776. *Aromatic Sulphonation. Part V.* Kinetic Isotope Effects and Mechanism.*

By J. C. D. Brand, A. W. P. Jarvie, and W. C. Horning.

Indicator measurements are used to obtain values for the autoprotolysis constant of sulphuric acid and the acidity constant of disulphuric acid. It is then shown that h_0 is proportional to the concentration of solvated hydrogen ions, $H_3SO_4^+$, over a considerable section of the range between the compositions H_2SO_4,H_2O and H_2SO_4,SO_3. Activity-coefficient ratios of the form $f_Bf_{H^+}/f_{BH^+}$ appear to be substantially constant in this region. It is therefore suggested that ratios having the more general form f_Xf_Y/f_{XY} are also approximately constant in sulphuric acid, and this hypothesis is used to analyse the kinetic dependence of sulphonation on the concentration of the medium in fuming sulphuric acid. Substrate and solvent deuterium isotope effects help to discriminate between possible mechanisms, and it is concluded that the reaction proceeds by stepwise attachment of SO_3 and H^+ to the substrate, followed by the loss of a proton from the benzene ring.

Accumulated evidence [1,2,3] on the mechanism of aromatic sulphonation in sulphuric acid still leaves several points undecided.[4] We try here to settle some of these with the help of new measurements on the kinetic effect of deuterium in the substrate as well as in the sulphonating medium.

(1) *Activity Coefficients in Sulphuric Acid.*—Rate constants for sulphonation in sulphuric acid encompass a profound change of the acid concentration. To give a trustworthy interpretation to the rates it is therefore necessary to have at least a qualitative estimate of the activity-coefficient changes, which otherwise represent an unknown factor in the rate equation. The widespread assumption that activity coefficients are constant in sulphuric acid has been proved inadequate,[5] although variations are less than in aqueous solution. Some activity-coefficient measurements are available in a region close to the composition H_2SO_4 and these will be mentioned later; unfortunately, they do not cover a sufficient range to be of direct application to the kinetics of sulphonation. Further information comes from an analysis of equilibria and this will be the concern of the present section. As the assumption of constant activity coefficients is unsound we take as a working hypothesis the proposition that

$$f_Xf_Y/f_{XY} \simeq \text{constant} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

a condition reminiscent of the Zucker–Hammett hypothesis.[6,7] Its status in sulphuric acid is that of an assumption yet to be tested by comparison with experimental data.

Acid–base equilibria in sulphuric acid have been studied extensively.[6,8,9] The formal equation

$$H_2SO_4 \rightleftharpoons H^+ + HSO_4^-; \; K_S = a_{H^+}\,a_{HSO_4^-}/a_{H_2SO_4} \quad . \quad . \quad . \quad (2)$$

gives [1a]

$$H_0 = pK_S + \log\,(x_{HSO_4^-}/x_{H_2SO_4}) + \log\,(f_{BH^+}f_{HSO_4^-}/f_Bf_{H_2SO_4}) \quad . \quad . \quad (3)$$

in which x stands for mole fraction. Eqn. (1) gives $f_{BH^+}/f_B \simeq f_{H_2SO_4}/f_{HSO_4^-} \propto f_{H^+}$, and

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* Part IV, *J.*, 1952, 3927.

[1] (*a*) Brand, *J.*, 1950, 997; (*b*) Brand, *J.*, 1950, 1004; (*c*) Brand and Horning, *J.*, 1952, 3922.

[2] Gold and Satchell, *J.*, 1956, 1635.

[3] Spryskov, *Zhur. obshchei Khim.*, 1955, **25**, 1731.

[4] Ingold, "Structure and Mechanism in Organic Chemistry," Bell, London, 1953.

[5] Brand, James, and Rutherford, *J.*, 1953, 2447.

[6] Hammett, "Physical Organic Chemistry," McGraw-Hill, New York, 1940.

[7] Long and Paul, *Chem. Rev.*, 1957, **57**, 935.

[8] Paul and Long, *Chem. Rev.*, 1957, **57**, 1.

[9] Brand, Horning, and Thornley, *J.*, 1952, 1374.

hence that the last term in (3) is constant in first approximation. In fact it was shown [1a] that the eqn.*

$$H_0 = -9{\cdot}49 + \log m_{\mathrm{HSO_4^-}} \quad . \; . \; . \; . \; . \; . \; . \; . \quad (4)$$

where $m_{\mathrm{HSO_4^-}}$ is the molality of bisulphate ion calculated on the simple assumption that water is quantitatively converted into $H_3O^+HSO_4^-$, gives an excellent account of the experimental H_0 curve in 90—99·5% H_2SO_4 (Fig. 1). [Incidentally, eqn. (1) predicts that H_+, H_0, and H_- will all have the same numerical values in sulphuric acid, and this accords with such facts as are known.[9, 10]] Equation (4) can now be used to estimate the bisulphate-ion molality in anhydrous acid ($H_0 = -11{\cdot}12$),[9] and we find $(m_{\mathrm{HSO_4^-}})_{m=0} = 0{\cdot}023_4$. Bisulphate ions are formed here by self-dissociation of the solvent to which Gillespie, Hughes, and Ingold [11] attribute the equilibria

$$2H_2SO_4 \rightleftharpoons H_3SO_4^+ + HSO_4^- \text{ (autoprotolysis)} \quad . \; . \; . \; . \; . \; . \; . \; . \quad (5)$$

$$2H_2SO_4 \rightleftharpoons H_3O^+ + HS_2O_7^- \text{ (ionic dehydration)} \quad . \; . \; . \; . \; . \; . \; . \quad (6)$$

