

## Multiple Structure–Reactivity Relationships for a Menschutkin-type $S_N2$ Reaction

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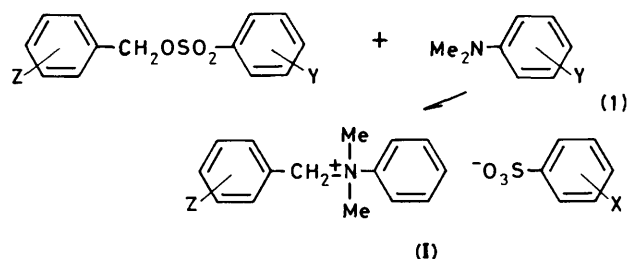
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The mechanisms of nucleophilic displacement was studied by using three variable systems of  $\rho_X$ ,  $\rho_Y$ , and  $\rho_Z$  obtained from the change of substituents X, Y, and Z for the reaction of (Z)-substituted benzyl (X)-benzenesulphonates with (Y)-substituted *N,N*-dimethylanilines in acetone at 35 °C. The coefficient of the interaction term,  $\rho_{XY}$ , has a value of 0.21 which means that bond-making and -breaking are concerted in the  $S_N2$  transition state. In the range Z = H to *p*-NO<sub>2</sub>, in which the  $S_N2$  mechanism is predicted to be dominant, the  $|\rho_{ZY}|$  value is very large, 0.5, which means that the interaction between Z and Y is very large.  $|\rho_{ZX}|$  is ca. 0.06 which means that the interaction is small between X and Z. In contrast, in the range Z = H to *p*-Me, in which the  $S_N1$  mechanism is dominant, the  $|\rho_{ZY}|$  value is nearly zero, indicating no interaction between Z and Y. Changes of substituent effect and interaction terms,  $\rho_{XY}$ ,  $\rho_{YZ}$ , and  $\rho_{ZX}$  are useful tools for distinguishing wrong reaction mechanisms.

The Hammett equation is widely used for the resolution of structure–reactivity problems. Several parameters which influence the values of  $\rho$  for a given set of substrates and reaction conditions have been investigated; among these are temperature and solvent composition,<sup>1</sup> distance of substituent from the reacting centre,<sup>2</sup> and changes in the rate-determining step in proceeding from the most reactive to the least reactive members of the series.<sup>3</sup> However, the effect of the reactivity of the reactants themselves upon  $\rho$  has received scanty consideration. We therefore thought it of interest to investigate the kinetics of nucleophilic displacement for substrates containing leaving groups.

Nucleophilic displacement is promoted by facile bond formation with the nucleophile and facile bond breaking with the leaving group, in addition to stabilization of the transition state.<sup>4</sup> In the detailed analysis of the mechanism, it is important to evaluate contributions from three species, substrate, nucleophile, or solvent and leaving group, to establish the overall stabilization of the transition state. Stabilization is considered to be attained by dispersal of the charge developed in the three species in the transition state.



In the Menschutkin-type reaction of benzyl arenesulphonate with dimethylaniline,<sup>5</sup> the charge shared by the various species can be monitored by the respective  $\rho$  value for the effects of aryl substituents in the species.

We have studied the reaction mechanism by employing the

three variables  $\rho_X$ ,  $\rho_Y$ , and  $\rho_Z$  for the reaction of substituted (Z)-benzyl (X)-arenesulphonates with substituted (Y)-*N,N*-dimethylanilines in acetone at 35 °C.

Our ultimate goal of this study is to formulate a rule relating the concerted changes of the effects of substituents in the substrate, the leaving group, and the attacking nucleophile to the change in mechanism whereby the transition state moves from an  $S_N1$ -like state, which implies the predominance of bond breaking over bond formation, to an adduct-like state implying predominant bond-formation *via* a central  $S_N2$  mechanism.

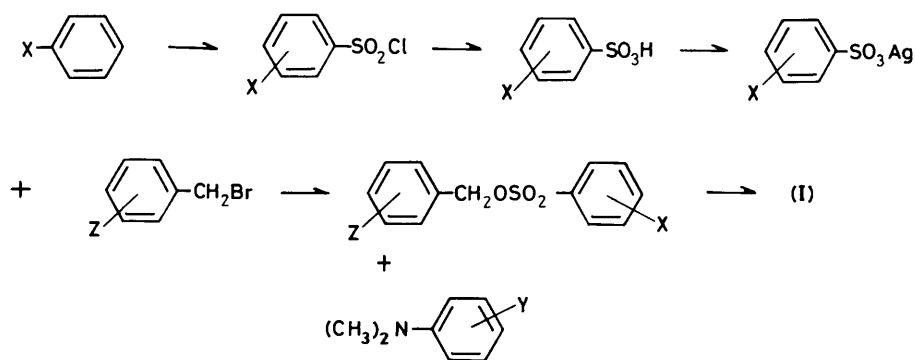
### Experimental

**Materials.**—Materials were commercial (Wako, Japan). Acetone was refluxed over KMnO<sub>4</sub> for one day, distilled, dried (K<sub>2</sub>CO<sub>3</sub>) for three days, and fractionated by using a 50 cm Widmer distillation column,<sup>6</sup> b.p. 56 °C. Pyridine dried over sodium hydroxide pellets was fractionated twice, b.p. 115–115.5 °C.

The synthetic route is shown in the Scheme.

**Substituted benzenesulphonyl chlorides.** Benzenesulphonyl chloride was obtained by distillation of commercial reagents, b.p. 137 °C at 24 mmHg (lit.,<sup>7</sup> b.p. 119–121 °C at 15 mmHg). *p*-Nitrobenzenesulphonyl chloride was prepared as previously<sup>8</sup> from *p*-chloronitrobenzene and recrystallized from benzene–light petroleum, m.p. 79 °C (lit.,<sup>8</sup> 80 °C). *m*-Nitrobenzenesulphonyl chloride was obtained by chlorosulphonation of sodium *m*-nitrobenzenesulphonate with chlorosulphonic acid and recrystallized from ligroin, m.p. 61 °C (lit.,<sup>9</sup> 61.5–62 °C). All other arenesulphonyl chlorides were synthesized by chlorosulphonation of substituted benzenes. *p*-MeO derivative, recrystallized from light petroleum, m.p. 41 °C (lit.,<sup>10</sup> 40–42 °C); *p*-Br derivative, recrystallized from ligroin, m.p. 73 °C (lit.,<sup>10</sup> 75 °C); *p*-Cl derivative, m.p. 52 °C (lit.,<sup>7</sup> 53 °C); *p*-CH<sub>3</sub> derivative, m.p. 68–69 °C (lit.,<sup>11</sup> 69 °C). Arenesulphonyl chlorides could be hydrolysed to the corresponding sulphonic acid by boiling with aqueous acetone.

