(1967).

(29) A. C. Cope, N. A. Lebel, H. H. Lee, and W. R. Moore, *J. Am. Chem. Soc.*, **79**, 4720 (1957).

(30) H. C. Brown and M. Nakagawa, *J. Am. Chem. Soc.*, 77, 3614 (1955).

(31) D. H. Froemsdorf and M. D. Robbins, *J. Am. Chem. Soc.*, **89**, 1737 (1967).

(32) The apparent deviation of the results obtained with the carbanion derived from *sec*-butyl benzyl ether where the ratio is around 2 may be due to a different elimination mechanism (J. L. Schmitt, unpublished results).

(33) T. M. Dolak and T. A. Bryson, *Tetrahedron Lett.*, 1961 (1977).

(34) I. D. Entwistle and R. A. W. Johnstone, *Chem. Commun.*, 29 (1965).

(35) B. Rickburn and J. Quartucci, *J. Org. Chem.*, **29**, 3185 (1964).

(36) H. C. Brown and R. L. Klimisch, *J. Am. Chem. Soc.*, **88**, 1430 (1966).

(37) P. Diehl and T. Leipert, *Helv. Chim. Acta*, **47**, 545 (1964).

(38) R. M. Gavin, Jr., and Z. F. Wang, *J. Am. Chem. Soc.*, **95**, 1425 (1973).

(39) M. St-Jacques, M. A. Brown, and F. A. L. Anet, *Tetrahedron Lett.*, 5947 (1966).

(40) These results were obtained from mass spectral data and are not corrected for the stereochemical purity. This is essentially due to the lack of a determination method. If we admit as suggested from the $^{2}$H NMR spectrum of *cis*-cyclooctene a content of 20% *trans*-**7** in *cis*-**6**, the isotope effects are then 6, 7, and 6.2. And clearly, the present discussion is still valid.

(41) R. P. Bell, *Chem. Soc., Rev.*, **3**, 513 (1974).

(42) W. B. Chiao and W. H. Saunders, Jr., *J. Am. Chem. Soc.*, **100**, 2802 (1978).

(43) In the absence of any data about thioether carbanion, those of thioethers were used.

(44) N. V. A. Oosthoek's Vitgevers Mij Utrecht, "Molecular Structures and Dimensions", Vol. A1, Crystallographic Data Center Cambridge and International Union of Crystallography, 1972.

(45) A similar idea has been proposed recently for the pyrolysis of sulfoxides and amine oxide.[46]

(46) H. Kwart, T. J. George, R. Louw, and W. Ultee, *J. Am. Chem. Soc.*, **100**, 3927 (1978).

(47) This excludes for this $\alpha'\beta$ elimination a triangular transition state as proposed for the pyrolysis of *tert*-butyl ethyl ether (H. Kwart and J. J. Stanulonis, *J. Am. Chem. Soc.*, **98**, 5249 (1976)).

(48) It should be noticed that, as in the case of the sulfoxides and of some amine oxides,[46] two transition states are possible for the $\alpha'\beta$ elimination: for the carbanion from benzyl cyclooctyl thioether, one where the phenyl group is over the cyclooctyl ring and one where the phenyl ring is anti. Further isotope effect studies should be carried out on the carbanion derived from cyclooctyl methyl thioether.

(49) H. Rheinboldt, F. Mott, and E. Motzkus, *J. Prakt. Chem.*, **134**, 257 (1932).

(50) Cyclooctyl propenyl thioether was not detected when an excess of butyllithium was used.

(51) C. Cope and R. D. Bach, "Organic Syntheses", Collect Vol. V, Wiley, New York, 1973, p 315.

(52) J. L. Schmitt, Thèse de Spécialité, Strasbourg, 1973.

(53) E. Fromm, A. Forster, and B. v. Scherschewitzki, *Justus Liebigs Ann. Chem.*, **394**, 343 (1912).