In anhydrous acid, therefore, $(m_{\mathrm{HSO_4^-}})_{m_2=0} = (m_{\mathrm{H_3SO_4^+}})_{m_2=0}$ and thus the (mole fraction) autoprotolysis constant, K_{ap}, is $5{\cdot}3 \times 10^{-6}$ at the temperature (20°) of the indicator measurements. Though high, this is consistent with the value $2{\cdot}9 \times 10^{-6}$ (at 20°) derived from thermodynamic measurements by Wyatt and Kirkbride.[12] Another value, K_{ap} (20°) $= 2{\cdot}0 \times 10^{-6}$, can be calculated from Gillespie and Oubridge's data [13] at 10·4° by use of ΔH_{ap}.[12] We do not think that K_{ap} from the indicator experiments is better than the other data (on the contrary, the high value of K_{ap} probably disguises a drift in the ratios $f_{\mathrm{X}}f_{\mathrm{Y}}/f_{\mathrm{XY}}$) but the fact that measurements in the range 90—99% H_2SO_4 give a reasonably good picture of the equilibria in anhydrous acid is reassuring evidence that eqn. (1) is valid as a first approximation. Naturally, eqn. (4) would also follow from (3) if all activity coefficients were constant but this, as we shall see, is certainly not correct.

On the fuming side of the composition H_2SO_4 an extra constant is needed to cope with the incomplete ionisation of disulphuric acid. The ionisation is represented by [11]

$$H_2S_2O_7 + H_2SO_4 \rightleftharpoons H_3SO_4^+ + HS_2O_7^- \quad . \; . \; . \; . \; . \; . \; . \; . \; . \quad (7)$$

Eqn. (1) gives $f_{\mathrm{H_3SO_4^+}}/f_{\mathrm{H_2SO_4}} \simeq f_{\mathrm{H_2S_2O_7}}/f_{\mathrm{HS_2O_7^-}}$, and thus

$$K_{\mathrm{A}} = x_{\mathrm{H_3SO_4^+}}x_{\mathrm{HS_2O_7^-}}/x_{\mathrm{H_2S_2O_7}}x_{\mathrm{H_2SO_4}} \quad . \; . \; . \; . \; . \; . \; . \quad (8)$$

[The assumption (1) must always eliminate activity coefficients from a "balanced" equilibrium of the form $AB + C \rightleftharpoons AC + B$.] Indicator data in fuming acid are of two sorts. First, one may determine H_0 in presence of a high molality of $HS_2O_7^-$ anions, as when potassium sulphate is dissolved in fuming sulphuric acid. The ions repress the ionic dehydration (6) which can then be ignored. Some results are given in the upper portion of Table 1; they resemble previous data [1a] which, however, are in error to the extent that indicator ratios were determined at a single wavelength, and have therefore been re-evaluated. As autoprotolysis is considerable in sulphuric acid it is necessary to allow for solvolysis of the $HS_2O_7^-$ ion in calculating K_{A}. The solvolysis has the form

$$HS_2O_7^- + H_2SO_4 \rightleftharpoons H_2S_2O_7 + HSO_4^-; \quad K_{\mathrm{H}} = K_{\mathrm{ap}}/K_{\mathrm{A}} \quad . \; . \; . \quad (9)$$

In Table 1, m_2 and m_3 are respectively the formal molalities of disulphuric acid and hydrogen disulphate ion, calculated on the assumption that the stoicheiometric SO_3 concentration

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* 0·12 unit has been subtracted from earlier values [9] of H_0 to render them consistent with Paul's redetermination of the acidity constant of *p*-nitroaniline.[8]

[10] Bonner and Lockhart, *J.*, 1957, 364.

[11] Gillespie, Hughes, and Ingold, *J.*, 1950, 2473; Gillespie, *J.*, 1950, 2493.

[12] Wyatt and Kirkbride, *Trans. Faraday Soc.*, 1958, **54**, 483.

[13] Gillespie and Oubridge, *J.*, 1956, 80.

equals $m_2 + m_3$. The actual molality of hydrogen sulphate ions (col. 4) is obtained from H_0 by eqn. (4). The requirements of electroneutrality and material balance then give

$$K_A = (K_{ap}/10{\cdot}2)(m_3 + \beta)/(m_2 - \beta)m_{HSO_4} \quad . \quad . \quad . \quad . \quad . \quad . \qquad (10)$$

where $\beta = m_{H_3SO_4^+} - m_{HSO_4^-}$ is calculable from $m_{HSO_4^-}$ and K_{ap}. This treatment yields the values of K_A given in the final column.

TABLE 1. *Acidity constant of disulphuric acid* (*nitrobenzene indicator*)

m_2	m_3	$-H_0$	$m_{HSO_4^-}$	β	$K_A \times 10^3$	m_2	$-H_0$	$m_{HSO_4^-}$	β	$K_A \times 10^3$
0·372	0·163	11·44	0·011	0·039	3·0	0·232	11·61	0·0076	0·065	2·8
0·250	0·280	11·17	0·021	0·005	3·1	0·310	11·68	0·0064	0·079	2·9
0·123	0·396	10·87	0·042	−0·029	3·2	0·400	11·74	0·0055	0·095	3·1
0·159	0·101	11·27	0·017	0·016	2·7	0·584	11·82	0·0047	0·113	2·8
0·107	0·151	11·12	0·023	0·000	3·3	0·641	11·84	0·0044	0·122	2·9
0·068	0·205	10·96	0·034	−0·018	3·5	0·747	11·88	0·0041	0·131	2·9
0·160		11·51	0·0095	0·048	2·7	0·855	11·92	0·0037	0·144	3·0

The second series of measurements refers to solutions of disulphuric acid containing no added salt, and appears in the right-hand section of Table 1. Values of K_A in the last column are calculated from eqn. (10) with m_3 set equal to zero. K_A as obtained by this means is described by Gillespie *et al.*[11] as the *apparent ionisation constant* on the ground that disulphuric acid is thought to be in equilibrium with higher polysulphuric acids, but as the evidence for polysulphuric acids is very indirect (at least for dilute oleums) it has been thought unprofitable to refine our calculation at this stage. Gillespie, Hughes, and Ingold express K_A more simply in terms of molalities and obtain, from cryoscopic data, the value $K_A = 0{\cdot}028$ mole kg.$^{-1}$ at 10°. This is clearly consistent with the overall average from Table 1; K_A (20°) $= 3{\cdot}0 \times 10^{-3}$ when the m_1 conversion factor is applied.

