for m-nitrobenzenesulphonyl chloride whereas p varies from 0.44 for m-nitroaniline to 1.14 for 3.4-dimethylaniline. These variations in  $\beta$  and  $\rho$  are interpreted to mean that electron-withdrawing substituents in the sulphonyl chloride increase bond formation whereas such substituents in the aniline leads to increased bondbreaking relative to bond formation in the transition state.

To investigate the effect of structure on reactivity in nucleophilic substitution at tetraco-ordinated sulphur, the rate constants for the reaction of some aromatic sulphonyl chlorides with a series of substituted anilines have been determined in methanol. This reaction,<sup>1,2</sup> which occurs in organic solvents according to equation (1), was chosen because of its expected simplicity and of

 $R^{1}SO_{2}Cl + 2H_{2}NR^{2} =$  $R^{1}SO_{2}NHR^{2} + H_{3}NR^{2} + Cl^{-}$  (1)

the possibilities of introducing substituents both in nucleophile and substrate. Methanolysis of sulphonyl chlorides is slow compared with their reactions with pyridine.<sup>3</sup> This is also expected to be the case in reactions with anilines, since pyridine and aniline show similar reactivity to benzenesulphonyl chloride.<sup>4</sup> Since primary sulphonanilides are relatively stable to alcoholysis,<sup>5</sup> the products are not expected to react further.

### EXPERIMENTAL

Materials.-The sulphonyl chlorides and anilines were commercial. Sulphonanilides were prepared by standard procedures.<sup>6</sup> The sulphonyl chlorides were fractionally distilled or recrystallized from light petroleum (b.p. 60-80 °C). G.l.c. showed only a single peak in each case.

The anilines, except 3-nitroaniline which was recrystallized from ethanol, were fresh samples of puriss grade (Fluka A.G.) and were used as supplied. Methanol containing  $\leq 0.05\%$  water (Merck) was used throughout. Small amounts of water in the methanol have no effect on the observed first-order rate constants since duplicate runs in methanol containing 1.0% water gave only slightly higher (4%) rate constants.

Rate Measurements.-Rate measurements were done conductometrically. The apparatus and procedure were as described 4 except that the sulphonyl chlorides were added to the reaction vessel in acetone (0.01 ml). The sulphonyl chloride concentration was generally ca.  $4 \times 10^{-4}$  M. All measurements were done with anilines in large excess over sulphonyl chloride. The concentration ranges used for

<sup>2</sup> Houben-Weyl, Methoden der Organischen Chemie, 1955, Vol. IX, 4th edn., p. 611.
O. Rogne, J. Chem. Soc. (B), 1971, 1334.
O. Rogne, J. Chem. Soc. (B), 1970, 1056.

- <sup>5</sup> S. Searles and S. Nukina, Chem. Rev., 1959, 59, 1077.

the various anilines varied from 0.005 to 0.03M for the fastest reactions to  $0{\cdot}05$  to  $0{\cdot}50{\mbox{\scriptsize M}}$  for the slowest.

Reactions were generally run to *ca*. 3 to 4 half-lives. The observed first-order rate constants were calculated from the resulting conductivity-time curve by Guggenheim's method.<sup>7</sup> Occasionally reactions were run to completion (10 half-lives) and tested for first-order behaviour by means of conventional plots of log (a - x) against time. Secondorder rate constants were calculated from the slopes of plots of the observed first-order rate constants against the aniline concentration. Rate constants are estimated to be accurate to +3%. Activation parameters were calculated at 25 °C in the usual way from Arrhenius plots.<sup>8</sup> The estimated precision is ca.  $\pm 0.5$  kcal mol<sup>-1</sup> in  $\Delta H^{\ddagger}$  and ca.  $\pm 2$  cal mol<sup>-1</sup>  $K^{-1}$  in  $\Delta S^{\ddagger}$ . The various Brønsted and Hammett slopes, their standard deviation, and correlation coefficients, were calculated by a least-squares treatment of  $\log k$  against  $pK_a$  or  $\sigma$ .

