Aromatic Sulphonation. Part L.[1] Sulphonation of the Trimethylbenzenes: Isomer Distributions and Hydrogen Kinetic Isotope Effect

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Isomer distributions for the sulphonation of 1,2,3- and 1,2,4-trimethylbenzene with concentrated aqueous sulphuric acid at 25.0° have been determined. The results are discussed in terms of sulphonation by $H_3SO_4^+$ and $H_2S_2O_7$ as sulphonating entities. The isomer distributions for the $H_2S_2O_7$ mechanism are 90 ± 1% 4- and 10 ± 1% 5-substitution for the 1,2,3-isomer and 75 ± 2% 5- and 25 ± 2% 6-substitution for the 1,2,4-isomer, those for the $H_3SO_4^+$ mechanism are 86 ± 1% 4- and 14 ± 1% 5-substitution with the former isomer and 89 ± 2% 5- and 11 ± 2% 6-substitution by the latter. The deviations of the observed isomer distributions and of the partial rate factors for the $H_3SO_4^+$ mechanism from those calculated on the basis of the additivity principle are discussed. The sulphonation of 1,3,5-trimethylbenzene with sulphur trioxide proceeds without a primary hydrogen kinetic isotope effect, k_H/k_D being 1.15 ± 0.13 and 0.98 ± 0.09 for nitromethane at 0° and trichlorofluoromethane at −35° respectively.

THE sulphonation of the trimethylbenzenes has been studied occasionally. The 1,2,3-isomer upon sulphonation with concentrated sulphuric acid is reported to yield the 4-sulphonic acid,[2,†] whereas the main product with 1,2,4-trimethylbenzene is the 5-sulphonic acid.[3] We now report the sulphonation isomer distributions of

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† For reasons of convenience, the aromatic ring positions of the sulphonic acids have been numbered as for the parent hydrocarbon.

[1] Part XLIX, H. Cerfontain, A. Koeberg-Telder, C. Ris, and C. Schenk, *J.C.S. Perkin II*, 1975, preceding paper.

[2] K. von Auwers and F. Wieners, *Chem. Ber.*, 1925, **58**, 2815.

[3] C. Gerhardt and A. Cahours, *Annalen*, 1841, **38**, 67; L. I. Smith and O. W. Cass, *J. Amer. Chem. Soc.*, 1932, **54**, 1603.

these two substrates. 1,3,5-Trimethylbenzene is rapidly sulphonated in concentrated aqueous sulphuric acid (72—78% H_2SO_4) but now, in contrast to the other two substrates, an equilibrium between the substrate and its sulphonic acid is obtained.[4] The apparently high rate of desulphonation of 1,3,5-trimethylbenzene-2-sulphonic acid may be explained in terms of relief of steric strain between the sulpho-group and the two adjacent methyl groups on forming the σ complex intermediate. The high rate of isomerization of 1,3-dimethylbenzene-2-sulphonic acid in concentrated sulphuric acid[5] may be explained in a similar fashion. Accordingly, it was thought of interest to learn whether the steric hindrance for sulphonation would give rise to a hydrogen kinetic isotope effect for the sulphonation of 1,3,5-trimethylbenzene (*cf.* ref. 6). Because of the high rate of hydrogen exchange in sulphuric acid, the isotope effect had, however, to be determined under aprotic sulphonation conditions.

RESULTS

Isomer Distributions.—Varying amounts of 1,2,3- or 1,2,4-trimethylbenzene were sulphonated at 25.0° with various concentrations of sulphuric acid. The isomer ratios of the resulting sulphonic acids (the only products) were found to depend on the amount of sulphonated substrate.[7] The isomer ratios under conditions of homogeneous sulphonation were obtained by graphical extrapolation to zero substrate conversion.[8] The results are in Table 1.