Eqns. (2) and (5) give the thermodynamic expression $K_S = K_{ap}\, a_{H^+}\, a_{H_2SO_4}/a_{H_3SO_4^+}$ from which, on introduction of the definition of H_0 [6] as well as the assumption expressed in (1), one finds

$$H_0 = \log K_{ap}/K_S - \log x_{H_3SO_4^+}/x_{H_2SO_4} \quad . \quad . \quad . \quad . \quad . \quad . \qquad (11)$$

which, on insertion of numerical constants, becomes

$$H_0 = -12{\cdot}75 - \log m_{H_3SO_4^+} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \qquad (12)$$

The expression (12) includes the previous eqn. (4). The circles in Fig. 1 represent values of H_0 calculated from (12) on the basis of $K_A = 3{\cdot}0 \times 10^{-3}$. On the fuming side, agreement is good for disulphuric acid molalities up to 2 molal and is fair even at much higher molalities. The behaviour that could be implied by Fig. 1, *viz.*, that h_0 is essentially proportional to $m_{H_3SO_4^+}$ between the composition limits $H_2O^+HSO_4^-$ and $H_2S_2O_7$, gives a broad measure of support to the hypothesis represented by (1). It seems improbable that the proportionality would hold so well over so great a range of concentration unless the underlying assumption in regard to the activity coefficients were correct.

When activity coefficients are referred to a standard state in sulphuric acid, eqn. (1) becomes $f_X f_Y / f_{XY} \simeq 1$. As to the individual activity coefficients, however, it is almost certain that they cannot remain at unity. The case of electrolytes has been discussed elsewhere.[5, 12] Fig. 2 illustrates the manner of variation for three non-electrolytes in aqueous acid as determined by partition with cyclohexane, that is, from the equation

$$f_B = P/P^{\circ} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \qquad (13)$$

in which P is the partition coefficient. Evidently a rising molality of water has a salting-out effect, and this appears to be true not merely for the nitro-compounds shown in Fig. 2 but also for small molecules such as SO_2.[14] The changes in f_B need to be kept in perspective moreover. Between 99 and 91·5% H_2SO_4, f_B for 1-chloro-2,4-dinitrobenzene increases

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[14] Miles and Carson, *J.*, 1946, 786; Miles and Fenton, *J.*, 1920, **117**, 59.

5-fold whilst the change in h_0 is only 18-fold: thus if the agreement in Fig. 1 is significant, a drift in f_B must be cancelled by an opposite change in f_{H^+}/f_{BH^+}.

One kinetic application of (1) is known to us. If aromatic nitration in sulphuric acid follows a Brønsted rate law, the second-order coefficient, k_2, is given (in the region where $m_{NO_2^+}$ equals the formal nitric acid molality) by

$$k_2 = kf_S f_{NO_2^+}/f_{X^+}$$

in which k is a thermodynamic constant, and S and X denote substrate and transition state. k_2 for nitration of the *p*-bromophenyltrimethylammonium ion is given in Table 2. Were (1) to hold rigorously, k_2 would be independent of the composition of the medium; the actual variation is less than 2-fold. (On the aqueous side the variation is somewhat larger, 2·5-fold between 94·7 and 100% H_2SO_4.[15]) Although the quality of the approximation $f_S f_{NO_2^+} \simeq f_{X^+}$ is only fair in this instance, there are no large effects due to the medium left unexplained.

TABLE 2. *Nitration of* p-*bromophenyltrimethylammonium ion* (25°).

Free SO_3 (%)	0·00	1·29	7·38	14·1	18·6	22·2
$k_2 \times 10^3$	2·79	2·90	3·54	4·68	4·85	4·67

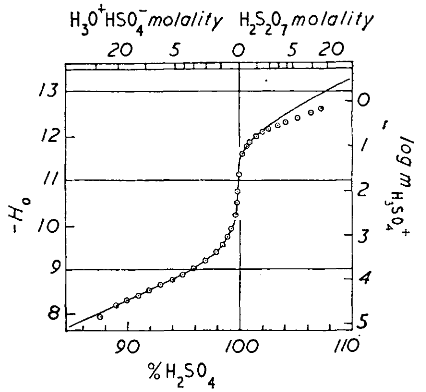

FIG. 1. *The limits of the concentration range correspond to the compositions* H_2SO_4,H_2O *and* H_2SO_4,SO_3.

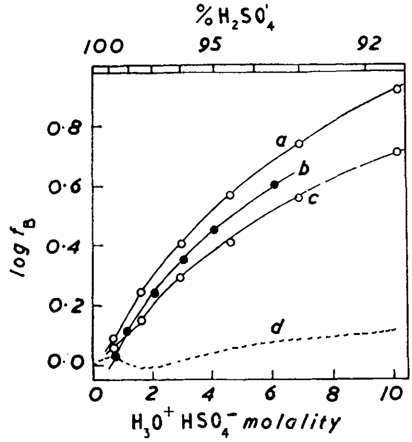

FIG. 2. *Activity coefficients of some non-electrolytes in* H_2SO_4 (20°).

a, *p*-Chloronitrobenzene. *c*, 1-Chloro-2,4-dinitrobenzene.
b, Nitrobenzene. *d*, Sulphur dioxide.[14]

(2) *Kinetic Effect of Deuterium on the Rate of Sulphonation.*—In fuming sulphuric acid, reaction conditions can be adjusted so that the sulphonation rate greatly exceeds the rate of deuterium exchange between substrate and solvent. Thus a kinetic isotope effect can be observed on one hand by substituting deuterium in the substrate, and on the other by substitution in the sulphonating medium.