**Silver arenesulphonates.**<sup>12</sup> Silver benzenesulphonate was



Scheme. Synthetic route

Table 1. Physical constants and analytical data of substituted (Z)-benzyl (X)-arenesulphonates

Z	X	M.p. (lit.) (°C)	C	H	Analysis (%) <sup>*</sup>		
					S	N	
H	H	58 (59) <sup>a</sup>	62.9 (62.9)	4.9 (4.9)	12.8 (12.9)		
H	<i>p</i> -MeO	75	60.5 (60.4)	5.0 (5.1)	11.55 (11.5)		
H	<i>p</i> -CH <sub>3</sub>	58 (58.5—58.9) <sup>b</sup>	64.3 (64.1)	5.4 (5.4)	11.9 (12.2)		
H	<i>p</i> -Br	66—68	47.65 (47.7)	3.3 (3.4)	9.6 (9.8)		
H	<i>p</i> -Cl	56—57	55.1 (55.2)	3.8 (3.9)	11.5 (11.3)		
H	<i>m</i> -NO <sub>2</sub>	68 (decomp.)	53.5 (53.2)	3.7 (3.8)	11.1 (10.9)		4.8 (4.8)
H	<i>p</i> -NO <sub>2</sub>	75 (decomp.) <sup>c</sup>	53.2 (53.2)	3.8 (3.8)	11.0 (10.9)		4.65 (4.8)
NO <sub>2</sub>	<i>m</i> -NO <sub>2</sub>	109—110	46.2 (46.2)	2.8 (3.0)	9.3 (9.5)		8.1 (8.3)
NO <sub>2</sub>	H	90—91	53.1 (53.2)	3.6 (3.8)	10.8 (10.9)		4.7 (4.8)
NO <sub>2</sub>	<i>p</i> -Cl	130—131	47.5 (47.6)	3.0 (3.1)	9.7 (9.8)		4.5 (4.3)
CH <sub>3</sub>	H	Unstable				Pure compound (single peak on g.c.)	

<sup>a</sup> Beilstein, vol. E11 II, p. 21; Die literature von 1920—1929, Umfasst. <sup>b</sup> J. K. Kochi and G. S. Hammond, *J. Am. Chem. Soc.*, 1953, **75**, 3443.

<sup>c</sup> A. Streitwieser, *J. Am. Chem. Soc.*, 1965, **87**, 3690.

\* Calculated figures in parentheses.

prepared by the Emmons procedure,<sup>12</sup> washed with ethanol, and dried *in vacuo* to a constant weight at 60 °C, yield 80%. Other silver salts were prepared similarly.

**Benzyl bromides.** Benzyl bromide, b.p. 54.5—55 °C at 0.6—0.7 mmHg, and *p*-nitrobenzyl bromide, m.p. 98.2—99.2 °C were from Eastman Kodak and were redistilled or recrystallized from benzene—light petroleum. 3-Methoxy- and 4-methoxy-benzyl bromides were prepared from the corresponding benzyl alcohols with phosphorus tribromide according to literature procedures.<sup>13</sup> Other benzyl bromides were from Aldrich and were redistilled before use.

**Benzyl tosylate.** Benzyl tosylate was prepared by treating silver tosylate (6.1 g, 0.0218 mol) in dried acetonitrile (300 ml) with benzyl bromide (3.71 g, 0.0217 mol). After stirring for 5 h at 50 °C, precipitated silver bromide was filtered out, the solvent was evaporated under reduced pressure, and the residual mass was extracted with dry ether, the solvent evaporated, recrystallized from ether, and stored in ether solution at low temperature. Small portions were crystallized for use as needed, m.p. 58 °C. Other substituted benzyl arenesulphonates were obtained similarly (Table 1).

***N*-Benzyl-*N,N*-dimethylanilinium tosylate.** Dried *N,N*-dimethylaniline (0.69 g, 0.0057 mol) was added to a solution of benzyl tosylate (1.50 g, 0.0057 mol) in anhydrous acetone (30 ml). The mixture was refluxed for 24 h, the solvent was evaporated, and the crude product was washed with dried ether (20 ml), and recrystallized from isopropyl alcohol to give colourless needles (2.0 g, 91%), m.p. 164—165 °C;  $\nu_{\max}$  (Nujol) 1 600, 1 355, 1 200, 1 050, 835, 740, 710, and 690 cm<sup>-1</sup>;  $\delta$  (D<sub>2</sub>O) 7—8 (10 H, m, Ph), 5.0 (2 H, s, CH<sub>2</sub>), and 3.7 (6 H, s, CH<sub>3</sub>) (Found: C, 68.95; H, 6.5; N, 3.45; S, 8.6. Calc. for C<sub>22</sub>H<sub>25</sub>NO<sub>3</sub>S: C, 68.9; H, 6.6; N, 3.65; S, 8.4%).

***N,N*-Dimethyl-*p*-toluidine.** *N,N*-Dimethyl-*p*-toluidine methiodide was prepared by Sandler's method<sup>14,15</sup> from *p*-toluidine (42 g, 0.40 mol) and CH<sub>3</sub>I (182 g, 1.3 mol). To freshly distilled, anhydrous tetrahydrofuran (220 ml) was added, with caution, powdered lithium aluminium hydride (8.0 g, 0.2 mol).<sup>16</sup> The mixture was heated under reflux for 1 h. Finely ground *p*-methyl-dimethylaniline methiodide (11.08 g, 0.04 mol) was introduced and the mixture heated under reflux with stirring until evolution of methane ceased. The mixture was cooled and cautiously hydrolysed by gradual addition of water (200 ml).