Product Analysis.-Qualitative and quantitative product analyses were by g.l.c. by comparing retention times, and peak areas for the final reaction mixtures with methanolic solutions of the corresponding sulphonanilides. In the quantitative analysis the sulphonyl chloride concentrations were five times that used in the kinetic runs.

Products were isolated in a few cases as follows; to a M-solution of aniline in methanol (25 ml) was added sulphonyl chloride (final concentration  $8.0 \times 10^{-2}$ M). When reaction was complete the methanol was evaporated, the residue treated with aqueous M-sodium hydroxide (20 ml), and extracted twice with ether. The aqueous layer was acidified and the precipitate filtered off, washed, and dried. G.l.c. showed only a single peak.

### RESULTS

The observed rates of reaction were always of the first order. Plots of the observed first-order rate constants against concentration of aniline were also in all cases linear, showing that the reactions are of the first order in nucleo-The second-order rate constants at 25 °C obtained phile. from these plots are in Table 1. A few of the reactions were also studied at 15 and 35 °C. These rate constants are in Table 2 together with the calculated activation parameters. The kinetics are thus as expected from equation

<sup>6</sup> A. I. Vogel, 'Elementary Practical Organic Chemistry,' Longmans, Green and Co., London, 1958, p. 471.

 <sup>7</sup> E. A. Guggenheim, *Phil. Mag.*, 1926, 2, 538.
 <sup>8</sup> J. F. Bunnett, 'Technique of Organic Chemistry,' ed.
 A. Weissberger, Interscience, New York, 1961, vol. VIII, part I, p. 199.

<sup>&</sup>lt;sup>1</sup> C. M. Suter, 'The Organic Chemistry of Sulphur,' Wiley, New York, 1945, ch. 6.

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(1) with the rate law (2). The sulphonanilides were

$$Rate = k[R^{1}SO_{2}Cl][H_{2}NR^{2}]$$
(2)

identified in the final reaction mixture by g.l.c. No other products were observed. Products of the reactions of benzene- and toluene-*p*-sulphonyl chloride with aniline were isolated as described, giving products of m.p. 108 and 102 °C respectively (lit.,<sup>9</sup> for benzenesulphonanilide 110°, and toluene-*p*-sulphonanilide 103°). The rate constants for the reactions of each sulphonyl chloride with the various anilines are related to the  $pK_a$  (Table 1) in water of the corresponding protonated aniline as exemplified by the Brønsted plot in Figure 1. The slopes, standard deviations, and correlation coefficients are in Table 3. The Brønsted slopes, which provide a measure of the sensitivity of the reaction to the basicity of the nucleophile, depends on the electron-attracting power of the substituents in the sulphonyl chloride, as shown in Figure 2.

### Table 1

Second-order rate constants for the reaction of substituted benzenesulphonyl chlorides with anilines in methanol at 25 °C

		$10^{2}k/1 \text{ mol}^{-1} \text{ s}^{-1}$					
Aniline	Substituent $pK_{a}$ †	p-MeO (-0·40) *	<i>p</i> -Me (−0·17)	H (0)	<i>р</i> -І (0·27)	<i>m</i> -NO <sub>2</sub> (0·71)	$p-NO_2$ (0.78)
3,4-Dimethylaniline	5·17 ‡	9.70	16.5	24.9	53.6	196.0	185.5
4-Methylaniline	5.08	6.20	10.9	16.9	30.0	115.5	119.0
3-Methylaniline	4.71	4.51	7.35	10.6	20.8	61.9	67.4
Aniline	4.59	2.75	4.75	6.86	11.5	38.5	41.9
4-Chloroaniline	3.98	1.25	1.91	2.75	3.75	9.34	10.8
3-Chloroaniline	3.52	0.704	1.06	1.26	1.94	4.40	4.90
3-Nitroaniline	$2 \cdot 46$	0.139	0.193	0.206	0.261	0.412	0.516

\*  $\sigma$  Values, from P. R. Wells, *Chem. Rev.*, 1963, **63**, 171, except for *p*-OMe which is arbitrarily set to -0.40.  $\dagger$  In aqueous solution at 25 °C, from P. D. Bolton and F. M. Hall, *Austral. J. Chem.*, 1967, **20**, 1797; 1968, **21**, 939; *J. Chem. Soc.* (B), 1969, 259, unless noted otherwise.  $\ddagger$  D. D. Perrin, 'Dissociation Constants of Organic Bases in Aqueous Solution,' Butterworths, London, 1965.