Berglund-Larsson and Melander[16] determined the kinetic effect of deuterium in the substrate for the sulphonation of [4-^{2}H]- and [4-^{3}H]-bromobenzene in a mixed solvent of nitrobenzene and oleum. The effect found was small (k_D/k_H = 0·7) and lacked any significant variation with temperature. These conclusions are confirmed by the present measurements (Table 3), which also show that k_D/k_H is insensitive to the composition of the sulphonation medium.

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[15] Bonner, Bowyer, and Williams, *J.*, 1952, 3274; *J.*, 1953, 2650.

[16] Berglund-Larsson and Melander, *Arkiv Kemi*, 1953, **6**, 219; Berglund-Larsson, *ibid.*, 1957, **10**, 549.

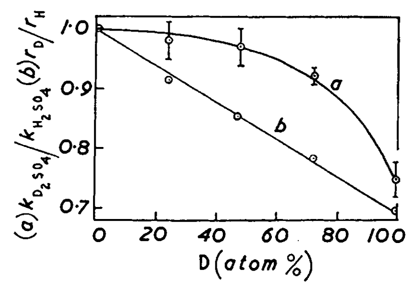
TABLE 3. *Kinetic effect of deuterium substitution in the substrate.*

	Substrate:	p-X·C_6H_4·NMe_3^+				C_6H_5·NO_2 [a]
	Medium:	X = CH_3	X = F	X = Cl	X = Br	
Temp.	free SO_3 (%)			k_D/k_H (±0·03)		
0°	11·6	$0{\cdot}54_7$	—	—	—	—
25	11·6	$0{\cdot}57_7$	—	—	—	—
25	14·3	—	—	—	—	0·59
25	22·2	$0{\cdot}57_7$	—	—	—	0·60
25	35·3	—	$0{\cdot}49_6$	$0{\cdot}48_4$	$0{\cdot}51_1$	0·63
25	42·7	—	$0{\cdot}48_1$	$0{\cdot}50_8$	0·50 [b] $0{\cdot}52_4$	—

[a] Substrate, 5 × 10^{-4}M. [b] Substrate, 0·01M. Otherwise the substrate concn. was 0·15—0· 3M.

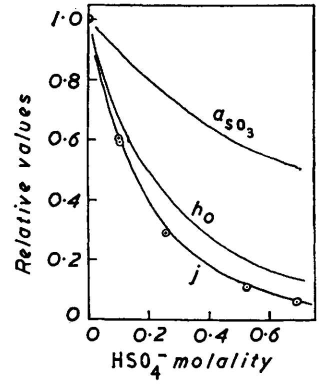
The kinetic effect of deuterium substitution in the solvent can be seen from Fig. 3. The measurements refer to a changing proportion of deuterium in a fuming acid medium of otherwise constant composition: the effect then represents a slight retardation, with $k_{D_2SO_4}/k_{H_2SO_4} = 0{\cdot}7_5$. Under the chosen conditions no deuterium was introduced into the substrate during reaction. Fig. 3 also shows the influence of solvent deuterium on the ionisation ratio, $r = c_B/c_{BH^+}$, of the indicator *m*-fluoronitrobenzene. Enrichment increases the proportion of the conjugate acid of the indicator, a change which is in the same sense as that observed for (weak) acids in aqueous solution.[17,18] No other photometric measurements seem to have been made in fuming acid, though Schubert and Burkett [19] record $r_D/r_H = 0{\cdot}44$ for mesitaldehyde in 59—70% H_2SO_4. (Flowers, Gillespie, and Oubridge,[20] however, report conductometric measurements for *m*-nitrotoluene in anhydrous D_2SO_4 which imply *less* ionisation than in H_2SO_4. The relation of this to the photometric results stands unexplained.)

FIG. 3. *Effect of solvent deuterium: sulphonation rates* (25°, *curve a*) *and indicator ratios* (20°, *curve b*).



The ordinate is $k_{D_2SO_4}/k_{H_2SO_4}$ for the velocity data (p-Me·C_6H_4·NMe_3^+ ion), and r_D/r_H ($r = c_{base}/c_{ion}$) for the indicator measurements (m-F·C_6H_4·NO_2 indicator). The mole fraction of free SO_3 is 0·0857 throughout (equivalent to 7·1% of free SO_3 in a non-enriched solvent).

FIG. 4. *Effect of hydrogen disulphate ion on the rate of sulphonation* (25°).



The curves connect relative values of a_{SO_3}, h_0, and j with the moles of hydrogen sulphate ion added (as potassium sulphate) to 1 kg. of a solvent containing 15·6% of free SO_3. The points are relative rate constants for the trimethylphenylammonium ion.[15]

(3) *Kinetic Dependence of Sulphonation Rate on Acidity.*—Sulphonation rates in sulphuric acid are of apparently first order (k_1). In fuming acid, it was noted earlier [1] that log k_1 varies almost linearly with $-H_0 + \log a_{SO_3}$ ($\equiv -J$), the slopes ranging from 1·0 to 1·2 for different substrates, over a 5000-fold change in k_1. Likewise, the results in Fig. 4 show that sulphonation rates in presence of potassium sulphate correlate with j($= -$antilog J)

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[17] Wiberg, *Chem. Rev.*, 1955, **55**, 713.