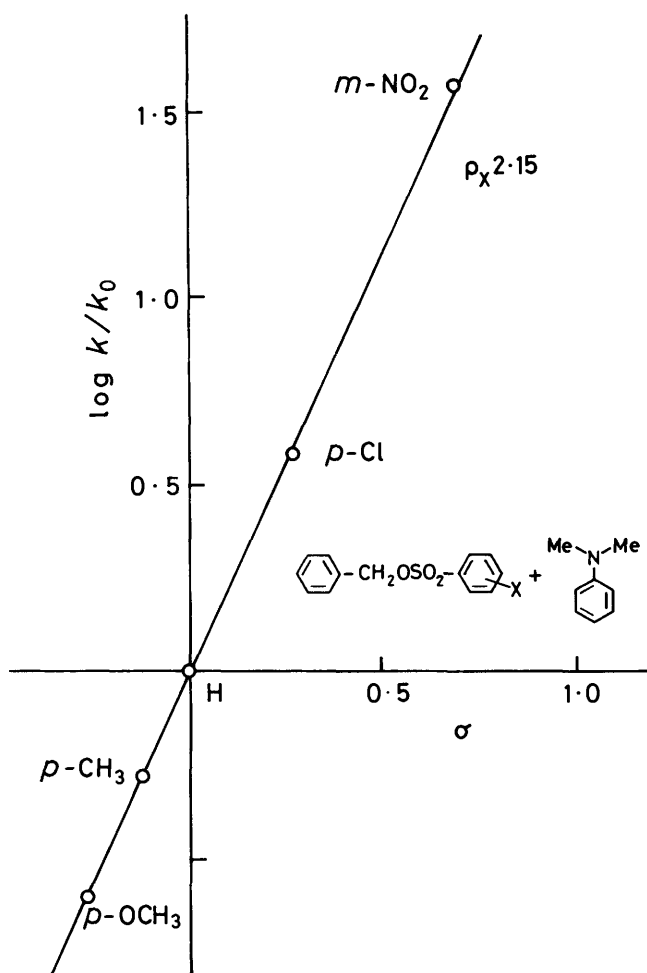


Figure 1. Hammett plot for the reaction of benzyl arenesulphonates with *N,N*-dimethylaniline in acetone at 35 °C

To isolate *N,N*-dimethyl-*p*-toluidine, the mixture was extracted with ether (200 ml) and dried ( $\text{MgSO}_4$ ). After removal of the solvent by distillation, the residue was vacuum distilled as a liquid (3.5 g, 65%), b.p. 95 °C at 30 mmHg (lit.,<sup>17</sup> 204–206 °C at 740 mmHg). *N,N*-Dimethyl-*p*-anisidine was prepared by the same method, yield 63%, m.p. 48 °C (lit.,<sup>18</sup> 48–49 °C).

*p*-Acetyl-*N,N*-dimethylaniline. A mixture of *p*-aminoacetophenone and dimethyl sulphate in sodium hydroxide solution was cooled and crystals were separated by filtration and dried. Acetylation with acetic anhydride and extraction with benzene gave the acetyl derivative, m.p. 107–108 °C (lit.,<sup>19</sup> 105.5 °C) (Found: C, 73.4; H, 8.1; N, 8.4. Calc. for  $\text{C}_{18}\text{H}_{13}\text{NO}$ : C, 73.6; H, 8.0; N, 8.6%).

*p*-Cyano-*N,N*-dimethylaniline. *p*-Bromo-*N,N*-dimethylaniline was refluxed with a dimethylformamide solution of  $\text{CuCN}$  by Friedmann's method.<sup>20</sup> The mixture was poured into  $\text{FeCl}_3$  and  $\text{HCl}$  solution and then heated, neutralized with ammonia solution, extracted with ether, m.p. 75 °C (lit.,<sup>20</sup> 75.6 °C) (Found: C, 73.9; H, 6.8; N, 19.0. Calc. for  $\text{C}_9\text{H}_{10}\text{N}_2$ : C, 73.9; H, 6.9; N, 19.2%). Other commercial *N,N*-dimethylanilines were recrystallized from appropriate solvents: *p*-CHO (benzene–ligroin); *p*- $\text{NO}_2$  (benzene); *p*-Br, *m*- $\text{NO}_2$  (ethanol). Commercial *N,N*-dimethylaniline was distilled under nitrogen and stored in a brown ampoule filled with nitrogen.

**Kinetic Measurements.**—The rates of the Menshutkin reaction of various sulphonates with *N,N*-dimethylaniline at

35 °C were measured conductometrically using a Yanakimoto electric conductivity meter, model MY-8, by the procedure previously reported.<sup>21</sup> In a typical run, an acetone solution (50 ml) of amine and a solution of an ester (0.015M) in acetone (10 ml) were mixed in a reaction cell, with resulting initial concentrations of ester 0.0025M and 1.0M amine. The conductivity change was followed with time; the infinity conductance was taken after 10 half-lives. A first-order rate plot of  $\log(v_\infty - v_t)$  versus time did not give a good straight line. In order to obtain reasonable rate constants, conductance readings were converted into the concentrations of quaternary ammonium salt with the aid of a conductance–concentration relationship. This calibration gave excellent linear first-order rate plots with correlation coefficients >0.9999. Pseudo-first-order rate constants  $k_1$  were derived from the calibrated concentrations. Second-order rate constants  $k_2$  were obtained by dividing  $k_1$  with the initial amine concentration.

## Results and Discussion

**Substituent Effect of Leaving Groups.**—The reaction of benzyl arenesulphonate with *N,N*-dimethylaniline in acetone yields *N*-benzyl-*N,N*-dimethylanilinium arenesulphonates quantitatively [equations (1)]. The reaction rate was measured by observing the increase of conductance of the salt formed in the reaction. The reactions, carried out with a large excess of *N,N*-dimethylaniline, follows pseudo-first-order kinetics to at least 85% completion. The rate constants  $k_{\text{obs}}$  are linearly correlated with the *N,N*-dimethylaniline concentration, indicating that the reaction is second order overall and first order with respect to each reagent, according to the simple rate law (2). The second-

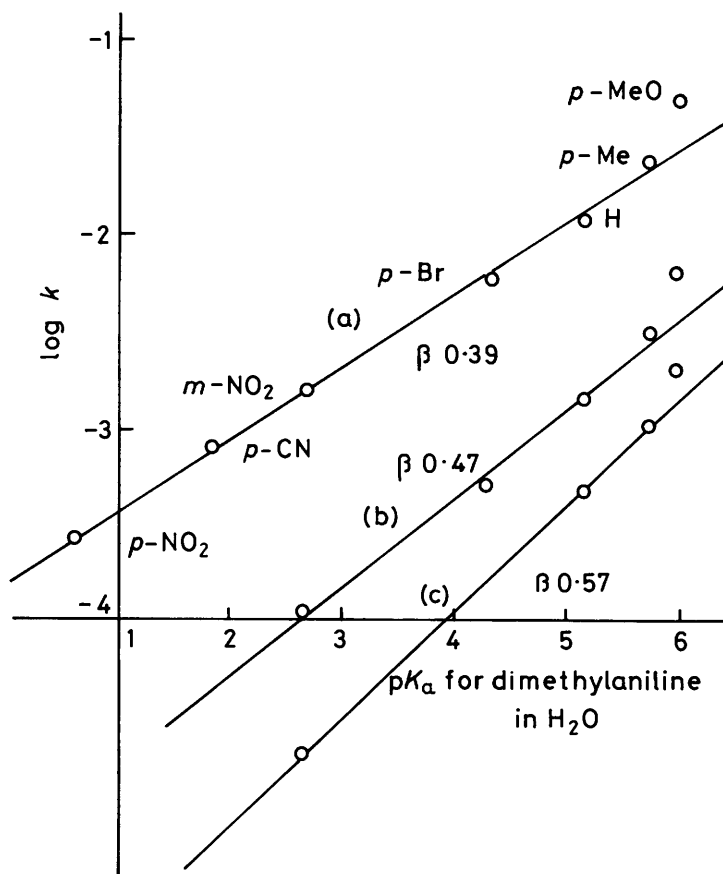
$$k_{\text{obs}} = k_2[\text{amine}] \quad (2)$$

order rate constants for the reaction of benzyl arenesulphonates with *N,N*-dimethylanilines are summarized in Table 2.

