1252. *The Rate of Displacement of Toluene*-p-*sulphonate Relative to Bromide Ion. A New Mechanistic Criterion*

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The rate of nucleophilic displacement of toluene-*p*-sulphonate has been studied for a series of compounds and compared with the displacement rate of bromide ion as a standard. The ratio k_{OTs}/k_{Br} is small (large), if the nucleophile is powerful (weak) and the substrate has a poor (strong) ionisation tendency; it varies from 0·36 to 5000, corresponding to a continuous spectrum of transition states. Two extreme regions are shown to exist: (i) substitutions for which the ratio k_{OTs}/k_{Br} is less than unity, (ii) substitutions and $E1$ reactions for which the ratio is of the order of 10^3 and greater. In (i), the condition $k_{OTs}/k_{Br} < 1$ can be fulfilled for nucleophiles such as thiolate ions in various solvents, for halide ions in aprotic media, and for other reactions including eliminations which involve strong bond-making (or $E1cb$ character) in the transition state. The substrate is usually a methyl or a primary alkyl derivative with little tendency towards ionisation. In (ii), k_{OTs}/k_{Br} is very large for substrates that are easily ionised. Other S_N1, $E1$, and solvolytic reactions, and most reactions involving secondary alkyl substrates, give ratios which may be smaller than 10^3, but are usually greater than unity.

It is shown that the main cause for the versatility of toluene-*p*-sulphonate as a leaving group is delocalisation of negative charge over this group in the transition state. Solvation and/or steric factors may enter, but are less important than has been hitherto assumed. As a consequence, for the the reactions discussed in this Paper, the k_{OTs}/k_{Br} ratio depends largely on the degree of charge separation between carbon and the leaving group in the transition state; large ratios indicate very ionic transition states and *vice versa*. Delocalisations of charge in the transition state is encountered in many leaving groups including other anions derived from oxy-acids. Even chloride, bromide, and iodide can become very selective, provided that charge separation in the transition state is advanced, and disturbances from hydrogen-bonding are eliminated.

IN the preceding Paper [1] a number of unstable toluene-*p*-sulphonates were prepared and identified. In order to gain some quantitative measure of their reactivity, various

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[1] H. M. R. Hoffmann, preceding Paper.

displacement reactions of these esters have been studied and their rates compared (in Table 1) with those of the corresponding bromides.*

TABLE 1

Rates and k_{OTs}/k_{Br} ratios for the reactions

$$\text{(A) MeCHPh·X} \xrightarrow[\text{MeCN}]{E1} \text{CH}_2\text{=CHPh} + \text{HX}$$

$$\text{(B) MeCHPh·X} + \text{EtOH} \longrightarrow \text{Me·CHPh·OEt} + \text{HX}$$

$$\text{(C) Bu}^t\text{X} \xrightarrow[\text{MeCN}]{E1} \text{Me}_2\text{C=CH}_2 + \text{HX (X = OTs or Br)}$$

	10^5k_{OTs} (sec.$^{-1}$)		10^7k_{Br} (sec.$^{-1}$)		k_{OTs}/k_{Br}	
	0°	50°	0°	50°	0°	50°
(A)	0·0681	45·6	0·0146	10·6	466	430
(B)	45·1	9840	1·99 [a]	1162 [a]	2270	845
(C)	18·5	4227 [b]	0·361	253	5126	1670

[a] Ref. 2. [b] Extrapolated from data at lower temperature (ref. 1).

Clearly, the ratio k_{OTs}/k_{Br} is remarkably large for these two systems, irrespective of a possible temperature dependence. Qualitatively, we find a similarly high ratio for the diphenylmethyl system. Not only tertiary and secondary, but even primary toluene-*p*-sulphonates can be unstable relative to their bromides provided they are derived from an alkyl residue stabilised by mesomerism. Whereas, *e.g.*, *p*-methylbenzyl bromide can be kept indefinitely at room temperature, the corresponding toluene-*p*-sulphonate starts to decompose visibly after 2 hours under these conditions;[1] and *p*-methoxybenzyl toluene-*p*-sulphonate is a remarkably unstable compound.[1]

TABLE 2

Rates and k_{OTs}/k_{Br} ratios for the displacements

$$p\text{-CH}_3\text{C}_6\text{H}_4\text{S}^- + \text{R–X} \xrightarrow{S_N2} p\text{-CH}_3\text{C}_6\text{H}_4\text{SR} + \text{X}^- \text{ (X = OTs, Br)}$$

			10^3k_2 (l. mole^{-1} sec.$^{-1}$)		
R	Solvent (% in v/v)	Temp.	k_{OTs}	k_{Br}	k_{OTs}/k_{Br}
Me	EtOH	0°	52·0	144	0·36
Et	EtOH	0	6·25	15·7	0·40
Et	50% aq.EtOH	24·9	1·67	4·27	0·39 [a]
Pr^n	EtOH	24·9	8·56	19·4	0·44
Bu^n	92·4% aq.EtOH	25·1	8·47	17·5	0·48 [a, b]
n-C_8H_{17}	EtOH	24·9	11·6	18·5	0·63
n-$C_{12}H_{25}$	EtOH	24·9	11·1	19·3	0·58
n-$C_{16}H_{33}$	EtOH	24·9	18·3	19·0	0·96
p-$NO_2C_6H_4CH_2$	40% $HCOMe_2$ in EtOH	−30	340	880	*ca.* 0·39
Bu^s	92·4% aq.EtOH	25·1	1·55	0·682	2·3 [a, b]

[a] Sodium thiophenoxide used as nucleophilic reagent; k_{OTs} and k_{Br} are apparent rate constants disregarding the equilibrium $\text{ArSNa} + \text{H}_2\text{O} \rightleftharpoons \text{ArSH} + \text{NaOH}$. The true rate constants are probably greater, but the ratio k_{OTs}/k_{Br} remains unaffected. [b] Ref. 4.