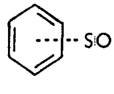
[18] Bell, " Acid-Base Catalysis," Oxford Univ. Press, London, 1949.

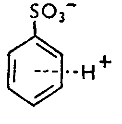
[19] Schubert and Burkett, *J. Amer. Chem. Soc.*, 1956, **78**, 64.

[20] Flowers, Gillespie, and Oubridge, *J.*, 1958, 667.

rather than with h_0 or a_{SO_3}. The inference is then that a proton and an SO_3 molecule attach to the substrate in the transition state. However, in view of evidence that sulphur trioxide (or its dimer) is an effective agent in aprotic solvents.[4,21] it is necessary to consider whether the correlation is significant, or whether the changing medium merely affects k_1 in a manner that happens to lead to the parallelism with $-J$. Experiments in aqueous acid have recently been interpreted in favour of a transition state containing SO_3 only in addition to the substrate, rather than $SO_3 + H^+$.[2]

In view of the isotopic measurements, three mechanisms need consideration. The first is that developed by Gold and Satchel [2] for aqueous acids. These authors consider


(I)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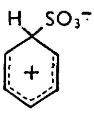
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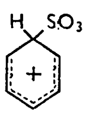
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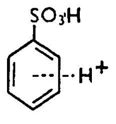

(V)

that rearrangement of the non-classical structure (I) to the corresponding structure (II), probably by way of the Wheland intermediate (III), is rate-controlling. Their mechanism is then,

$$\mathrm{ArH + SO_3 = ArH{,}SO_3\ (I)} \quad . \; . \; . \; . \; . \; . \; . \; . \; . \quad \text{(Fast) (A)}$$

$$\mathrm{ArH{,}SO_3 = ArSO_3^-{,}H^+\ (II)} \quad . \; . \; . \; . \; . \; . \; . \; . \; . \quad \text{(Slow) (B)}$$

$$\mathrm{ArSO_3^-{,}H^+ = ArSO_3^- + H^+} \quad . \; . \; . \; . \; . \; . \; . \; . \; . \quad \text{(Fast) (C)}$$

The Brønsted rate eqn. gives

$$v/[\mathrm{ArH}] = k_1 = Ab.a_{SO_3}.f_{\mathrm{ArH}}/f_{\mathrm{X}} \quad . \; . \; . \; . \; . \; . \quad (14)$$

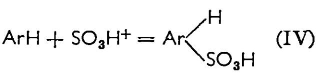
in which A denotes the equilibrium constant for (A), and b the thermodynamic rate constant for step (B). Introducing (1) in the form $f_{\mathrm{ArH}}f_{SO_3} \simeq f_{\mathrm{X}}$, we find

$$k_1 = Ab.a_{SO_3}/f_{SO_3} \quad . \; . \; . \; . \; . \; . \; . \; . \quad (15)$$

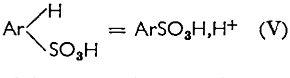
a_{SO_3} can be identified with the vapour pressure of sulphur trioxide. Because of the range of rates, eqn. (15) is more clearly tested by logarithmic graphs. Curve I, Fig. 5, is a plot of log k_1 against log a_{SO_3}; [21] the graph is not linear and has the further implication that, if eqn. (15) is valid, f_{SO_3} must decrease about 65-fold in the range of acid composition encompassed by the Figure (101—109% H_2SO_4). Likewise, the results in Fig. 4 imply that f_{SO_3} also decreases with electrolyte concentration (" salting-in "), whereas salting-out would have been expected owing to the increasing ionic strength (cf. Section 1). Although f_{SO_3} is not known, it would be plausible to assume that its variation is like that of f_{SO_2} which decreases 2-fold in the region 101—109% H_2SO_4.[14] While this mechanism cannot be ruled out, it does not seem adequately to express the sulphonation rates in fuming acid.

The second mechanism is one of attack by SO_3H^+,[1]

$$\mathrm{SO_3 + H^+ = SO_3H^+} \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \quad \text{(Fast) (D)}$$



$$\mathrm{ArH + SO_3H^+ = Ar}\begin{matrix}\diagup \mathrm{H} \\ \diagdown \mathrm{SO_3H}\end{matrix} \quad \text{(IV)} \quad . \; . \; . \; . \; . \; . \; . \; . \; . \quad \text{(E)}$$



$$\mathrm{Ar}\begin{matrix}\diagup \mathrm{H} \\ \diagdown \mathrm{SO_3H}\end{matrix} = \mathrm{ArSO_3H{,}H^+} \quad \text{(V)} \quad . \; . \; . \; . \; . \; . \; . \; . \; . \quad \text{(F)}$$

The rearrangement of a Wheland intermediate (IV) to the non-classical structure (V) is regarded as rate-controlling, although variants are possible. [In Part III [1c] the step (E) was erroneously taken to be rate-controlling; this is not consistent with a substrate deuterium effect.] This mechanism leads to a rate equation of the correct form, but is unacceptable on other grounds. The indicator measurements imply that SO_3D^+ in

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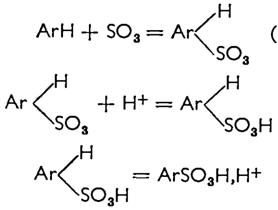
[21] Vicary and Hinshelwood, *J.*, 1939, 1372; Wadsworth and Hinshelwood, *J.*, 1944, 469; Dresel and Hinshelwood, *J.*, 1944, 649.

D_2SO_4 should be more abundant than SO_3H^+ in H_2SO_4, and therefore that the rate should increase in a deuterium solvent. The observations show a decrease of rate (Fig. 3). Although it is conceivable that the expected, small increase has been cancelled by, for example, an effect of the medium accompanying deuterium substitution in the solvent, yet the data evidently contain no support for the mechanism.