It is evident that electron-attracting substituents in the leaving group facilitate the reaction; this is also illustrated by the positive  $\rho$  value (Figure 1), which is consistent with attack by the nucleophile at  $\text{CH}_2$  being helped by electron-attracting X and with dispersal of the developing negative charge on  $\text{SO}_3$  being helpful to the departure of the leaving group.

The rate of reaction of benzyl *m*-nitrobenzenesulphonate with substituted *N,N*-dimethylanilines were measured in acetone to elucidate the effect of substituents in the nucleophile. The rate constants for the various *m*- and *p*-substituted *N,N*-dimethylanilines reveal that electron-donating substituents increase the rate while electron-attracting ones decrease it (Table 2). Activation parameters for the reaction of benzyl tosylate with *N,N*-dimethylanilines in Table 2 are characterized by the large negative entropy of activation ( $-34.8 \text{ cal mol}^{-1} \text{ K}^{-1}$ ) and small enthalpy of activation ( $9.20 \text{ kcal mol}^{-1}$ ). Both are general characteristics of an  $\text{S}_{\text{N}}2$  reaction.<sup>22</sup> Reactions of neutral molecules such as the Menshutkin reaction to yield ions invariably show negative entropies of activation. For such cases, charge separation begins in the transition state and each end of the dipole becomes solvated with a sheath of solvent molecules, which must however be suitably oriented. The increase in orientation means, of course, a decrease in entropy.

When we compare the nucleophilicity of pyridine with that of *N,N*-dimethylaniline in protic solvents, the latter is larger than the former ( $n$  5.64 for dimethylaniline and 5.23 for pyridine in methanol solvent<sup>23</sup>). This value is in accord with the order of basicity in water, but pyridine<sup>5a,b</sup> reacts 2.5 times faster with benzylbenzenesulphonate than *N,N*-dimethylaniline (Table 2), which is the reverse of the order of Pearson's nucleophilicity in MeOH.



**Figure 2.** Brønsted correlation: upper line,  $\text{PhCH}_2\text{OSO}_2\text{C}_6\text{H}_4\text{NO}_2$ -*m* with dimethylanilines; middle line,  $\text{PhCH}_2\text{OSO}_2\text{C}_6\text{H}_4\text{Cl}$ -*p* with dimethylanilines; lower line,  $\text{PhCH}_2\text{OSO}_2\text{Ph}$  with dimethylanilines

The nucleophilic order of nucleophiles can sometimes be reversed<sup>24</sup> under certain conditions, especially a change in solvent. The gas-phase basicity of amines gives particularly valuable information about solvent effects because there are so many reliable data available for amine basicity in solution. Taft and his co-workers<sup>25</sup> showed that in the gas phase the basicity as measured by an ion cyclotron resonance intensity–pressure plot,<sup>26</sup> is substantially greater for pyridine (proton affinity PA  $225 \pm 2$  kcal mol<sup>-1</sup>) than for ammonia (PA  $207 \pm 3$  kcal mol<sup>-1</sup>) and comparable with aliphatic amines, e.g.  $(\text{CH}_3)_2\text{NH}$  (PA  $225 \pm 2$  kcal mol<sup>-1</sup>). Such a substantial inversion in base strength of amines between the gas and aqueous phases makes substituent effects on gas-phase proton affinity particularly significant. The dominant factor for nucleophilic reactivity in an  $\text{S}_{\text{N}}2$  reaction is the  $\alpha$  polarizability effect,<sup>27</sup> in addition to the basicity of nucleophile, but the nucleophilic order of these two amines in this reaction seems to be determined by the basicity. The reason for the adverse results in acetone, unlike in the protic solvent, is that the order of basicity is the same as that in the gas phase because there is no interaction such as hydrogen bonding.

The substituent effects of the leaving group for the reaction of substituted dimethylanilines shows  $\rho_{\text{sulphonate}}$  grows progressively larger from *p*-MeO (2.10;  $r$  0.998) to H (2.15;  $r$  0.998) and *m*-NO<sub>2</sub> (2.32;  $r$  0.999) [see Table 3(a)].

The plot of  $\rho_{\text{X}}$  with  $\sigma_{\text{Y}}$  (substituent constant of the nucleophile Y) is described by equation (3). When we compare the substituent effects of the leaving group in benzyl with *p*-

$$\rho_{\text{X}} = 0.21\sigma_{\text{Y}} + 2.15 \quad (3)$$

nitrobenzyl arenesulphonates, the former has a  $\rho$  value of 2.15 and the latter 2.10, which indicates that the substituent effect of the leaving group is very similar in both cases even though the NO<sub>2</sub> group is introduced at the *para*-position of the benzyl group. This suggests that the introduction of the *p*-NO<sub>2</sub> group does not affect C–O bond breaking.

The relationships between nucleophilicity and basicity for the *m*-nitro, *p*-chloro, and unsubstituted sulphonate compounds are illustrated in Figure 2. The slopes  $\beta$  of these plots decrease with the increasing electron-attracting ability of the substituents in the benzyl arenesulphonates. Since  $\beta$  is a measure of the degree of bond formation in the transition state,<sup>28</sup> it can be inferred that N–C bond formation increases progressively from *m*-nitro to unsubstituted sulphonate, for which the  $\beta$  values of the *m*-nitro, *p*-chloro, and unsubstituted sulphonate are 0.39, 0.47, and 0.57, respectively. According to the above data, the order of bond formation is unsubstituted > *p*-chloro > *m*-nitro sulphonate respectively and agrees with predictions of substituent effects on the  $\text{S}_{\text{N}}2$  transition state.<sup>29</sup>

The  $|\rho_{\text{Y}}|$  reaction constant for the reaction of each leaving group with substituted *N,N*-dimethylanilines, and various  $\beta$  values show regular variations and the directions of change are the same.  $|\rho_{\text{Y}}|$  is a measure of charge on the nitrogen atom of the nucleophile and is related to the extent of bond formation in the transition state. The larger the value of  $|\rho_{\text{Y}}|$ , the more bond formation has proceeded in the transition state.