TABLE 2

Rate constants and activation parameters for the reactions in Table 1 which were also studied at 15 and 35 °C

	10 <sup>2</sup> k/l mol <sup>-1</sup> s <sup>-1</sup>				
Sulphonyl chloride	Aniline	15 °C	35 °C	$\Delta H^{\ddagger}/\text{kcal mol}^{-1}$	$\Delta S^{\ddagger}/cal \text{ mol}^{-1} \text{ K}^{-1}$
p-NO. C. H. SO.Cl	3.4-Dimethylaniline	$122 \cdot 8$	269.5	6.3	-38
PhSO,Cl	3,4-Dimethylaniline	14.8	38.4	7.8	-35
p-MeO·C.H.SO.Cl	3.4-Dimethylaniline	5.24	16.7	9.7	-30
p-NO, C, H, SO, Cl	Aniline	26.4	62.8	7.1	-36
PhSO,Cl	Aniline	3.98	11.5	8.8	-34
p-MeÕ·C₄H₄·SO₄Cl	Aniline	1.55	5.11	9.9	-32
p-NO, C, H, SO, Cl	3-Chloroaniline	3.01	7.98	8.0	38
PhSO,Cl	3-Chloroaniline	0.740	2.22	8.8	-37
$p-MeO·C_6H_4·SO_2Cl$	3-Chloroaniline	0.373	1.32	10.5	-33

The stoicheiometry was investigated by g.l.c. for the following reactions: p-nitrobenzenesulphonyl chloride with 3,4-dimethylaniline, benzenesulphonyl chloride with aniline,

#### TABLE 3

Slopes ( $\beta$ ) and correlation coefficients (r) of the Brønsted plots (Figure 1) for the reaction of the anilines with sulphonyl chlorides

Sulphonyl chloride	β	r
p-NO. C. H. SO. Cl	0.93 + 0.02 *	0.998
m-NO, C, H, SO, Cl	$0.96 \stackrel{-}{\pm} 0.03$	0.997
<i>p</i> -I·C <sub>6</sub> H₄·ŠO₂Cl	$0.82 \pm 0.03$	0.995
PhSO <sub>2</sub> Cl	$0.75 \pm 0.02$	0.998
<i>p</i> -Me·Č <sub>β</sub> H₄·SO₂Cl	$0.69 \pm 0.02$	0.996
p-MeO·C <sub>6</sub> H <sub>4</sub> ·SO <sub>2</sub> Cl	$0.65\pm0.03$	0.995
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Standard deviation.

and p-methoxybenzenesulphonyl chloride with 3-chloroaniline. The amount of sulphonanilide was in all cases  $\geq 94\%$  of that expected from the formation of one mol of anilide per mol of acid chloride consumed, in agreement with equation (1). From the consistency of the rate data and the well known nature of the reactions it seems safe to assume also that the other reactions occur quantitatively.

<sup>9</sup> 'Handbook of Chemistry and Physics,' The Chemical Rubber Co., Ohio, 45th edn., 1964.

These rates could alternatively be correlated by means of the Hammett equation. In this case a series of  $\rho$  values ranging from -1.90 to -2.80 is obtained.