The third mechanism differs chiefly in its estimate of the timing. SO_3 and H^+ may add to the substrate consecutively: then one has,



$$\mathrm{ArH} + \mathrm{SO_3} = \mathrm{Ar}\langle^{\mathrm{H}}_{\mathrm{SO_3}} \quad \text{(III)} \quad \ldots\ldots\ldots \quad \text{(Fast) (G)}$$

$$\mathrm{Ar}\langle^{\mathrm{H}}_{\mathrm{SO_3}} + \mathrm{H^+} = \mathrm{Ar}\langle^{\mathrm{H}}_{\mathrm{SO_3H}} \quad \text{(IV)} \quad \ldots\ldots\ldots \quad \text{(H)}$$

$$\mathrm{Ar}\langle^{\mathrm{H}}_{\mathrm{SO_3H}} = \mathrm{ArSO_3H,H^+} \quad \ldots\ldots\ldots\ldots \quad \text{(F)}$$

Here the intermediate (III) is considered to accept a proton before the final, non-reversing step (F). The form attributed to the reversible step (H) merely recognises that the approximation (1), which is implied throughout the analysis, means that the reaction

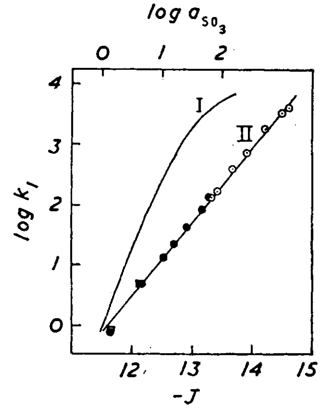
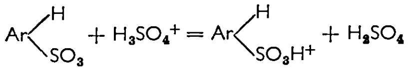


Fig. 5.

Curve I (individual points not shown): log k_1 *against* a_{SO_3}.

Curve II: log k_1 *against* $-J$. ●, $C_6H_5{\cdot}NMe_3^+$; □, p-Me·$C_6H_4{\cdot}NMe_3^+$, log $k^1 - 2{\cdot}56$; ⊙, p-F·$C_6H_4{\cdot}NMe_3^+$, log $k_1 + 1{\cdot}81$.



$$\mathrm{Ar}\langle^{\mathrm{H}}_{\mathrm{SO_3}} + \mathrm{H_3SO_4^+} = \mathrm{Ar}\langle^{\mathrm{H}}_{\mathrm{SO_3H^+}} + \mathrm{H_2SO_4}$$

leads to the same rate equation as its formal representation (H). Taking (G) as a pre-equilibrium, applying the stationary-state hypothesis to the concentration of (IV), and introducing the simplifying assumption (1), we obtain the rate equation,

$$k_1 = Gf\frac{h_+}{h_- + f}h_0a_{SO_3}/f_{SO_3} \quad \ldots\ldots \quad (16)$$

in which h_+ and h_- are rate constants for the forward and the reverse step (H). The scheme (D, E, F) when treated likewise gives an equation of the same form, namely,

$$k_1 = Df\frac{e_+}{e_- + f}h_0a_{SO_3}/f_{SO_3} \quad \ldots\ldots \quad (17)$$

Both mechanisms predict, therefore, that the graph of log k_1 against $-J[= \log(h_0 \times a_{SO_3})]$ should have a slope in excess of 1·0, because f_{SO_3} is expected to rise with oleum concentration. This, however, is a somewhat naïve explanation of the observed slope of 1·2 (Fig. 5), for the expressions (16) and (17) involve the hypothesis (1) and must be in error to the extent that this approximation fails.

Whereas deuterium can be expected to retard a reaction involving proton transfer by a factor of 2½—10, the results for the *m*-fluoronitrobenzene indicator imply that a pre-equilibrium involving proton transfer will lead to acceleration in the deuterium solvent by a factor up to 1·4. These factors being descriptively called large and small respectively,

TABLE 4.

p-X·C_6H_4·NMe_3^+	Medium: free SO_3 (%)	F_D of isolated product max.	obs.	p-X·C_6H_4·NMe_3^+	Medium: free SO_3 (%)	F_D of isolated product max.	obs.
X = CH_3	2·09	1·40	0·090	X = F	35·7	1·80	(0·019)
CH_3	4·53	1·48	0·038	Cl	35·7	1·80	(0·023)
CH_3	8·00	1·52	(0·018)	Br	35·7	1·80	(0·021)

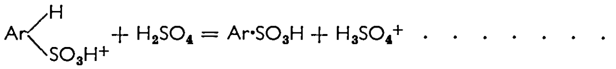
TABLE 5.

			First-order kinetic effect of D in:	
Mechanism	Limit	Description	Solvent	Substrate
(D, E, F)	$e_- \gg f$	(E) pre-equilibrium	small increase	large decrease
(G, H, F)	$h_- \gg f$	(H) pre-equilibrium		
(D, E, F)	$e_- \ll f$	(E) non-reversing	small increase	none
(G, H, F)	$h_- \ll f$	(H) non-reversing	large decrease	none

Table 5 summarises the predictions of the last two mechanisms under limiting conditions. For instance, when $h_- \ll f$ the right-hand side of (16) becomes $Gh_+ \, h_0 a_{SO_3}/f_{SO_3}$, and thus the scheme (G, H, F) predicts that solvent deuterium will bring about a large decrease in rate owing to the isotope effect on the coefficient h_+. It is worth noting that in the limits $e_- \gg f$ and $h_- \gg f$ [when (E) and (H) are pre-equilibria in their respective mechanisms] the mechanisms are not distinguishable kinetically, for the rate-controlling step is then the rearrangement of the intermediate (IV) whose concentration is unaffected by the order of previous events.*