# Separation of Polar and Resonance Substituent Effects in the Reactions of Acetophenones with Bisulfite and of Benzyl Halides with Nucleophiles[1]

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**Abstract:** Application of the modified Yukawa-Tsuno equation $\log(k/k_0) = \rho\sigma^n + \rho^r(\sigma^+ - \sigma^n)$ to the reversible reaction of bisulfite with substituted acetophenones gives $\rho = 0.6$ and $\rho^r = -0.45$ for the hydroxide ion catalyzed cleavage reaction, $\rho = 1.8$ and $\rho^r = 0.45$ for attack of sulfite dianion, and $\rho = 1.2$ and $\rho^r = 0.95$ for $K_{eq}$ for bisulfite addition. Rate constants for the cleavage reaction exhibit a U-shaped Hammett plot and require a negative value of the $r^+$ parameter, although the reaction is facilitated by electron donation by resonance. Furthermore, the values of $\rho$ and $\rho^r$ for the equilibrium and rate constants in the two directions are additive, but the $r^+$ values are not. The same treatment accounts for most of the curvature in Hammett plots for the $S_N2$ reactions of nucleophiles with benzyl halides without invoking changes in mechanism or transition-state structure. The changes in transition-state structure that do occur in some of these reactions are discussed and it is suggested that the "reactivity-selectivity principle" represents an oversimplification that should be abandoned for all but the simplest reactions.

Hammett $\sigma$ values are based on the ionization constants of benzoic acids, and $\rho\sigma$ correlations are successful when the balance between resonance and polar effects of substituents on a reaction center is the same as for the ionization of benzoic acids. Other $\sigma$ scales have been developed to describe reactions with a different balance of resonance and polar effects, including the $\sigma^+$ scale for reactions in which the relative contributions of resonance and polar effects are the same as in the solvolysis of cumyl chlorides, and the $\sigma^n$ and $\sigma^o$ scales for reactions with no direct resonance contribution.[3-6] The simplest of the several[3,5-11] correlations that have been proposed to allow for varying relative amounts of electron donation by resonance in different reactions is the Yukawa-Tsuno equation[9,10]

$$\log(k/k_0) = \rho(\sigma^n + r^+(\sigma^+ - \sigma^n)) \qquad (1)$$

in which $\sigma^+ - \sigma^n$ is an empirical measure of the ability of a particular substituent to donate electrons by resonance and $r^+$ varies in some manner with varying contributions of resonance effects in different reactions.

We have advocated the use of a slight modification[12] of the Yukawa-Tsuno equation

$$\log(k/k_0) = \rho\sigma^n + \rho^r(\sigma^+ - \sigma^n) \qquad (2)$$

This equation is based on the use of separate $\rho$ and $\rho^r$ parameters for polar and resonance effects, respectively, as suggested earlier by Taft and others,[3,5,6,8,11] but preserves the simplicity of the Yukawa-Tsuno approach.[13] The principal advantage in the use of eq 2 is that $\rho^r$ is a direct measure of the contribution of resonance effects to a particular reaction, in the same sense that $\rho$ is a measure of polar effects, whereas $r^+$, which is equal to the ratio $\rho^r/\rho$, is a measure of the *relative* contributions of polar and resonance effects. The value of $r^+$, therefore, can vary in magnitude, and even in sign, for a series of reactions with a constant resonance contribution if $\rho$ varies independently of $\rho^r$; such variation is known to occur.[8] Furthermore, the values of $\rho$ and $\rho^r$ (in contrast to values of $r^+$) are additive for the equilibrium and rate constants of a reaction in the forward and reverse directions according to

$$\rho_{eq} = \rho_{fwd} - \rho_{rev}$$

and

$$\rho^r{}_{eq} = \rho^r{}_{fwd} - \rho^r{}_{rev}$$

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because $\rho\sigma^n$ and $\rho^r(\sigma^+ - \sigma^n)$ are measures of Gibbs free energy differences. An analogous equation

$$\log (k/k_0) = \rho\sigma^n + \rho^r(\sigma^- - \sigma^n) \qquad (3)$$

may be written for reactions with significant electron withdrawal by resonance. Correlations according to eq 2 and 3 are particularly useful for comparing resonance effects in different reactions and for describing reactions in which resonance and polar effects act in opposite directions, as will be described here.