This reactivity of toluene-*p*-sulphonates derived from alkyl groups stabilised by mesomerism stands in striking contrast to the behaviour of some simple primary esters in displacements by thiolate ions (Table 2).

In addition to their low k_{OTs}/k_{Br} ratios, a second interesting feature of these substitutions

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* Reversible ionisation and dissociation, which might obscure the ionisation tendency, is insignificant for the 1-phenylethyl system in ethanol[3] and acetonitrile. For 1-phenylethyl bromide the unimolecular rate of racemisation in acetonitrile at 59·8° is $k_1^* = 6{\cdot}4 \times 10^{-6}$ sec.$^{-1}$ (from initial rates using the equation $\ln \alpha_0/\alpha_t = 2k_1^*t$). The unimolecular rate of elimination under identical conditions has $k_1 = 3{\cdot}16 \times 10^{-6}$ sec.$^{-1}$.

[2] A. H. Fainberg and S. Winstein, *J. Amer. Chem. Soc.*, 1957, **79**, 1602.

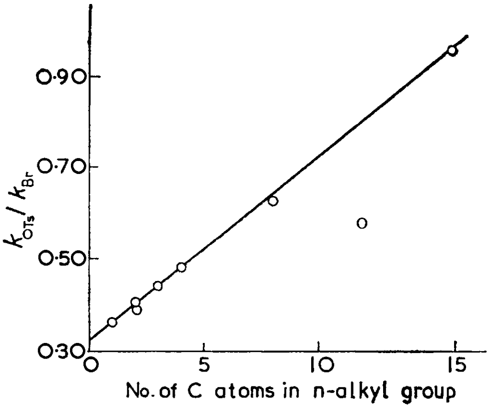
[3] S. Winstein, A. H. Fainberg, and E. Grunwald, *J. Amer. Chem. Soc.*, 1957, **79**, 4151.

[4] (*a*) E. L. Eliel and R. G. Haber, *J. Amer. Chem. Soc.*, 1959, **81**, 1249; (*b*) E. L. Eliel and R. S. Ro, *ibid.*, 1957, **79**, 5995.

is the linear increase in the ratio as the alkyl chain lengthens * (Figure). In contrast, the absolute rates of substitution first decrease considerably and then stay practically constant.

Small k_{OTs}/k_{Br} ratios are not found only for these S_N2 reactions. Table 3 represents an attempt to correlate an elimination for which the low reactivity of toluene-*p*-sulphonate has been first observed,[5,25] with a substitution by comparing the sensitivity of the rates to a change in leaving group. Apart from reaction (C) in Table 3 there is evidence, as shown by Bishop and DePuy,[7] that other Finkelstein reactions (or more generally, displacements on simple primary alkyl compounds in aprotic solvents) may involve k_{OTs}/k_{Br} ratios below unity (Tables 3 and 4).

k_{OTs}/k_{Br} ratios for thiolate displacements on n-alkyl substrates, as a function of chain-length



Although these ratios are only approximate, because the data were obtained by different workers under different conditions, the mean value 0·4 of the ratio for primary substrates is close to the values for comparable reactions in Tables 2 and 3.

TABLE 3

Relative rates and k_{OTs}/k_{Br} ratios for the reactions

$$\text{(A)}\quad \text{EtO}^- + \text{Ph}\cdot\text{CH}_2\cdot\text{CH}_2\text{X} \xrightarrow[\text{EtOH}]{E2} \text{Ph}\cdot\text{CH}{=}\text{CH}_2 + \text{X}^- + \text{EtOH}$$

$$\text{(B)}\quad p\text{-CH}_3\cdot\text{C}_6\text{H}_4\cdot\text{S}^- + \text{Pr}^n\text{X} \xrightarrow[\text{EtOH}]{S_N2} p\text{-CH}_3\cdot\text{C}_6\text{H}_4\cdot\text{SPr}^n + \text{X}^-$$

$$\text{(C)}\quad \text{Cl}^- + \text{MeX} \xrightarrow[\text{Me}_2\text{CO}]{S_N2} \text{MeCl} + \text{X}^- \quad (\text{X} = \text{Cl, Br, I, or OTs})$$

Reaction	Temp.	I	Br	OTs	Cl	k_{OTs}/k_{Br}
Rel. k_2 (A)[a]	30°	380	60	5·8	1	0·10
(B)	24·9	473	136	60	1	0·44
(C)	25·0	3400[b]	425[b]	180[c]	1[b]	0·42

[a] Ref. 5. [b] Ref. 6. [c] $k_{obs.} = 6{\cdot}7 \times 10^{-3}$ l. mole^{-1} sec.$^{-1}$ using 0·0239M-LiCl. After correction for ion-pairing, $k_2 = 0{\cdot}247$ l. mole^{-1} sec.$^{-1}$ (cf. ref. 6).