One aspect of the Table is that, as noted earlier, the scheme (D, E, F) cannot be reconciled with the observed retardation by solvent deuterium, since the limiting situations correspond to an unchanged rate and a small acceleration. Thus we feel bound to discard SO_3H^+ as the sulphonating species in oleum. The scheme (G, H, F) is acceptable, however, because the predicted effect of solvent deuterium ranges from a large decrease to a small increase, while that for solute deuterium extends from no effect to a large decrease. Therefore an intermediate situation, in which h_- and f are to be thought of as being of the same order of magnitude, may well yield the observed low-order retardation by both solvent and solute deuterium. Physically, the the reaction intermediate (IV) may lose either nuclear hydrogen (giving rise to sulphonation) or hydrogen from the sulphonic acid group [regenerating the intermediate (III)], these two events having roughly equal probability. On general grounds, the loss of a nuclear proton from (IV) will certainly occur more readily than from (III), and this may be important for the relatively difficult sulphonations studied in fuming acid. Moreover, the electronic demand of a substituent in the aromatic nucleus affects the coefficients h_- and f in the same sense, and hence the balance between them need not be disturbed when one substituent is replaced by another.

An alternative to the unimolecular step (F) is



$$\mathrm{Ar}\begin{smallmatrix}\diagup \mathrm{H} \\ \diagdown \mathrm{SO_3H^+}\end{smallmatrix} + H_2SO_4 = Ar{\cdot}SO_3H + H_3SO_4^+ \quad . \; . \; . \; . \; . \; . \; . \; . \quad (F')$$

in which the proton is transferred directly to the solvent without the intervention of a non-classical structure. The criteria used in this paper do not distinguish (F) and (F′). (F) has been used in the foregoing discussion only because the balance of evidence from desulphonation [2] appears to favour a mechanism of this kind.

EXPERIMENTAL

Deuterium Analysis.—Sufficient organic compound to provide about 50 mg. of water was burnt in a standard semimicro-combustion apparatus. The water was purified by refluxing

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* We thank a Referee for drawing attention to this point.

over alkaline potassium permanganate[24] and degassed by several distillations *in vacuo*. Deuterium was determined, essentially as described by Gaunt,[25] from the intensity of infrared absorption at 4·03 μ. The cells used were of thin silica, their depth being 0·23 mm. for estimations in the range (0·3—0·8 atom % D) usually employed. The atom % D ($\equiv F_D$) is quoted (Table 4) relative to the natural abundance and is based on the manufacturer's analysis (99·75% w/w) of deuterium oxide. In the range $0{\cdot}3 < F_D < 0{\cdot}8$, individual analyses were reliable to ±0·005, the mean deviation being ±0·003%. However, at very low enrichments the method gave erroneously high results; for instance, combustion of unenriched compounds tended to give water with an apparent F_D of $\leqslant 0{\cdot}02$. Attempts to remove this discrepancy, attributed to the "memory" of the combustion train, were unsuccessful. Enrichments of this order could not be obtained reliably, or even distinguished from zero.

Sulphonation Media.—The concentration of fuming acid media was controlled by water-titration and conductivity measurements.[9] Partially deuterated acids were prepared by dilution of a more concentrated medium with deuterium oxide. Fully deuterated media ($F_D = 99{\cdot}7$) were obtained by slowly distilling sulphur trioxide *in vacuo* into deuterium oxide at 0°, the composition being calculated from the vacuum-corrected masses of the components.

Preparation of Derivatives of Methyl [3-^{2}H]*Phenyltrimethylammonium Sulphate.*—No attempt was made to replace nuclear hydrogen quantitatively by deuterium, and substrates studied in sulphonation usually had $F_D = 0{\cdot}3$—$0{\cdot}5$. If necessary, deuterated material was recrystallised with light compound to bring the enrichment down into this range.

Methyl [3-^{2}H]4-*methylphenyltrimethylammonium sulphate.* 5-Amino-2-methylphenyllithium was decomposed with deuterium oxide, and the product fractionally distilled to yield [3-^{2}H]4-methylaniline which was converted into the quaternary salt by standard procedure.[1b] Freedom from unwanted [2-^{2}H]4-methylaniline was established by bromination of the base ($F_D = 0{\cdot}385$) to [3-^{2}H]2,6-dibromo-4-methylaniline ($F_D = 0{\cdot}502$). If deuterium is present exclusively in the 3-position the ratio of the enrichments is 9/7 = 1·286, the observed ratio being 1·30 ± 0·03.

[3-^{2}H]4-*Fluoro-*, [3-^{2}H]4-*chloro-, and* [3-^{2}H]4-*bromo-phenyltrimethylammonium methyl sulphates.* Preliminary experiments indicated that deuterium could be introduced conveniently into *p*-nitroacetanilide by treatment with an enriched sulphuric acid–water mixture (0·52 mole fraction of H_2SO_4) at 20°. The components were shaken for several hours, the *p*-nitroacetanilide was hydrolysed, and the resulting *p*-nitroaniline recrystallised from water to displace all deuterium linked to nitrogen, and analysed isotopically. The treatment introduced deuterium in the 2- and 3-positions, though about 95% of the exchange occurred in the latter. This was demonstrated by several experiments of which the following is typical. [2,3-^{2}H]4-Nitroaniline ($F_D = 1{\cdot}06$) was diazotised and converted into *p*-chloronitrobenzene by the Sandmeyer method, and then hydrogenated in ethanol over Raney nickel to *p*-chloroaniline ($F_D = 1{\cdot}02$). As deuterium *ortho* to an amino-group is known to exchange over Raney nickel,[26] the 0·04 atom % of D lost in this process is that originally present as [2-^{2}H]4-nitroaniline. The inference that hydrogenation yielded [3-^{2}H]4-chloroaniline was confirmed by bromination of a sample in methanol to give [3-^{2}H]2,6-dibromo-4-chloroaniline, $F_D = 1{\cdot}53$ (calc., 1·53). The [3-^{2}H]-chloroaniline was then converted into [3-^{2}H]4-chlorophenyltrimethylammonium methyl sulphate by the method previously described.[1c] Similar reactions were used to prepare [3-^{2}H]4-fluorophenyltrimethylammonium methyl sulphate.