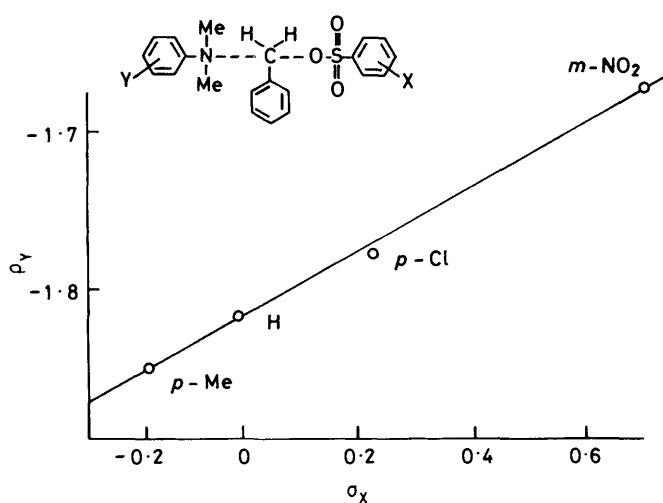
The plot of  $\rho_{\text{Y}}$  with  $\sigma_{\text{X}}$  (substituent constant of the leaving group X) (Figure 3) is described by equation (4). When the  $|\rho_{\text{Y}}|$

$$\rho_{\text{Y}} = 0.21\sigma_{\text{X}} - 1.82 \quad (4)$$

**Table 2.** Relative rate constants for the reaction of (Z)-substituted benzyl (X)-substituted benzenesulphonates with (Y)-substituted *N,N*-dimethylanilines in acetone at 35 °C ( $k_{XY}/k_{HH}$  value)

Z	X	Y				
		<i>p</i> -MeO	<i>p</i> -Me	H	<i>p</i> -Br	<i>m</i> -NO <sub>2</sub>
H	<i>p</i> -MeO		0.683	0.252		
H	<i>p</i> -Me	2.62	1.19	0.526	0.165	
H	H	4.76	2.25	1.00 <sup>b</sup>	0.313	0.0497
H	<i>p</i> -Cl	18.3	8.74	3.78	1.21	0.198
H	<i>m</i> -NO <sub>2</sub>	143 <sup>a</sup>	74.3	34.3	11.2	2.33
<i>p</i> -Me	H	4.30	2.10	1.00 <sup>c</sup>	0.348	
<i>p</i> -NO <sub>2</sub>	<i>p</i> -Me			0.547		
<i>p</i> -NO <sub>2</sub>	H	6.25	2.51	1.00 <sup>d</sup>	0.259	
<i>p</i> -NO <sub>2</sub>	<i>p</i> -Cl			3.54		
<i>p</i> -NO <sub>2</sub>	<i>m</i> -NO <sub>2</sub>	177	75.7	31.9	7.61	

<sup>a</sup>  $\Delta H^\ddagger$  9.20 kcal mol<sup>-1</sup>,  $\Delta S^\ddagger$  -34.8 cal mol<sup>-1</sup> K<sup>-1</sup> for Z = H, X = *m*-NO<sub>2</sub>, and Y = *p*-MeO. <sup>b</sup>  $k_{HH}^{Z=H}$  3.454 × 10<sup>-4</sup> l mol<sup>-1</sup> s<sup>-1</sup>, 8.70 × 10<sup>-4</sup> l mol<sup>-1</sup> s<sup>-1</sup> (for pyridine). <sup>c</sup>  $k_{HH}^{Z=p-Me}$  9.429 × 10<sup>-4</sup> l mol<sup>-1</sup> s<sup>-1</sup>. <sup>d</sup>  $k_{HH}^{Z=p-NO_2}$  0.6736 × 10<sup>-4</sup> l mol<sup>-1</sup> s<sup>-1</sup>.

**Figure 3.** Plot of  $\rho_{\text{amine}}$  versus  $\sigma_X$ 

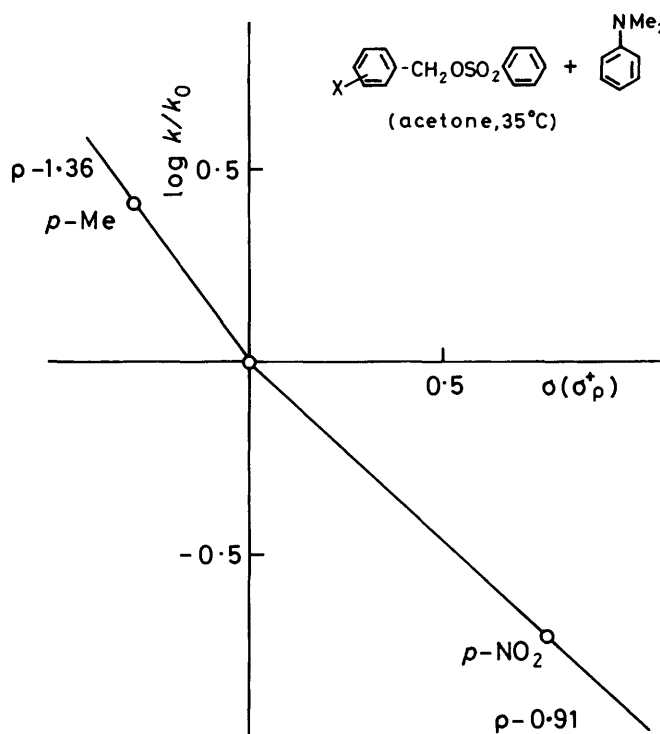
value of benzyl *m*-nitrobenzenesulphonate is compared with that of *p*-nitrobenzyl *m*-nitrosulphonate, an increase from -1.67 to -2.05 is manifest. In contrast, the  $\rho_X$  value of benzyl and of *p*-nitrobenzyl benzenesulphonate is the same.

As shown in Figure 2, the *p*-MeO group deviates from linearity and the reaction is faster than for other compounds. Perhaps this resulted from a solvent effect; the  $pK_a$  values of dimethylanilines have been determined in water, but these reactions were carried out in acetone. The methoxy group has a hydrogen bond which disappears entirely in acetone, and thus the amino group has more electron-donating power and accelerates the rate of reaction. These solvent effects are in agreement with Tsuruta's work.<sup>30</sup>

From the average of  $\beta$  values, it can be inferred that in this reaction, the reaction proceeds by a concerted  $S_N2$  transition mechanism in which bond formation and breaking are concerted.