With a change from thiolate to alkoxide or hydroxide ion as the nucleophilic reagent, the k_{OTs}/k_{Br} ratio increases, usually above unity (Table 5).

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* The n-dodecyl compounds are an exception.

[5] C. H. DePuy and D. H. Froemsdorf, *J. Amer. Chem. Soc.*, 1957, **79**, 3710; cf. W. H. Saunders and D. H. Edison, *ibid.*, 1960, **82**, 138.

[6] A. J. Parker, *J.*, 1961, 1328.

[7] C. A. Bishop and C. H. DePuy, *Chem. and Ind.*, 1959, 297.

Table 4

Approximate $k_{\text{OTs}}/k_{\text{Br}}$ ratios for Finkelstein displacements in acetone

$$N^- + RX \longrightarrow RN + X^- \quad (X = OTs, Br;\ N = Br, I)$$

N^-	R	Temp.	$k_{\text{OTs}}/k_{\text{Br}}$	Ref.
Br^-	Bu^n	25°	1 [a]	8, 9
I^-	Bu^n	25	0·3 [b]	8, 11
I^-	Pr^n	40	0·2	7, 12
I^-	Bu^i	40°	0·2	7, 12
I^-	Pr^i	40	1·4	7, 12
Br^-	MeCHPh	25	4	This work and 13

[a] Assuming $k_{\text{OBs}}/k_{\text{OTs}} = 3$. [b] From $\alpha = 0{\cdot}52$ for 0·02M-KI in acetone (ref. 10).

Table 5

$k_{\text{OTs}}/k_{\text{Br}}$ ratios for displacements by alkoxide and hydroxide ions

$$N^- + RX \longrightarrow RN + X^- \quad (X = OTs, Br;\ N^- = EtO^-, HO^-)$$

N^-	R	Solvent	Temp.	$k_{\text{OTs}}/k_{\text{Br}}$	Ref.
EtO^-	p-$NO_2C_6H_4CH_2$	50% v/v $HCOMe_2$ in EtOH	0°	*ca.* 0·56	This work
EtO^-	Me	EtOH	25	5·4 [a]	This work
HO^-	Me	H_2O	25	6·3 [b]	14
EtO^-	Et	EtOH	25	5·8 [b]	14
EtO^-	Et	EtOH	55	3·7	15, 16

[a] $k_2 = 1{\cdot}39 \times 10^{-3}$ l. mole^{-1} sec.$^{-1}$ for the displacement of bromide ion. [b] $k_{\text{O·SO}_2\text{·Ph}}/k_{\text{Br}}$ ratio.

Discussion

The observed variation of the $k_{\text{OTs}}/k_{\text{Br}}$ ratio from 0·36 (for the thiolate displacement on the methyl compounds) to 5000 (for the *E*1 reaction of the t-butyl compounds) demonstrates the flexible response of toluene-*p*-sulphonate to the reaction conditions. As has been pointed out before,[7] toluene-*p*-sulphonate can no longer be automatically regarded as a better leaving group than iodide or even bromide ion. It is important that toluene-*p*-sulphonate can be less reactive than bromide and hitherto, only few isolated examples for $k_{\text{OTs}}/k_{\text{Br}}$ ratios below unity for substitutions were known.[4,7] On the other hand the high reactivity of toluene-*p*-sulphonates in solvolytic displacements* is familiar[14] and has been explained mainly on two grounds.

(i) Toluene-*p*-sulphonate has been regarded by various authors as a well-solvated group, since it contains oxygen atoms which should be capable of hydrogen bonding. Acid catalysis has been observed for a number of reactions[17,18] including the unimolecular elimination of t-butyl toluene-*p*-sulphonate in acetonitrile[1] and for the degree of hydrogen bonding, the order F $\gg$ OTs $>$ Cl $>$ Br $>$ I has been given.[3]

(ii) Toluene-*p*-sulphonate has been regarded as sufficiently bulky to cause nonbonded repulsion in the ground state of certain molecules, and a steric acceleration has been envisaged as an alternative to a non-classical acceleration for a number of solvolyses.[19]

We now show that these two factors cannot satisfactorily explain our results.

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* However, cf. the ratio for "slow" S_N1 reactions, *e.g.*, $k_{\text{OTs}}/k_{\text{Br}} = 4{\cdot}0$ for the aqueous hydrolysis of the neopentyl derivatives (following Paper).

[8] S. Winstein, L. G. Savedoff, S. Smith, I. D. R. Stephens, and J. S. Gall, *Tetrahedron Letters*, 1960, no. 9, 24.

[9] C. C. Evans and S. Sugden, *J.*, 1949, 270.

[10] J. F. J. Dippy and S. R. C. Hughes, *J.*, 1954, 953.