Kinetic Isotope Effect.—1,3,5-Trimethyl[2-^{2}H]benzene was sulphonated with SO_3 in both trichlorofluoromethane and nitromethane. The resulting sulphonic anhydride was subjected to mass spectrometric analysis. The kinetic isotope effects of hydrogen were calculated from the $(C_9H_{11}SO_2)_2O : C_9H_{11}SO_2OSO_2C_9H_{10}D : (C_9H_{10}DSO_2)_2O$ ratio. The results are in Table 2. The isotope composition of the starting and unchanged 1,3,5-trimethylbenzene is the same. This rules out the possibility of deuterium exchange of the substrate during sulphonation and work-up.

TABLE 1

Isomer distribution in the homogeneous sulphonation at 25.0°

H_2SO_4 (wt %) (±0.1)	1,2,3-$Me_3C_6H_4$ 4-SO_3H	1,2,3-$Me_3C_6H_4$ 5-SO_3H	1,2,4-$Me_3C_6H_3$ 5-SO_3H	1,2,4-$Me_3C_6H_3$ 6-SO_3H
	% (±1.0)		% (±2.0)	
74.0	86.2	13.8	87	13
77.8	86.0	14.0	89.7	10.3
80.0	86.3	13.7		
84.8			84.5	15.5
85.5	88.4	11.6		
90.4	89.2	10.8	78.8	21.2
95.8	90.2	9.8	75.2	24.8
98.5	91.3	8.7	77.2	22.8

TABLE 2

Hydrogen isotope effects in the reaction of 1,3,5-trimethyl[2-^{2}H]benzene with sulphur trioxide

Solvent	Temp. (°C)	Content 1,3,5-$(CH_3)_3C_6H_2D$ (%) Starting material	Content 1,3,5-$(CH_3)_3C_6H_2D$ (%) Unconverted substrate	k_H/k_D
CH_3NO_2	0	83.7		1.15 ± 0.13
CCl_3F	−35	84.5	84.4	0.98 ± 0.09

DISCUSSION

Sulphonation at low sulphuric acid concentration proceeds with $H_3SO_4^+$ as sulphonating entity and at high sulphuric acid concentration by $H_2S_2O_7$.[9] The former type of sulphonation has a ' later ' transition state and exhibits a larger degree of steric hindrance than the latter. In fact, with both 1,2,3- and 1,2,4-trimethylbenzene the degree of substitution at the most sterically hindered position does increase with increasing sulphuric acid concentration (Table 1).

The sulphuric acid concentration of change-over in mechanism from $H_3SO_4^+$ to $H_2S_2O_7$ as sulphonating entity depends both on the reactivity of the position to be sulphonated, and the steric hindrance for substitution at that position.[9] Thus, for the various positions of a given substrate the change-over in mechanism in general occurs at different sulphuric acid concentrations.[9] The acid concentration regions at which the various substitutions occur by one and the same sulphonation mechanism are those in between 95 and 98% H_2SO_4 and at acid concentrations <80% H_2SO_4. The isomer distributions for the two types of sulphonation are given in Table 3. The sulphonation of the trimethylbenzenes in the 95—98% H_2SO_4 region is so fast as to render the rate determinations, and thus the calculation of partial rate factors for the $H_2S_2O_7$ mechanism, impossible. The partial rate factors for the acid region below 80% H_2SO_4, *i.e.* for $H_3SO_4^+$ as sulphonating entity, were estimated from the data of Table 1 and from the rate studies of Kilpatrick[10] in combination with the study on *m*-xylene[11] on the assumption that the sulphonation rate ratios are the same at 25.0 and 12.3°. The results are in Table 3. The partial rate factors for the $H_3SO_4^+$ mechanism were also calculated on the assumption of additivity of substituent effects with the reported[12] partial rate factors of the methyl substituent. The partial rate factors for the xylenes[11] are listed for comparison.

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[5] A. Koeberg-Telder, A. J. Prinsen, and H. Cerfontain, *J. Chem. Soc.* (*B*), 1969, 1004.

[6] E. Baciocchi, G. Illuminati, G. Sleiter, and F. Stegel, *J. Amer. Chem. Soc.*, 1967, **89**, 125.