**Substituent Effects of Substrate.**—Solvolytic and nucleophilic reactions of benzyl halides can proceed through an  $S_N1$ ,  $S_N2$ , or mixed mechanism depending on the solvent polarity and the substrate and nucleophile structures.<sup>3a,21</sup>

For these reactions, the Hammett law does not hold for the  $\sigma$  or  $\sigma^+$  substituent constants, which indicates that there is some change in the reaction mechanism. Although we studied

**Figure 4.**

only three substituted benzyl arenesulphonates, *i.e.* *p*-Me, H, and *p*-NO<sub>2</sub>, in reactions with *N,N*-dimethylaniline, either  $\sigma$  or  $\sigma^+$  gives a curved line. This trend is indicative of mechanistic changeover from  $S_N2$  to  $S_N1$  on going from electron-withdrawing to electron-donating substituents.<sup>31,32</sup> All rates are dependent on the amine concentrations. The reaction of *p*-methylbenzyl benzenesulphonate also proceeds by a mechanism which is essentially  $S_N2$ , but not far from the  $S_N1$  limit, as with solvolysis reactions.<sup>33</sup> Electron-donating substituents in benzyl benzenesulphonate favour bond breaking, while electron-withdrawing ones favour bond making. In the  $S_N2$  transition state, bond making and breaking are concerted, and the Hammett  $\rho$  value, which is variable but always negative as shown in Figure 4, indicates the prevailing contribution of bond breaking on the transition state, which is looser or tighter depending on the substituent effect.

In particular, electron-donating substituents accelerate

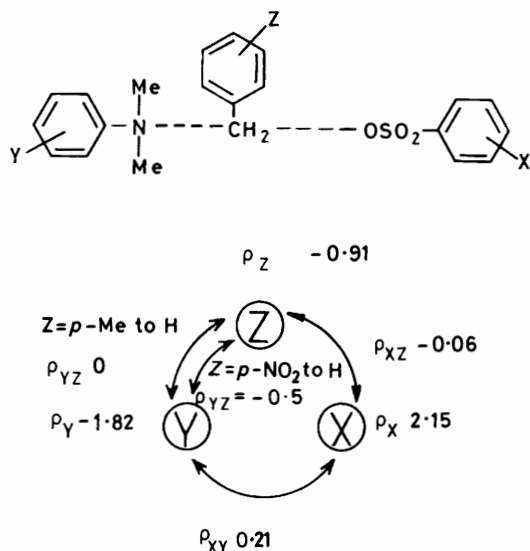


Figure 5. Interaction values between X, Y, and Z

sulphonate ion displacement from the saturated carbon atom more than they decrease nucleophilic attack on it (slope more negative in Figure 4), and electron-withdrawing ones balance the difficulty in leaving group displacement by favouring nucleophilic attack (slope less negative). Since the substituted benzyl benzenesulphonates do not relate to the normal Hammett substituent constant, it is impossible to calculate the  $\rho$  values for the range involving all the three substituent groups (*p*-Me, H, and *p*-NO<sub>2</sub>).  $\rho_{\text{benzyl}(Z)} = 1/0.778$  ( $\log k_{p\text{-NO}_2}/k_0$ ) [Table 3(c)] is the rate ratio between *p*-NO<sub>2</sub>-substituted and unsubstituted benzyl benzenesulphonate; as  $\rho_Z = 1/-0.311$  ( $\log k_{p\text{-Me}}/k_0$ ), where  $-0.311$  is the  $\sigma_{p\text{-Me}}^+$  value.

It is interesting to note from Table 3(c) that the  $\rho_Z$  value becomes progressively more negative when there is a transfer from a small substituent constant to a large one in the nucleophile, and also that the  $\rho_Z$  is a function of  $\sigma_Y$ .  $\rho_Z$  is, however, nearly constant even though the substituent of leaving sulphonate varies from H to *m*-NO<sub>2</sub> ( $-0.91$  versus  $-0.85$ ). In the case of  $Z = p\text{-NO}_2$ , there is no or little interaction between substituents Z and X, but an interaction between Z and Y. On the other hand,  $\rho_Z$  as calculated from the plot for  $Z = p\text{-Me}$  to H is nearly constant on changing from *p*-MeO to *p*-Br in the nucleophile. This fact suggests that interactions between substituents Z and Y are small or absent. The degree of interaction between substituents Z and Y corresponds to the change of reaction mechanism from S<sub>N</sub>2 to S<sub>N</sub>1 upon variation of the substituents.

We can summarize all substituent effects as follows. We consider the free energy change,  $\Delta F^\ddagger$  (XY), for the system of variable substituents, X and Y, and the standard free energy change,  $\Delta F^\ddagger$  (00), for that of substituents X = Y = H, when Z is constant. The Taylor expansion (5) can be written for

$$\Delta F^\ddagger(XY) = \Delta F^\ddagger(00) + \frac{\partial \Delta F^\ddagger}{\partial X} \Delta X + \frac{\partial \Delta F^\ddagger}{\partial Y} \Delta Y + \frac{\partial^2 \Delta F^\ddagger}{\partial X \partial Y} \Delta X \Delta Y + \frac{\partial^2 \Delta F^\ddagger}{\partial X^2} \Delta X^2 + \frac{\partial^2 \Delta F^\ddagger}{\partial Y^2} \Delta Y^2 + \quad (5)$$

$\Delta F^\ddagger(XY)$  and  $\Delta F^\ddagger(XY) - \Delta F^\ddagger(00)$  may be substituted for  $\log k_{XY}/k_{00}$ . Substituting  $\Delta X$  and  $\Delta Y$  into  $\sigma_X$  and  $\sigma_Y$ , we can write  $\partial(\log k_{XY})/\partial X = \rho_X$  and  $\partial(\log k_{XY})/\partial Y = \rho_Y$ .  $\partial^2 \Delta F^\ddagger/\partial X^2 = \partial(\partial \Delta F^\ddagger/\partial X)/\partial X$  corresponds to  $\partial \rho_X/\partial X$ , i.e. the variation of  $\rho_X$  with substituent X, corresponding to deviations

from the Hammett plots,  $\partial^2 \Delta F^\ddagger/\partial Y^2$  corresponds to the variation of  $\rho_Y$  with Y.

Owing to the linearity of our Hammett plot in this study, the quadratic differential terms in the right-hand side of equation (5) are negligible. Then we have  $\partial^2 \Delta F^\ddagger/\partial X \partial Y = \partial \rho_Y/\partial X$  corresponding to the variation of  $\rho_Y$  with substituent X and  $\partial^2 \Delta F^\ddagger/\partial X \partial Y = \partial \rho_X/\partial Y$  corresponding to that of  $\rho_X$  with substituent Y. These quantities can be interchanged:  $\partial \rho_Y/\partial X = \partial \rho_X/\partial Y$  and therefore  $\partial \rho_Y/\partial \sigma_X = \partial \rho_X/\partial \sigma_Y$ .