The rate constants for the reactions of each aniline with the various sulphonyl chlorides are correlated by the  $\sigma$  values (Table 1) giving a series of Hammett plots. An example is shown in Figure 3. The  $\rho$  values, standard deviations, and

#### TABLE 4

Slopes  $(\rho)$  and correlation coefficient (r) of the Hammett plots (Figure 3) for the reactions of the sulphonyl chlorides with anilines

Aniline	ρ	r
3,4-Dimethylaniline	$1.14 \pm 0.04 *$	0.998
4-Methylaniline	$1.11 \pm 0.03$	0.998
3-Methylaniline	$1.02\pm0.02$	0.999
Aniline	$1.01 \pm 0.03$	0.998
4-Chloroaniline	$0.78 \pm 0.03$	0.998
3-Chloroaniline	$0.71 \pm 0.02$	0.998
3-Nitroaniline	$0.44 \pm 0.03$	0.990
* St	andard deviation.	

correlation coefficients are in Table 4. The  $\sigma$  value for the *p*-MeO substituent was arbitrarily set to -0.40 to linearize the plots. A similar value was also necessary to linearize the Hammett plot for the reactions of pyridine with sulphonyl chlorides,<sup>4</sup> and taken to indicate a certain amount of resonance stabilization of the sulphonyl chloride. The  $\rho$  values, and thus the sensitivity of the reaction to substituents in the sulphonyl chloride, depends on the basicity of the nucleophile, as shown in Figure 4.

An apparent anomaly exist in the rate data (Table 1) in that 3,4-dimethylaniline reacts more slowly with p-nitrobenzenesulphonyl chloride than with the *m*-nitro-compound.



FIGURE 1 Brønsted plot for the reaction of substituted anilines with benzenesulphonyl chloride in methanol at 25 °C. The other sulphonyl chlorides gave similar plots. The slopes, standard deviation, and correlation coefficients are in Table 3



FIGURE 2 Dependence of the Brønsted slopes,  $\beta$  (Table 3), upon the  $\sigma$  values for the sulphonyl chloride substituents. The line has a slope of 0.263  $\pm$  0.017 (r = 0.991)

No explanation can be given for this. It has, however, no effect on the conclusions.

<sup>10</sup> E. Ciuffarin and A. Fava, *Progr. Phys. Org. Chem.*, 1968, **6**, 81.



FIGURE 3 Hammett plot for the reaction of aniline with substituted benzenesulphonyl chlorides in methanol at 25 °C. Similar plots were obtained for the other anilines. The slopes, standard deviation, and correlation coefficients are in Table 4



FIGURE 4 Dependence of the Hammett  $\rho$  values (Table 4) upon the basicity of the aniline. The line has a slope of 0.261  $\pm$  0.010 (r = 0.996)

### DISCUSSION

Mechanism.—The mechanism for the reaction of anilines with aromatic sulphonyl chlorides is most reasonably formulated as a bimolecular nucleophilic substitution on sulphur. The kinetics, products, stoicheiometry, and activation parameters are in agreement with such a mechanism. A nucleophilic substitution on sulphur can conceivably take place by a synchronous one-step process, or by an addition–elimination mechanism involving a quinquecovalent intermediate.<sup>10-12</sup> For reasons given below, a one-step process is preferred.

 L. Senatore, E. Ciuffarin, and A. Fava, J. Amer. Chem. Soc., 1970, 92, 3035.
 W. A. Pryor and K. Smith, J. Amer. Chem. Soc., 1970, 92, 2731.

Substituent Effects.—The effect of structural variations in nucleophile and substrate is apparent from the Brønsted and Hammett plots, the rate being increased by electron-donating substituents in the aniline and by electron-attracting substituents in the acid chloride. This is as expected for nucleophilic attack of amines on the sulphur atom. However, the various Brønsted  $(\beta)$ and Hammett ( $\rho$ ) slopes are not equal, but show a regular variation. This can be understood in terms of changes in bond formation  $(N \cdot \cdot \cdot S)$  and bond breaking  $(S \cdot \cdot \cdot Cl)$ in the transition state with changes in electron-attracting ability of the substituents. Since  $\beta$  provide a measure of the degree of bond formation in the transition state, it is apparent from Table 3 and Figure 2 that bond formation increases with increasingly electron-attracting substituents in the sulphonyl chloride. This is in agreement with predictions of substituent effects on  $S_N 2$ transition-state structure.13,14