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[8] H. Cerfontain, Z. R. H. Nienhuis, and W. A. Zwart-Voorspuy, *J.C.S. Perkin II*, 1972, 2087.

[9] H. Cerfontain and C. W. F. Kort, *Internat. J. Sulfur Chem.* (*C*), 1971, **6**, 123.

[10] M. Kilpatrick and M. W. Meyer, *J. Phys. Chem.*, 1961, **65**, 530.

[11] A. J. Prinsen and H. Cerfontain, *Rec. Trav. chim.*, 1969, **88**, 833.

[12] C. W. F. Kort and H. Cerfontain, *Rec. Trav. chim.*, 1968, **87**, 24.

For the $H_3SO_4^+$ mechanism the observed partial rate factors of the methylbenzenes differ from the calculated ones. Most striking is the complete absence of the 3-sulphonic acid with 1,2,4-trimethylbenzene as substrate. It may be explained in terms of an enhanced steric hindrance as a result of an increasing buttressing effect, which mainly operates on forming the arenesulphonic acid from the preceding σ complex. Evidence supporting these steric explanations is first the observed higher overall enthalpy of activation for the sulphonation of 1,3,5-trimethylbenzene-2- compared with that of 1,3-dimethylbenzene-4-sulphonic acid,[13] secondly the observed substantial geometric deformations in the molecular structure of dipotassium 1,3,5-trimethylbenzene-2,6-disulphonate,[14] and thirdly the observation that the degree of 2-substitution of *m*-xylene is much lower than the calculated value (Table 3).

The deviation for 5-substitution of 1,2,4-trimethylbenzene cannot originate in a buttressing effect, and may be explained in terms of an 'earlier' transition state for the sulphonation of this position compared with the transition states for the sulphonation of toluene and benzene, for the stabilizing hyperconjugative effect of a methyl group will be less for a transition state which is nearer to the initial, *i.e.* the ground state.

TABLE 3

Sulphonation of di- and tri-methylbenzenes at 25.0°

		Partial rate factors $H_3SO_4^+$ mechanisms			Isomer distribution (%)			
					$H_3SO_4^+$ mechanism	$H_2S_2O_7$ mechanism		
Polymethylbenzene	Position	obs. (±25%)	calc. (±25%)	f_{obs}/f_{calc} (±50%)	obs.	obs.	calc.	Ref.
1,2,3-Trimethylbenzene	4	18 700	367 000		86 ± 1	90 ± 1	96.1	
	5	6 100	37 000		14 ± 1	10 ± 1	3.9	
1,2,4-Trimethylbenzene	3	0	33 000	0	⩽2	⩽2	35.8	
	5	21 000	367 000		90 ± 2	75 ± 2	61.3	
	6	2 500	3 400		10 ± 2	25 ± 2	2.9	
o-Xylene	3	140	480	0.29	6.5 ± 0.9	45.1 ± 0.4	43.3	11
	4	2 000	5 300	0.38	93.5 ± 0.9	54.9 ± 0.4	56.7	
m-Xylene	2	120	4 800	0.025	0.5 ± 0.2	14.5 ± 0.6	36.5	11
	4	13 000	52 000	0.25	98.9 ± 0.4	84.3 ± 0.6	63.2	
	5	160	50	3.2	0.6 ± 0.2	1.2 ± 0.2	0.3	
p-Xylene	2	100	480	2.3	100	100	100	11

As for the $H_2S_2O_7$ mechanism, the f_5/f_6 ratio of 1,2,4-trimethylbenzene also deserved some comment, as the observed value (3.0) is substantially smaller than the calculated one based on the partial rate factors of the methyl group (21.2), but about the same as the one calculated for adding a methyl to *m*-xylene (2.66).* The observed f_4 for *m*-xylene for the $H_2S_2O_7$ sulphonation mechanism is *ca.* 13 times smaller than the calculated value.[11] The deviation between the observed and calculated f_5/f_6 ratio is therefore ascribed to f_5, *i.e.* the calculated f_5 is larger than the observed. This may be explained in terms of an 'earlier' transition state for the sulphonation of the 5-position, compared with those of benzene and toluene, as was also proposed to explain the deviation in the observed and calculated f_4 values for *m*-xylene.[11]