The cleavage of carbonyl-bisulfite addition compounds ($\alpha$-hydroxysulfonic acids) is subject to both acid and base catalysis.[14-16] The breakdown of bisulfite addition compounds of substituted acetophenones is catalyzed by hydroxide ion through an equilibrium ionization of the $\alpha$-hydroxysulfonic acid, followed by expulsion of sulfite from the dianionic addition intermediate.[15] The rate constants for this reaction are unusual in that a *negative* value of $r^+ = -0.75$ is required to correlate the experimental data according to eq 1, although the reaction is aided by electron donation by resonance from para substituents.

## Experimental Section

**Materials.** Reagent grade inorganic salts were used without further purification. Organic compounds were purified by recrystallization or distillation. Glass-distilled water was used throughout.

Stock solutions of the carbonyl bisulfites were prepared by dissolving a sufficient amount of the carbonyl compound in 1-4 M potassium bisulfite solution to give a final concentration of about 0.01 M and were stored at 4 °C under a nitrogen or argon atmosphere. Aliquots (10-20 $\mu$L) were diluted into thermostated spectrophotometer cells containing 3.0 mL of the desired buffer solution and sufficient hydrogen peroxide (10 $\mu$L of a 31% solution) to oxidize the excess sulfite to sulfate, thereby driving the reaction to completion.[15] Addition of excess hydrogen peroxide gave no detectable change in the observed rate constant. The oxidation of sulfite under the conditions used was much faster than the breakdown of the ketone bisulfites, being complete in the mixing time.

**Kinetic Measurements.** The rates of dissociation of the carbonyl bisulfites were followed by measuring the increase in carbonyl absorbance as previously described.[15,16] Reaction rates were followed using a Zeiss PM6KS spectrophotometer equipped with an automatic cell changer and a digital printout. Constant temperature was maintained at 25 °C by the use of a thermostated cell compartment; the ionic strength was maintained at 1.0 with potassium chloride. First-order rate constants were determined from semilogarithmic plots of $(A_\infty - A_t)$ against time and were typically linear for over 3-4 half-times. The pH of each solution was determined at the completion of the experiment using a Radiometer PHM-26 pH meter equipped with a combined glass electrode. Rate constants for the breakdown of carbonyl bisulfites were determined in acetate, formate, or chloroacetate buffers in the pH range 2.5-5.0. Typically, eight buffer dilutions covering the concentration range 0.1-1.0 M were examined. Rate constants for the buffer-independent breakdown of the carbonyl bisulfites ($k_0$) were obtained by extrapolation of observed rate constants to zero buffer concentration. Rate constants for the specific-base-catalyzed breakdown of the carbonyl bisulfites, $k_{OH}$, were calculated from $k_{OH} = k_0/10^{(pH-14)}$.

## Results and Discussion

**Bisulfite-Acetophenone Reaction.** Rate constants, $k_{OH}$, for the specific-base-catalyzed breakdown of the bisulfite addition compounds of a series of substituted acetophenones are given in Table I. The second-order rate constants, $k_1$, for the attack of sulfite dianion on the acetophenones in the reverse direction were calculated from $k_1 = k_{OH}K_wK_{add}/K_S$, in which $K_{add}$ is the equilibrium constant for bisulfite addition

$$K_{add} = \frac{[\text{>C(OH)SO}_3^-]}{[\text{>C=O}][\text{HSO}_3^-]}$$

(most of these values have been reported previously[12]), $K_S = 10^{-6.61}$ is the observed dissociation constant of bisulfite at ionic strength 1.0, 25 °C, and $K_w$ is the ion product of water (Table I).