[11] P. D. Bartlett and L. J. Rosen, *J. Amer. Chem. Soc.*, 1942, **64**, 543.

[12] L. Fowden, E. D. Hughes, and C. K. Ingold, *J.*, 1955, 3187.

[13] E. D. Hughes, F. Juliusburger, A. D. Scott, B. Topley, and J. Weiss, *J.*, 1936, 1173.

[14] A. Streitwieser, *Chem. Rev.*, 1956, **56**, 571.

[15] M. S. Morgan and L. H. Cretcher, *J. Amer. Chem. Soc.*, 1948, **70**, 375.

[16] M. L. Dhar, E. D. Hughes, and C. K. Ingold, *J.*, 1948, 2055.

[17] V. Ioan, D. Săndulescu, S. Tìteica, and C. D. Nenitzescu, *Tetrahedron*, 1963, **19**, 323.

[18] S. G. Smith, A. H. Fainberg, and S. Winstein, *J. Amer. Chem. Soc.*, 1961, **83**, 618.

[19] H. C. Brown, "The Transition State," *Chem. Soc. Special Publ.*, No. 16, 1962, p. 140.

Concerning Factor (i).—It is interesting that the heat of hydration of the benzenesulphonate ion, as estimated by an empirical relationship, is smaller[20] than that of the iodide ion. Although we do not know the entropy of hydration of benzenesulphonate, we do know that most ionic entropies are negative and lie in the range[21] of −10 to −100 e.u. Assuming $\Delta S^\circ = 0$, we obtain $\Delta G^\circ = -56{\cdot}4$ kcal./g.-ion. One might contend now that, at least for water as the solvent, it is necessary to distinguish between hydration of the entire benzenesulphonate anion and more specific hydrogen bonding to oxygen atoms of this anion, since the comparatively large benzene molecule requires energy for dissolution in water. We have therefore calculated ΔG_1° for the change:

TABLE 6

Free energies and heats of hydration of halides[a] and benzenesulphonate[b] at 25°

	F^-	Cl^-	Br^-	I^-	$C_6H_5SO_3^-$
$-\Delta H^\circ$ (kcal./g.-ion)	122·6	88·7	81·4	72·1	56·4
$-\Delta G^\circ$,, ...	113·9	84·2	77·8	70·0	56·4[c]

[a] Ref. 21. Standard states of 1 mole/l. for gaseous ions and hypothetical molal solution for aqueous ions. [b] Ref. 20. [c] Assuming $\Delta S^\circ = 0$.

$$\text{Benzene vapour (1 mole/l. hypothetical)} \longrightarrow \text{solution of benzene in water (1 molal, hypothetical)} \quad (1)$$

using the same standard states as those chosen for the halide ions in Table 6 and the data of Alexander.[22] From the value $\Delta G_1^\circ = 10{\cdot}7$ kcal./mole (equation 1) the free energy of hydration of the hydrophilic part of benzenesulphonate is *ca.* −67 kcal./mole (standard states as in Table 6). Irrespective of the accuracy of this estimate it appears that the hydration (and solvation) of sulphonate ion is energetically less favoured than has been hitherto assumed.

Hydrogen bonding or solvation of toluene-*p*-sulphonate cannot explain the high $k_{\text{OTs}}/k_{\text{Br}}$ ratios in acetonitrile, an aprotic solvent (cf. Table 1). Moreover, diphenylmethyl, *p*-methylbenzyl, and *p*-methoxybenzyl toluene-*p*-sulphonate are generally unstable relative to their bromides. These arguments, of course, do not rule out hydrogen bonding in other cases and acid catalysis is definitely observable; but the question remains *how* important it is in determining the general pattern of reactivity as set out in Tables 1—5. It would appear that most examples of acid catalysis involve "fast" S_N1 reactions of easily ionisable substrates, in which toluene-*p*-sulphonate is the best leaving group anyway.

Concerning Factor (ii).—So far, the experimental evidence for a steric acceleration in toluene-*p*-sulphonate displacements is scarce. For the solvolysis of cyclohexyl derivatives in which toluene-*p*-sulphonate is severely crowded by a 1,3-diaxial interaction with an alkyl group, an acceleration by a factor of 14 is possible, as has been recently shown by Grob and his co-workers.[23] Thus, for most other secondary toluene-*p*-sulphonates relief of steric strain appears to be comparatively unimportant. Even for t-butyl toluene-*p*-sulphonate it is difficult to decide how much of the enhanced rate relative to 1-phenylethyl toluene-*p*-sulphonate is due to nonbonded repulsion in the former molecule, since t-butyl bromide eliminates faster in acetonitrile than does 1-phenylethyl bromide. This is a factor (see below) expected to increase the $k_{\text{OTs}}/k_{\text{Br}}$ ratio for t-butyl. Moreover the ratio is dependent upon the temperature, increasing (decreasing) with decreasing (increasing) temperature. Eliel and Gerber[24] concluded that, at least for S_N2 reactions, there is neither steric inhibition nor acceleration if the departing toluene-*p*-sulphonate (but not the incoming nucleophile) is crowded by alkyl groups. Most significantly, even primary esters such as *p*-methylbenzyl and *p*-methoxybenzyl toluene-*p*-sulphonate

[20] D. F. C. Morris, *Tetrahedron*, 1958, **4**, 423.
[21] R. A. Robinson and R. H. Stokes, "Electrolyte Solutions," Butterworths, London, 1955, p. 69.
[22] D. M. Alexander, *J. Phys. Chem.*, 1959, **63**, 1021.
[23] C. A. Grob, W. Schwarz, and H. P. Fischer, *Helv. Chim. Acta*, 1964, **47**, 1385.
[24] E. L. Eliel and R. P. Gerber, *Tetrahedron Letters*, 1961, no. 14, 473.

are extremely unstable, whereas the *p*-nitrobenzyl ester is comparatively unreactive (cf. following Paper).