Evidence in favour of this explanation comes from the activation parameter differences for the $H_2S_2O_7$ mechanism. With toluene $\Delta H_o^‡ - \Delta H_p^‡ = -1.3 \pm 0.1$ kcal mol^{-1} and $\Delta S_o^‡ - \Delta S_p^‡ = -4.9 \pm 0.4$ cal K^{-1} mol^{-1}, whereas for *o*-xylene $\Delta H_3^‡ - \Delta H_4^‡ = -0.1 \pm 0.2$ kcal mol^{-1} and $\Delta S_3^‡ - \Delta S_4^‡ = -0.6 \pm 0.6$ cal K^{-1} mol^{-1}.[11] This illustrates that the electrostatically stabilizing–sterically destabilizing proximity effect between the methyl and sulpho group in the 2-methyl-1-sulphoarenium σ complex is very much less for sulphonation of the 3-position of *o*-xylene, compared with the *ortho*-position of toluene. This then implies an 'earlier' transition state for the former substitution. It is to be expected (*cf.* the data for the $H_3SO_4^+$ mechanism) that f_5 of 1,2,4-trimethylbenzene will be greater than f_3 of *o*-xylene. Accordingly, the non-additivity of substituent effects for the calculation of f_5 of 1,2,4-trimethylbenzene is ascribed to an 'earlier' transition state for this substitution compared with those of toluene and benzene.

The absence of a primary hydrogen kinetic isotope effect in the sulphonation of 1,3,5-trimethylbenzene with sulphur trioxide both in nitromethane and in trichlorofluoromethane (Table 2) is as was observed for benzene.[15] It may be explained in a similar way,[15] and illustrates that the presence of two *o*-methyl groups still does not make the conversion of the arenium pyrosulphonate σ complex intermediate into the arenepyrosulphonic acid a rate-limiting step in the sulphonation sequence.

EXPERIMENTAL

Materials.—The trimethylbenzenes were commercial AnalaR grade products. 1,3,5-Trimethyl[2-^{2}H]benzene was obtained by dropwise addition of purified 2-bromo-1,3,5-trimethylbenzene (25 g) to a solution of butyl-lithium (35 g of a 20—25% solution in hexane; Fluka) in ether (75 ml) at −7°. The mixture was stirred overnight at room temperature. It was then hydrolysed by adding deuterium

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* For 1,2,4-trimethylbenzene $f_3 : f_5 : f_6 = {}^{Me}f_m{}^{\cdot m-x}f_2 : {}^{Me}f_m{}^{\cdot m-x}f_4 : {}^{Me}f_o{}^{\cdot m-x}f_5$, based on adding a methyl to *m*-xylene at position 4.

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[14] M. A. M. Meester and H. Schenk, *Rec. Trav. chim.*, 1972, **91**, 213.

[15] J. K. Bosscher and H. Cerfontain, *J. Chem. Soc.* (*B*), 1968, 1524.

oxide (15 ml) dropwise over 1 h. After extraction with ether, the mesitylene (6.5 g) was distilled and purified by preparative g.l.c. (2 m × 0.25 in. 20% polyethylene glycol 2 000 on Kieselguhr; 120°; He flow rate 150 ml min^{-1}). The preparations of potassium 1,2,3-trimethylbenzene-4- and -5-, and 1,2,4-trimethylbenzene-5-sulphonate and that of 1,2,3-trimethylbenzene-4,6-disulphonic acid have been described.[13,16]