The reaction constant, p, which is a measure of the change in charge at the reaction centre, is related to the extent of bond formation and bond breaking in the transition state.<sup>15</sup> The more positive  $\rho$  is, the more will bond making have proceeded relative to bond breaking. Table 4 shows that bond breaking increases relatively to bond formation with increasingly electron-attracting substituents in the nucleophile, in agreement with predictions of substituent effects on  $S_N 2$  transition states.<sup>13,14</sup> The variable  $\rho$  value is thus consistent with a concerted mechanism with the transition state occurring progressively further along the reaction co-ordinate with decreasing reactivity of the nucleophile.

The variable slope of the Hammett plots could perhaps also be interpreted in terms of a quinquecovalent intermediate with a gradual change in rate-determining step from amine addition to chloride expulsion with decreasing nucleophilicity of the amine. This does not appear likely, however, because of the good leaving ability of chloride compared with the much more basic anilines.

The linearity of the Brønsted plots also suggests that there is no large change in transition-state structure from the most reactive to the least reactive aniline. A synchronous one-step process is thus preferred.

Multiple Structure-Reactivity Correlation.-The Hammett and Brønsted equations, which correlate structural changes in sulphonyl chloride and aniline respectively, can be combined to give an expression (3) which shows that the various  $\rho$ 's and  $\beta$ 's are inter-related; <sup>16,17</sup> C is a

$$\frac{pK_{a}^{1} - pK_{a}^{2}}{\rho_{1} - \rho_{2}} = \frac{\sigma_{i}}{\beta_{i} - \beta_{0}} = C$$
(3)

constant. Equation (2) predicts a linear variation of  $pK_a$  with  $\rho$  and of  $\sigma$  with  $\beta$ . This is the case as shown in Figures 2 and 4. The value of C, evaluated from the slope of the plots in Figure 2 or 4, is 3.8. Its positive value means that an increase in the nucleophilic reactivity of the nucleophile increases the sensitivity of the reaction to substituent effects. Likewise, the selectivity to the nucleophilic reagents increases with the reactivity of the substrate.

Activation Parameters.—Table 2 illustrates the activation parameters. The large negative entropy of activation is as expected for bimolecular reactions with highly polar transition states.<sup>18</sup> The enthalpy of activation shows a regular variation in that electron-donating substituents in the acid chloride increase  $\Delta H^{\ddagger}$  whereas electron-donating substituents in the aniline decrease  $\Delta H^{\ddagger}$ . This is consistent with the assumption that  $\Delta H^{\ddagger}$  reflects the repulsive energies between the reactants as they are brought close together.<sup>19</sup> An additional contribution to the activation parameters from solvation effects is suggested by the observed variations in  $\Delta S^{\ddagger,20}$ 

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<sup>17</sup> W. P. Jencks, Progr. Phys. Org. Chem., 1964, 2, 63.
<sup>18</sup> A. Frost and R. G. Pearson, 'Kinetics and Mechanism,' Wiley, New York, 1961, 2nd edn., ch. 7.
<sup>19</sup> H. S. Venkataraman and C. Hinshelwood, J. Chem. Soc., 10007

1960, 4977.

<sup>20</sup> W. P. Jencks, 'Catalysis in Chemistry and Enzymology,' McGraw-Hill, New York, 1969, p. 313.

<sup>&</sup>lt;sup>13</sup> E. R. Thornton, J. Amer. Chem. Soc., 1967, 89, 2915.

<sup>14</sup> J. C. Harris and J. L. Kurtz, J. Amer. Chem. Soc., 1970, 92, 349.

<sup>&</sup>lt;sup>15</sup> C. G. Swain and W. P. Langsdorf, J. Amer. Chem. Soc., 1951, **78**, 2813. <sup>16</sup> E. H. Cordes and W. P. Jencks, J. Amer. Chem. Soc., 1962,

<sup>84, 4319.</sup>