The key to an understanding of the properties of toluene-*p*-sulphonate is provided by the high $k_{\mathrm{OTs}}/k_{\mathrm{Br}}$ ratios observed, *e.g.*, for the unstable esters of Table 1 and the low reactivity in, *e.g.*, the thiolate displacements (Table 2). For the latter reactions the $k_{\mathrm{OTs}}/k_{\mathrm{Br}}$ ratio is below unity if the leaving group is attached to a simple primary carbon atom; for the methyl system in particular, $k_{\mathrm{OTs}}/k_{\mathrm{Br}} = 0{\cdot}36$, this being the smallest value which we have so far observed in a substitution; apparently, the *p*-nitrobenzyl compounds do not give a lower ratio. Since $k_{\mathrm{OTs}}/k_{\mathrm{Br}} < 1$, k_{OTs} can be less sensitive to a change in alkyl structure than k_{Br} for these displacements. This is shown, *e.g.*, by the ratio $k_{\mathrm{MeBr}}/k_{\mathrm{EtBr}} = 9{\cdot}2$ and, on the other hand $k_{\mathrm{MeOTs}}/k_{\mathrm{EtOTs}} = 8{\cdot}3$. The linear increase (cf. the Figure) is remarkable and might suggest a solvation effect, but this merits further investigation.

The dramatic rise in the recorded $k_{\mathrm{OTs}}/k_{\mathrm{Br}}$ ratios to values above 1000 and the fall to ratios below unity must arise from a delocalisation of negative charge over toluene-*p*-sulphonate in the transition state.* Therefore, the more the charge is separated between carbon and the leaving group in the transition state, the more can toluene-*p*-sulphonate run ahead of bromide ion as a leaving group. A delocalisation of charge over toluene-*p*-sulphonate (and other anions derived from oxy-acids) is feasible from a consideration of spectra, as well. Common arenesulphonic esters $\mathrm{RO{\cdot}SO_2Ar}$ show the characteristic symmetric and antisymmetric stretching frequencies of the sulphur–oxygen bonds (cf. ref. 26), $\nu_{\mathrm{SO_2}}$ (sym) = 1165—1185 and $\nu_{\mathrm{SO_2}}$ (asym) = 1350—1375 cm.$^{-1}$. On replacing R by a more electron-releasing group, a slight shift of $\nu_{\mathrm{SO_2}}$ (sym) and a corresponding shift of $\nu_{\mathrm{SO_2}}$ (asym) to lower frequency is observed, which has been attributed to the decreasing double-bond character of the sulphur–oxygen bonds. For the toluene-*p*-sulphonate ion, however, the S–O bands are reduced to 1030 and 1240 cm.$^{-1}$, respectively. This frequency shift is much larger than that observed for any neutral molecule $\mathrm{RP{\cdot}SO_2Ar}$, and is consistent with the comparatively weak double-bond character of these bonds in the free anion and some delocalisation of charge over the benzene ring.†

It is instructive to restate the argument by expressing the $k_{\mathrm{OTs}}/k_{\mathrm{Br}}$ ratio in thermodynamic terms.[29] The free energy of activation $\Delta F^{\ddagger}$ for the substitution

$$\mathrm{N^- + R - X \longrightarrow R - N + X^-} \qquad (2)$$

is essentially the sum of three terms:

$$\Delta F^{\ddagger} = \Delta F_{\mathrm{v}} + \Delta F_{\mathrm{g}}^{\ddagger} + \Delta F_{\mathrm{s}}^{\ddagger} \qquad (3)$$

as can be seen from the free-energy cycle Scheme 1.

The free-energy charge for the escape of the reactants from solution into the gas-phase, ΔF_{v}, is made up predominantly by the large positive free-energy contribution for sloughing off the solvation shell from the anion (cf. Table 6) and to a lesser extent, by

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* DePuy and Bishop [25] clearly deserve credit for having first put forward the suggestion that "it may be possible, in carefully controlled cases, to use bromide–toluene-*p*-sulphonate rate ratios as a measure of bond-breaking in the transition state."