In another series of experiments [2,3-^{2}H]4-nitroaniline was diazotised and reduced to [2,3-^{2}H]nitrobenzene by treatment with hypophosphorous acid at 0°. Catalytic hydrogenation (Raney nickel) then gave [3-^{2}H]aniline which on bromination in acetic acid yielded [3-^{2}H]-bromoaniline. [3-^{2}H]4-Bromophenyltrimethylammonium methyl sulphate was obtained from the amine by quaternisation in the usual way.[1c]

Kinetic Effect of Nuclear Deuterium.—The relative velocities of displacement of nuclear hydrogen and deuterium were determined competitively. Sulphonation of a quaternary ion of the type (VI) yields a product isolable as the dipolar ion (VII) or (VIII). The results, given in Table 3, are the average of two or more concordant experiments. The uncertainty attached

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[22] Brand and Rutherford, *J.*, 1952, 3916.

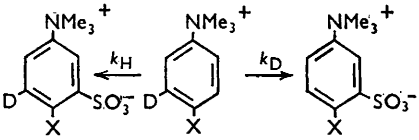
[23] Brayford and Wyatt, *J.*, 1955, 3453.

[24] Keston, Rittenberg, and Schonheimer, *J. Biol. Chem.*, 1937, **122**, 227.

[25] Gaunt, *Spectrochim. Acta*, 1956, **8**, 57.

[26] Lauer and Errede, *J. Amer. Chem. Soc.*, 1954, **76**, 5162.

there to k_D/k_H is based on a limit of error of $\pm 0{\cdot}005$ in F_D. Sulphonation of the aryltrimethylammonium ions was allowed to run for ten half-lives of the reaction at a fixed temperature (usually 25°). The solution was then diluted with water, neutralised with barium carbonate, and concentrated to small volume, any barium remaining in solution [mainly as $Ba(SO_4Me)_2$] then being precipitated with the correct quantity of sulphuric acid. Evaporation at reduced pressure gave a residue of the trimethyl-3-sulphoarylammonium betaine (VII) or (VIII) which was recrystallised once from aqueous alcohol. The isotope analyses were erratic if crystallisation was omitted, probably owing to occlusion of methyl hydrogen sulphate.



(VII) (VI) (VIII)

The calculation of k_D/k_H assumes no exchange between nuclear deuterium and sulphuric acid and would fail to the extent that this assumption is invalid. As deuterium exchange is electrophilic in character, it was expected that exchange would affect the substrate (VI) rather than the product and that it would most likely be observed with the *p*-tolyl compound (VI; X = Me). Table 4 summarises tests in which non-enriched aryltrimethylammonium methyl sulphate was sulphonated with acid containing deuterium: col. 3 gives the value of F_D expected if partition of deuterium between solvent and substrate (3-position) had reached equilibrium, while col. 4 cites the enrichment observed. As mentioned earlier, apparent enrichments of $F_D \leqslant 0{\cdot}025$ are certainly too high and may well correspond to $F_D = 0$. The results show that exchange is inappreciable relative to the rate of sulphonation, except in media of low sulphur trioxide concentration. Separate experiments confirmed that non-enriched betaines recovered from solution in a deuterium solvent had not undergone significant exchange.

Experiments with nitrobenzene were made with a sample of pentadeuteronitrobenzene kindly supplied by Dr. T. Bonner and Professor G. Williams.[15] Here, rate constants were determined separately for the light and heavy compounds by the method described earlier.[1c]

Kinetic Effect of Deuterium in the Sulphonation Medium.—The effect of deuterium as solvent was measured for the sulphonation of (non-enriched) methyl *p*-tolyltrimethylammonium sulphate in enriched acid containing *ca.* 7·1% of free sulphur trioxide. The substrate does not exchange in this medium (cf. Table 4) and thus the results refer to sulphonation of unenriched substrate by enriched acid. Rate constants were determined as described previously,[1c] and the isotope effect is expressed by the ratio, $k_{D_2SO_4}/k_{H_2SO_4}$, of the first-order rate coefficients in enriched and non-enriched acids of the same molar composition.

Nitration of Methyl p-*Bromophenyltrimethylammonium Sulphate.*—The substrate (*ca.* 10^{-3}M initially) was nitrated in a solution of potassium nitrate (0·1M) in fuming sulphuric acid, progress of the reaction being followed photometrically (at 365 mμ). The first-order rate observed is the sum of the rate constants for nitration and sulphonation. Subtraction of the rate constant for sulphonation (significant in the stronger acids only) gave the first-order constant for nitration, which was expressed as a second-order constant (k_2, Table 2) by dividing by the formal nitric acid concentration.

Indicator Measurements.—Ionisation ratios, *r*, for the indicator *m*-fluoronitrobenzene were measured [9] in relation to the deuterium content of the medium in an acid of the same composition (7·1% of free SO_3) as that used to determine the kinetic effect of solvent deuterium.

Partition Experiments.—5 ml. of a solution of the non-electrolyte in cyclohexane were shaken for 15 min. with an equal volume of sulphuric acid at 20° (equilibration required 3—8 min.), and the concentration in each of the separated phases was then determined spectrophotometrically. In some experiments the relative volumes of the two phases were altered: this had no observable effect on the constancy of the partition coefficient, *P*.

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