We can then generalize equation (6). The third term on the

$$\log k_{XY}/k_{00} = \rho_X \sigma_X + \rho_Y \sigma_Y + \rho_{XY} \sigma_X \sigma_Y \quad (6)$$

right-hand side of equation (6) represents the degree of interaction with X and Y. If  $\rho_{XY}$  is constant, the reaction proceeds with the same mechanism for all X and Y. The relationship can be further generalized for Z, Y, and X in the form (7).  $\rho_{XY}$  indicates the degree of concertedness in the

$$\log k_{XYZ}/k_{000} = \rho_X \sigma_X + \rho_Y \sigma_Y + \rho_Z \sigma_Z + \rho_{XY} \sigma_X \sigma_Y + \rho_{XZ} \sigma_X \sigma_Z + \rho_{YZ} \sigma_Y \sigma_Z \quad (7)$$

N...C...O bond,  $\rho_{YZ}$  and  $\rho_{XZ}$  are the degrees of N...C bond formation and C...O bond fission, respectively.

$\rho_X$  has a large positive value in accord with the change in the  $\sigma$  value from electron-donating  $Y = p\text{-MeO}$  to electron-withdrawing  $Y = m\text{-NO}_2$  groups of nucleophiles. In contrast, the  $|\rho_Y|$  value is decreased upon an increase in the  $\sigma$  value of the leaving group when  $Z = \text{H}$ . These results qualitatively suggest that the stronger (weaker) the nucleophilicity of nucleophiles, the less (more) bond breaking of the C-O bond proceeds in the transition state.

The results are in accord with the structure of the S<sub>N</sub>2 transition state predicted by Swain,<sup>34</sup> Thornton,<sup>29b</sup> and Harris and Kurz.<sup>29a</sup> Plots of  $\rho_Y$  versus  $\sigma_X$  and  $\rho_X$  versus  $\sigma_Y$  are well correlated by equation (8).<sup>35</sup>

$$\log k_{XY} - \log k_{HH} = 2.15 \sigma_X + 0.21 \sigma_X \sigma_Y - 1.82 \sigma_Y \quad (8)$$

The most important point is that the coefficient of the interaction term [the second term on the right-hand side of equation (8)]  $\sigma_X \sigma_Y$  is the same value, 0.21, derived from either  $\rho_X$  or  $\rho_Y$ . This probably indicates the degree of concertedness for the interaction between nucleophile and leaving group. That is, bond making and breaking are concerted in the S<sub>N</sub>2 transition state within the range of variation of the substituents X and Y in which there is no variation of charge on the carbon atom, because the charge on the nitrogen atom is cancelled out by that on the oxygen atom.

With our knowledge of the theoretical analysis of the interaction term  $\rho_{XY} \sigma_X \sigma_Y$ , using the Taylor expansion,<sup>35</sup> we first attempted to analyse<sup>5</sup> the interaction term by experiment. Next, we considered the interactions between Y and Z, and between X and Z. In the range  $Z = \text{H}$  to *p*-NO<sub>2</sub>, in which the S<sub>N</sub>2 reaction mechanism is dominant, the  $|\rho_Y|$  value changed from  $-1.67$  to  $-2.05$  [Table 3(b),  $X = m\text{-NO}_2$ ] and the interaction term  $|\rho_{ZY}|$  is very large at 0.5, which means that the interaction between Z and Y is very large. But  $\rho_X$  is constant at  $2.15$ – $2.10$  [Table 3(a),  $Y = \text{H}$ ] for the same range and  $|\rho_{ZX}|$  is ca. 0.06, indicating that the interaction is very small between X and Z.

In contrast, in the range  $Z = \text{H}$  to *p*-Me, in which the S<sub>N</sub>1 mechanism is dominant,  $\rho_Y$  was constant,  $-1.86$  to  $-1.82$  [Table 3(b),  $X = \text{H}$ ], and  $\rho_{ZY}$  was nearly zero, i.e. there is no interaction between Z and Y. The interactions are in Figure 5.

It seems that the interaction between Z and Y, large or small, is indicative of a mechanistic change from the S<sub>N</sub>2 to S<sub>N</sub>1 on going from electron-withdrawing to electron-donating substit-

**Table 3.** The reaction constants,  $\rho_X$ ,  $\rho_Y$ , and  $\rho_Z$ (a)  $\rho_X$ 

Y	Z	
	H	<i>p</i> -NO <sub>2</sub>
<i>p</i> -MeO	2.10	
<i>p</i> -Me	2.14	
H	2.15	2.10
<i>p</i> -Br	2.18	
<i>m</i> -NO <sub>2</sub>	2.32	

(b)  $\rho_Y$ 

X	Z		
	<i>p</i> -Me	H	<i>p</i> -NO <sub>2</sub>
<i>p</i> -Me		-1.85	
H	-1.86	-1.82	-2.17
<i>p</i> -Cl		-1.78	
<i>m</i> -NO <sub>2</sub>		-1.67	-2.05

(c)  $\rho^*_Z$ 

Y	X	
	H	<i>m</i> -NO <sub>2</sub>
<i>p</i> -MeO	(-1.29)	-0.70
		-0.58
<i>p</i> -Me	(-1.31)	-0.78
H	-0.91	-0.85
	(-1.32)	
<i>p</i> -Br		-1.16

\* ( $\log k_{p\text{-NO}_2}/k_0$ )  $\times$  1/0.778: in parentheses ( $\log k_{p\text{-Me}}/k_0$ )  $\times$  1/-0.311.

uents<sup>32</sup> but the reaction always depends on the amine concentration. It proceeds by a mechanism which is essentially S<sub>N</sub>2 but not far from the S<sub>N</sub>1 limit.

In conclusion, changes in substituent effect and interaction terms,  $\rho_{XY}$ ,  $\rho_{YZ}$ , and  $\rho_{ZX}$  are useful tools in elucidating reaction mechanisms.