† In an interesting investigation Foote [27] and Schleyer [28] have recently shown that the rates of acetolysis of a number of secondary arenesulphonates ($\mathrm{RR'CH{\cdot}O{\cdot}SO_2Ar}$) can be quantitatively correlated with the infrared stretching frequencies of the corresponding ketones (RCOR′), increasing rates corresponding to decreasing CO frequencies. For a number of reactive esters the acetolysis rates were actually *faster* than predicted by the relationship, and it might be that, in addition to the factors discussed by these authors,[27,28] an enhanced spread of charge over the leaving group in the transition state can contribute to the observed deviations. This point can be illustrated as well by the data of A. K. Colter and R. D. Johnson (*J. Amer. Chem. Soc.*, 1962, **84**, 3289) on the ethanolysis of substituted 2-pentyl arenesulphonates. These authors find that a Hammett ρ–σ plot shows a marked curvature which we want to ascribe mainly to different degrees of charge spreading over the quasi-anion in the transition state.

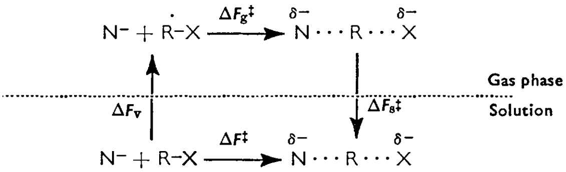
[25] C. H. DePuy and C. A. Bishop, *J. Amer. Chem. Soc.*, 1960, **82**, 2532.

[26] E. A. Robinson, *Canad. J. Chem.*, 1961, **39**, 247.

[27] C. S. Foote, *J. Amer. Chem. Soc.*, 1964, **86**, 1853.

[28] P. von R. Schleyer, *J. Amer. Chem. Soc.*, 1964, **86**, (*a*) p. 1854; (*b*) p. 2722.

[29] R. E. Robertson, R. L. Heppolette, and J. M. W. Scott, *Canad. J. Chem.*, 1959, **37**, 803.



Scheme 1

the desolvation and vaporisation energy of the neutral molecule RX$\cdot\Delta F_g^\ddagger$ is the free-energy change for the formation of the transition state complex from the reactants in the gas phase. $\Delta F_s^\ddagger$ represents the (usually negative) free-energy contribution arising from the solvation of the transition-state complex.

Now, applying the absolute rate equation to the displacement of toluene-*p*-sulphonate and bromide gives

$$\Delta F_{\mathrm{Br}}^\ddagger - \Delta F_{\mathrm{OTs}}^\ddagger = 2{\cdot}303\, \boldsymbol{R}T \log (k_{\mathrm{OTs}}/k_{\mathrm{Br}}) \qquad (4)$$

$$= \Delta\Delta F_v + \Delta\Delta F_g^\ddagger + \Delta\Delta F_s^\ddagger \qquad (5)$$

The success of the $k_{\mathrm{OTs}}/k_{\mathrm{Br}}$ ratio as a mechanistic criterion for reactions (2) suggests that initial- and transition-state solvation differences (expressed by $\Delta\Delta F_v$ and $\Delta\Delta F_s^\ddagger$) make only a minor and approximately constant contribution to equation (5), which therefore must be dominated by changes in the value for $\Delta\Delta F_g^\ddagger$; $\Delta\Delta F_g^\ddagger$ and thus the $k_{\mathrm{OTs}}/k_{\mathrm{Br}}$ ratio must be extremely sensitive to charge-separation between carbon and the leaving group in the transition state. A closer look at more $k_{\mathrm{OTs}}/k_{\mathrm{Br}}$ ratios in the light of nucleophilic reactivities provides additional evidence. All the reactions in Table 2 involve strong bond-making in the transition state, since their rates are all fast and thiolate ions are one of the strongest nucleophiles towards saturated carbon available at present.[30] The low $k_{\mathrm{OTs}}/k_{\mathrm{Br}}$ ratios in Finkelstein reactions (Tables 3 and 4) can be best ascribed to the dipolar aprotic solvent which, on the one hand, does not solvate a leaving group appreciably but, more important, can make good nucleophiles, largely by reducing the contribution of ΔF_v to the right-hand side of equation (3); Parker [6,31] has shown that small anions such as F^-, Cl^-, and CN^- in particular can be up to 10^7 times more reactive towards saturated carbon if the solvent is changed from a protic to a dipolar aprotic one. The increase in the ratio on changing from thiolate to alkoxide or hydroxide ion as the nucleophile (Table 5) is consistent with the fact that alkoxide ions are less reactive, usually by a factor of 100—1000, than thiolate ions in displacements towards saturated carbon.[32] With a change to a secondary alkyl compound the ratio appears to increase generally above unity, even for thiolate as the nucleophilic reagent.

The very low value of $k_{\mathrm{OTs}}/k_{\mathrm{Br}}$ (0·1) for the elimination of the phenethyl compounds (Reaction A, Table 3) is without precedent in substitutions, and, from recently published data [33] on a number of eliminations, we can calculate ratios that approach even zero. However, some care is needed when interpreting $k_{\mathrm{OTs}}k_{\mathrm{Br}}$ ratios of competitive bimolecular substitutions and eliminations, as will be shown in a future Communication.