Sulphuric Acid Sulphonation Procedure and N.m.r. Analysis.—The sulphonation of aromatic hydrocarbons has been described.[17] The isomer distributions were determined by multicomponent ^{1}H n.m.r. analysis [7a,18] of the aromatic hydrogen absorptions using a Varian HA 100 n.m.r. spectrometer. For 1,2,3-trimethylbenzene the n.m.r. spectra of the sulphonation mixtures exhibit δ 7.48 and 6.92 (AB, J 8 Hz) and 7.33 (s), and at acid concentrations $>90\%$ H_2SO_4 a small ingrowing absorption at δ 8.35. After the spectra had been compared with those of authentic samples, these absorptions were assigned to the 4-, 5-, and 4,6-disulphonic acid respectively. For 1,2,4-trimethylbenzene, the n.m.r. sulphonation mixture exhibits two sets of singlets of equal intensity, δ 7.62 and 7.10 and 7.56 and 7.26. By comparison with the spectra of an authentic sample the former set was assigned to the 5-sulphonic acid, the latter to the corresponding 6-sulphonic acid. The absence of the 3-sulphonic acid which would exhibit its aromatic hydrogen absorption at δ 7.05—7.30 was concluded from the observation that the sum of the absorptions at δ 7.62 and 7.56 was always equal within experimental error to the sum of those at δ 7.26 and 7.10.

Sulphur Trioxide Sulphonation Procedures and Deuterium Analyses.—To 1,3,5-trimethyl[2-^{2}H]benzene (1 g) in nitromethane (25 ml) was added at 0° with stirring over 15 min a solution of SO_3 (0.3 ml) in nitromethane (25 ml). After an additional stirring for 15 min, the precipitated sulphonic anhydride, $\nu_{\text{max.}}$ 1 390, 1 375, 1 190, 1 170, 730, 715, and 655 cm^{-1},[19] was filtered off and washed with ether. No 1,3,5-trimethylbenzene could be recovered.

To 1,3,5-trimethyl[2-^{2}H]benzene (1 g) in CCl_3F (50 ml) was added at $-35°$ with stirring over 15 min a solution of SO_3 (0.3 ml) in trichlorofluoromethane (75 ml). A precipitate was formed and the mixture left stirring for another 5 min. Then the reaction was quenched with an aqueous sodium hydrogen carbonate solution. The precipitated sulphonic anhydride was filtered off and washed with cold trichlorofluoromethane. The aqueous layer of the filtrate was extracted with trichlorofluoromethane and the combined trichlorofluoromethane extracts evaporated to obtain the unconverted substrate.

The isotope composition of both the substrate and the sulphonic anhydrides obtained from it were determined with AEI MS-9 and Varian 711 MAT mass spectrometers. The accelerating voltage of the bombarding electrons for the analysis of 1,3,5-trimethylbenzene and the sulphonic anhydrides was 13 eV (at which energy there is no $M - 1$ peak), and 30 eV (at which energy there is no fragmentation) respectively. Owing to its low vapour pressure, the anhydride had to be analysed from the probe at 150°.

The isotope composition of the anhydride was determined from the ratio m/e 382 $[(C_9H_{11}SO_2)_2O]$: 383 $(C_9H_{11}SO_2OSO_2C_9H_{10}D)$: 384 $[(C_9H_{10}DSO_2)_2O]$. The kinetic isotope effect was calculated from this ratio on the assumption that the formation of the anhydride proceeds with equal probability for the deuteriated and non-deuteriated (pyro)-sulphonic acid. The degree of monodeuteriated (pyro)-sulphonic acid was calculated from equation (1). Subsequently, the sulphonation kinetic isotope effect was calculated from equation (2).

$$(C_9H_{11}SO_2)_2O : C_9H_{11}SO_2OSO_2C_9H_{10}D : (C_9H_{10}DSO_2)_2O = (1 - x)^2 : 2(1 - x)x : x^2 \quad (1)$$

$$C_9H_{11}SO_2O(SO_3)D : C_9H_{10}DSO_2O(SO_3)H = (1 - x) : x = (k_D|C_9H_{11}D| + 2k_H|C_9H_{12}|)/2k_H|C_9H_{11}D| \quad (2)$$

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