## References

- (a) H. H. Jaffé, *Chem. Rev.*, 1953, **53**, 191; (b) J. E. Leffler and E. Grunwald, 'Rates and Equilibria of Organic Reactions,' Wiley, New York, 1963, p. 177.
- R. W. Taft, jun. and I. C. Lewis, *J. Am. Chem. Soc.*, 1958, **80**, 246.
- (a) C. G. Swain and W. P. Langsdorf, *J. Am. Chem. Soc.*, 1951, **73**, 2813; (b) R. F. Hudson and G. Klopman, *J. Chem. Soc.*, 1962, 1062; (c) B. M. Anderson and W. P. Jencks, *J. Am. Chem. Soc.*, 1960, **82**, 1773; J. F. Kirsch and W. P. Jencks, *ibid.*, 1964, **86**, 837; (d) D. J. McLennan, *Tetrahedron*, 1978, **34**, 2331.
- (a) A. J. Parker, *Chem. Rev.*, 1969, **69**, 1; (b) ref. 3a; (c) J. W. Hill and A. Fry, *J. Am. Chem. Soc.*, 1962, **84**, 2763; (d) S. Seltzer and A. A. Zavitsas, *Can. J. Chem.*, 1967, **45**, 2023; (e) D. C. Wigfield, *ibid.*, 1970, **48**, 2120.
- (a) S.-D. Yoh, Ph.D. Dissertation, Osaka University, 1973; (b) S.-D. Yoh, M. Sawada, Y. Tsuno, and Y. Yukawa, Abstracts of the 28th Spring Meeting of the Chemical Society of Japan, Tokyo, 1973, p. 1288; (c) Y. Tsuno, M. Fujio, S.-D. Yoh, M. Sawada, and Y. Yukawa, Abstracts of 25th Symposium on Reaction Mechanisms, Chemical Society of Japan, Tokyo, 1974, p. 119; (d) S.-D. Yoh, Y. Tsuno, and Y. Yukawa, *J. Korean Chem. Soc.*, 1984, **28**, 433.
- (a) J. A. Riddick, 'Organic Solvents,' Wiley, New York, 1970, p. 722; (b) Y. Yukawa, Y. Tsuno, and M. Sawada, *Bull. Chem. Soc. Jpn.*, 1972, **45**, 1198.
- H. Meerwein, G. Dittmar, R. Göllner, and K. Hafner, *Chem. Ber.*, 1957, **90**, 841.
- (a) H. Gilman, *Org. Synth.*, 1941, Coll. Vol. I, 220; 1941, Coll. Vol. II, 471; (b) F. Bell, *J. Chem. Soc.*, 1928, 2776.
- H. H. Hodgson and J. S. Whitehurst, *J. Chem. Soc.*, 1944, 482.
- M. S. Morgan and L. H. Crether, *J. Am. Chem. Soc.*, 1948, **70**, 375.
- R. L. Shriner, R. C. Fuson, and D. Y. Curtin, 'The Systematic Identification of Organic Compounds,' Wiley, New York, 1956, p. 331.
- W. D. Emmons and A. F. Freis, *J. Am. Chem. Soc.*, 1953, **75**, 2257.
- W. H. Saunders, jun. and R. A. Williams, *J. Am. Chem. Soc.*, 1957, **79**, 3712.
- S. R. Sandler and Wolf Karo, 'Organic Functional Group Preparation,' Academic Press, New York, 1968, p. 325.
- B. B. P. Tice and I. Lee, *J. Am. Chem. Soc.*, 1963, **85**, 329.
- A. C. Cope, *J. Am. Chem. Soc.*, 1960, **82**, 4651.
- D. D. Thomas, *J. Am. Chem. Soc.*, 1946, **68**, 895.
- F. G. Bordwell and P. J. Bouthan, *J. Am. Chem. Soc.*, 1956, **78**, 89.
- H. Staudinger and N. Kon, *Justus Liebig's Ann., Chem.*, 1911, **384**, 38.
- L. Friedlander and H. Shechter, *J. Org. Chem.*, 1961, **26**, 2522.
- M. Fujio, K. Ikeda, and Y. Tsuno, *Mem. Fac. Sci., Kyushu Univ., Ser. C*, 1978, **11**, 75.
- (a) G. Ostrogovich, C. Csunderlik, and R. Bacaloglu, *J. Chem. Soc. B*, 1971, 18; (b) A. A. Frost and R. G. Pearson, 'Kinetics and Mechanism,' Wiley, New York, 1961, 2nd edn., p. 137.
- R. G. Pearson, *J. Am. Chem. Soc.*, 1968, **90**, 319; 1967, **89**, 1827.
- A. J. Parker, *J. Chem. Soc.*, 1961, 1328.
- M. Taagepera, W. G. Henderson, R. T. C. Brownlee, T. L. Beauchamp, and R. W. Taft, *J. Am. Chem. Soc.*, 1972, **94**, 1369.
- D. Holtz and J. L. Beauchamp, *J. Am. Chem. Soc.*, 1969, **91**, 5913.
- A. Streitwieser, 'Solvolytic Displacement Reactions,' McGraw-Hill, New York, 1962.
- J. F. Bunnett, *Annu. Rev. Phys. Chem. (B)*, 1963, **14**, 271.
- (a) J. C. Harris and J. L. Kurtz, *J. Am. Chem. Soc.*, 1970, **92**, 349; (b) E. R. Thornton, *ibid.*, 1967, **89**, 2915.
- M. Tsuruta, K. Murai, T. Sato, and C. Kimura, *Nippon Kagaku Kaishi*, 1972, **6**, 1118.
- (a) C. K. Ingold, 'Structure and Mechanism in Organic Chemistry,' Cornell Univ. Press, Ithaca, 1969, 2nd edn., p. 421; (b) G. S. Hammond, C. E. Reeder, F. T. Fang, and J. K. Kochi, *J. Am. Chem. Soc.*, 1958, **80**, 568; (c) Y. J. Lim, S.-D. Yoh, and S. Y. Hong, *J. Korean Chem. Soc.*, 1971, **15**, 219; (d) S.-D. Yoh, D. S. Lee, and S. Y. Hong, *ibid.*, 1969, **13**, 215; (e) S. Y. Hong and S.-D. Yoh, *ibid.*, 1972, **16**, 284; (f) A. V. Willi, C. Ho, and A. Ghanbarpour, *J. Org. Chem.*, 1972, **37**, 1185.
- C. D. Johnson, 'The Hammett Equation,' Cambridge University Press, Cambridge, 1973, p. 49.
- (a) E. Tommila, *Acta Chem. Scand.*, 1966, **20**, 923; (b) E. Tommila and I. P. Pitkanen, *ibid.*, p. 937; (c) A. Streitwieser, H. A. Hammond, R. H. Jagow, R. W. Williams, R. G. Jesartis, C. J. Chang, and R. Wolf, *J. Am. Chem. Soc.*, 1970, **92**, 5141.
- C. G. Swain and E. R. Thornton, *J. Am. Chem. Soc.*, 1962, **84**, 817.
- P. R. Wells, 'Linear Free Energy Relationships,' Academic Press, London-New York, 1968.

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