One can predict that delocalisation of charge is encountered in other esters, including phosphates, phosphites, sulphites, etc. Moreover, it appears that alkyl–oxygen fission in carboxylic esters, which is observed for alkyl residues stabilised by mesomerism,[34] must be attributed, at least in part, to the delocalisation of negative charge over the quasi-carboxylate (and particularly quasi-benzoate) ion in the transition state. If this idea is correct, then one might expect to find mechanism $B_{\mathrm{AL}}2$, which is extremely rare,[35] for a primary alkyl group strongly stabilised by mesomerism. This remains to be tested.

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[30] H. M. R. Hoffmann, *J.*, 1964, 1249.

[31] A. J. Parker, *Quart. Rev.*, 1962, **16**, 163.

[32] P. B. D. de la Mare and C. A. Vernon, *J.*, 1956, 41.

[33] P. Veeravagu, R. T. Arnold, and G. W. Eigenmann, *J. Amer. Chem. Soc.*, 1964, **86**, 3072; cf. *ibid.*, p. 5711.

[34] A. G. Davies and J. Kenyon, *Quart. Rev.*, 1955, **9**, 203.

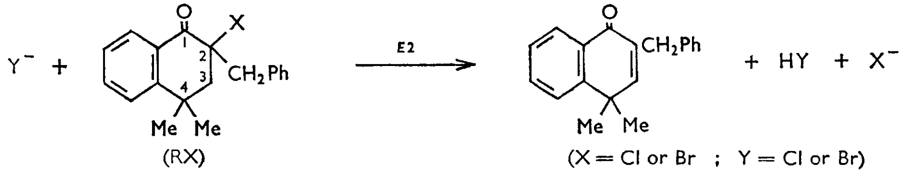
[35] C. K. Ingold, " Structure and Mechanism in Organic Chemistry," Bell, London, 1953, p. 765.

Even simple alkyl halides are sensitive to charge-spreading over the leaving halide group. So far, the experimental evidence has indicated that the departing ability of halides is remarkably constant, *e.g.*, an alkyl bromide usually reacts about 30—100 times faster than the corresponding alkyl chloride, irrespective of the alkyl group.[14]

This empirical rule is borne out by the data for the hydrolysis and methanolysis of t-butyl halides (Table 7).

TABLE 7

Relative rates of (A) ionisation of t-butyl halides, (B) dehydrohalogenation of RX, promoted by halide ions



Reaction	Solvent	Temp.	$\mathrm{Bu^tCl}$	$\mathrm{Bu^tBr}$	$\mathrm{Bu^tI}$	Refs.
(A)	H_2O	25°	I	26	53	36
	MeOH	25	I	40	143	36
	HCO·Me_2	50·7	I	450	—	37
(B)			RCl	RBr	—	
	MeCN	25	I	1500	(Cl^- promoted)	38
	MeCN	25	I	1160	(Br^- „)	38

However, for the dipolar aprotic solvent dimethylformamide, which does not hydrogen-bond[31] and thus makes leaving groups more selective, bromide is displaced 450 times faster than chloride ion. Finally, for the halide-ion induced elimination of 2-benzyl-2-halogeno-4,4-dimethyl-1-tetralone (reaction B), the bromide derivative reacts more than 1000 times faster than the chloride.[38] This is an elimination which, although bimolecular, has strong *E*1 character in the transition state, as shown by the deuterium-isotope effect and the complete Saytzeff control in the product formation.[38] Accordingly, charge-separation for the carbon–halogen bond in the transition state must be advanced and, with the absence of hydrogen bonding, the leaving groups have become very selective.

EXPERIMENTAL

Materials.—The preparation of the unstable toluene-*p*-sulphonates has been described.[1] *p*-Nitrobenzyl toluene-*p*-sulphonate was prepared from equimolar amounts of *p*-nitrobenzyl bromide (5·89 g.) and silver toluene-*p*-sulphonate (5·42 g.) in acetonitrile (100 ml.) at 25°. After 24 hr. at 25°, the silver bromide was filtered off, the mother liquor concentrated to *ca.* 35 ml. and then kept for 2 hr. at 75°. After filtering off a second crop of silver bromide, the acetonitrile was evaporated and the residue recrystallised from acetone in light petroleum (b. p. 40—60°) (yield 5·7 g., 68%), m. p. 103—104° (lit.,[39] 105°).

The n-alkyl toluene-*p*-sulphonates were prepared by adding pyridine (2 moles) to a suspension of toluene-*p*-sulphonyl chloride (1·1 moles) in the alcohol (1 mole) (cf. ref. 1). For the n-dodecyl and n-hexadecyl esters a greater excess of pyridine (4 moles) was required and a small amount of dichloromethane was added to obtain a homogeneous solution. After 20 hr. at 10°, the product was isolated in the usual way (cf. ref. 1) and purified by chromatography on alumina using light petroleum (b. p. below 40°) as the solvent. A small amount of an oily impurity was eluted first, then came the product, and finally unchanged alcohol.

The alkyl bromides were commercial materials (B.D.H.) and pure by gas-chromatographic andards. For n-dodecyl bromide and n-hexadecyl bromide the expected C, H, and Br

[36] E. A. Moelwyn-Hughes, *J.*, 1962, 4301.

[37] S. D. Ross and M. M. Labes, *J. Amer. Chem. Soc.*, 1957, **79**, 4155.

[38] D. N. Kevill, G. A. Coppens, and N. H. Cromwell, *J. Amer. Chem. Soc.*, 1964, **86**, 1553. The author is indebted to Dr. Kevill for the communication of these results in advance of their publication.

[39] J. K. Kochi and G. S. Hammond, *J. Amer. Chem. Soc.*, 1953, **75**, 3443.

analyses were obtained. The sodium salt of toluene-*p*-thiol was prepared from sodium ethoxide in ethanol and a 3% excess of the thiol. Solutions deteriorated on standing and turned yellowish; freshly prepared solutions were used. Particular care was taken to study the displacement of toluene-*p*-sulphonate and that of the corresponding bromide under identical conditions in order to obtain accurate $k_{\mathrm{OTs}}/k_{\mathrm{Br}}$ ratios.

TABLE 8

Rate constants and Arrhenius parameters for reactions (*a*), (*b*), (*c*), and (*d*). Initial concentrations of substrates and bases: 0·015—0·030M; k_1 in sec.$^{-1}$; $\Delta S^{\ddagger}$ at 298°K

$$(a)\ \mathrm{MeCHPh{\cdot}OTs} \xrightarrow[\mathrm{MeCN}]{E1} \mathrm{CH_2{=}CHPh} + \mathrm{HOTs}$$

10^5k_1 = 0·320 (10·3°); 2·23 (25·1°); 8·18 (35·0°); 26·6 (45·1°).
$\log k_1 = 12{\cdot}10 - (4990/T)$; E_A = 22·8 kcal.; $\Delta S^{\ddagger} = -5$ e.u.

$$(b)\ \mathrm{MeCHPh{\cdot}Br} \xrightarrow[\mathrm{MeCN}]{E1} \mathrm{CH_2{=}CHPh} + \mathrm{HBr}$$

10^5k_1 = 0·0597 (44·75°); 0·288 (59·25°); 0·825 (69·8°); 3·60 (84·9°).
$\log k_1 = 9{\cdot}66 - (5051/T)$; E_A = 23·1 kcal.; $\Delta S^{\ddagger} = -16$ e.u.

$$(c)\ \mathrm{Bu^tBr} \xrightarrow[\mathrm{MeCN}]{E1} \mathrm{Me_2C{=}CH_2} + \mathrm{HBr}$$

10^5k_1 = 0·120 (24·5°); 0·454 (35·0°); 0·445 (35·0°); 4·06 (54·7°) 6·71 (59·1°).
$\log k_1 = 10{\cdot}96 - (5026/T)$; E_A = 23·0 kcal.; $\Delta S^{\ddagger} = -10$ e.u.

$$(d)\ \mathrm{MeCHPh{\cdot}OTs} + \mathrm{EtOH} \longrightarrow \mathrm{MeCHPh{\cdot}OEt} + \mathrm{HOTs}$$

At 0°: 10^5k_1 = 45·1; 45·1; 45·5; 43·4 (0·03M-$\mathrm{NEt_3}$ present); 42·4 (titrimetric determination).
10·5°: 10^5k_1 = 162; 159 (0·025M-$\mathrm{Bu^n{}_3N}$ present).
25·0°: 10^5k_1 = 823.
$\log k_1 = 11{\cdot}77 - (4130/T)$; E_A = 18·9 kcal.; $\Delta S^{\ddagger} = -7$ e.u.

Kinetics.—Equimolar amounts (*ca.* 0·05M) of thiolate and substrate were chosen. The initial concentration of methyl bromide in ethanol was determined by reaction (80 min. at 60°) with a 3-fold excess of standard sodium toluene-*p*-thiolate. The other volatile halides were weighed into sealed tubes made from thin soda glass and then broken under the solvent. For the fast runs at 0° and below, standard solutions of nucleophilic reagent and substrate were kept separately in the two arms of an inverted Y-tube and mixed at time zero. Individual runs were followed by quenching timed samples in 0·05N-hydrochloric acid and back-titrating the excess of acid with 0·05N-sodium hydroxide (indicator Bromocresol-Green–Methyl Red 3 : 1). The method for following Finkelstein displacements has been described.[6] The unimolecular eliminations of 1-phenylethyl toluene-*p*-sulphonate, 1-phenylethyl bromide, and t-butyl bromide were followed as described for t-butyl toluene-*p*-sulphonate using tri-n-butylamine and 2,6-lutidine as base in concentrations below 0·03M (higher concentrations of base gave non-reproducible results). Free base was titrated with standard anhydrous perchloric acid in glacial acetic acid to the first pink colour using Oracet Blue B as indicator.[1,40]

The ethanolysis of 1-phenylethyl toluene-*p*-sulphonate was followed conductometrically in the presence and in the absence of base; k_1 was determined by a Guggenheim plot.[41] Excellent straight lines up to three and even six half-lives were obtained. The values for k_1 at 0° were in satisfactory agreement with a titrimetric rate determination.

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[40] A. H. Beckett and E. H. Tinley, " Titration in Nonaqueous Solvents," 3rd edn., British Drug Houses Ltd., Poole, Dorset.

[41] E. A. Guggenheim, *Phil. Mag.*, 1926, **2**, (7), 538.