**Table I.** Rate and Equilibrium Constants for the Reaction of Bisulfite with Substituted Acetophenones[a]

| substituent | $K_{add}/M^{-1}$ [b] | $k_1/M^{-1}\,s^{-1}$ [c] | $10^{-8}k_{OH}/M^{-1}\,s^{-1}$ [d] |
|---|---|---|---|
| $p$-OCH$_3$ | 1[e] | 23[e] | 5.8 |
| $p$-CH$_3$ | 3 | 46 | 3.8 |
| H | 5.5 | 77 | 3.5 |
| $p$-Cl | 8 | 192 | 6.2 |
| $p$-Br | 9 | 228 | 6.3 |
| $m$-Br | 16 | 384 | 6.2 |
| $p$-NO$_2$ | 44[e] | 1900[e] | 11 |

[a] Ionic strength maintained at 1.0 with KCl, 25 °C. [b] Equilibrium constant for the formation of ketone bisulfite.[12] [c] Second-order rate constant for the attack of sulfite dianion on the carbonyl compounds. [d] Second-order rate constant for the specific-base-catalyzed breakdown of the ketone bisulfites, based on measurements of pH and taking $K_W = 10^{-14}$. [e] Approximate values.

The data in Table I permit an evaluation of the polar and resonance contributions to the effects of substituents on the equilibrium constants and on the rate constants in the two directions for the addition of sulfite to ring-substituted acetophenones. The *equilibrium constants* for bisulfite addition, $K_{add}$, give a poor correlation with Hammett substituents[3] $\sigma$ or $\sigma^n$, with large negative deviations for the $p$-CH$_3$- and $p$-OCH$_3$-substituted compounds. These deviations presumably reflect a stabilization of the acetophenone carbonyl group through electron donation by resonance from these substituents. A better correlation is obtained using the $\sigma^+$ scale ($\rho^+ = 1.0$, correlation coefficient = 0.998) and a still better fit is obtained with the Yukawa-Tsuno approach using substituent constants that vary between $\sigma^+$ and $\sigma^n$ (eq 1 and 2), giving $\rho = 1.2$, $\rho^r = 0.95$, and $r^+ = 0.8$ (correlation coefficient = 0.999).

The rate constants for sulfite addition, $k_1$, give an almost linear correlation with $\sigma$ ($\rho = 1.8$, correlation coefficient = 0.995) and an optimal correlation to eq 1 and 2, with $\rho = 1.8$, $\rho^r = 0.45$, and $r^+ = 0.25$ (correlation coefficient = 0.999).

The rate constants for the specific-base-catalyzed cleavage reaction, $k_{OH}$, are increased by both electron-withdrawing and electron-donating substituents and give a U-shaped curve in correlations against $\sigma$ or $\sigma^n$, with a minimum at the unsubstituted compound and positive deviations for the $p$-Cl and $p$-Br compounds (Table I, Figure 1A). This behavior suggests that the reaction is facilitated both by electron withdrawal through a polar effect and by electron donation through resonance. This behavior can be explained if the observed substituent effects reflect a stabilization of the transition state by electron withdrawal through a polar effect and an additional stabilization by $p$-CH$_3$O, $p$-CH$_3$, and $p$-halide substituents that can donate electrons by resonance to the developing carbonyl group. The rate constants for the $p$-NO$_2$, $m$-Br, and unsubstituted compounds form a linear series against $\sigma^n$ with a value of $\rho = 0.6$. If it is assumed that this value of $\rho = 0.6$ is a measure of the polar effect of substituents, the resonance contribution of substituents may be evaluated from the deviations in the plot of log $k_{OH}$ against $\sigma^n$ (Figure 1A). A correlation of these deviations against $(\sigma^+ - \sigma^n)$, according to eq 2, gives a value of $\rho^r = -0.45$ for the resonance contribution (Figure 1C) and a plot of log $k_{OH}$ against $\sigma^n + (\rho^r/\rho)(\sigma^+ - \sigma^n)$ gives a linear correlation (Figure 1B, correlation coefficient = 0.998). The value of $r^+ = \rho^r/\rho = -0.75$ is negative.

This correlation illustrates one advantage of the use of $\rho^r$ rather than $r^+$ as a measure of the importance of electron donation by resonance. The value of $\rho^r$ and the appropriate substituent constant $(\sigma^+ - \sigma^n)$ provide a direct measure of the Gibbs free energy change caused by electron donation through

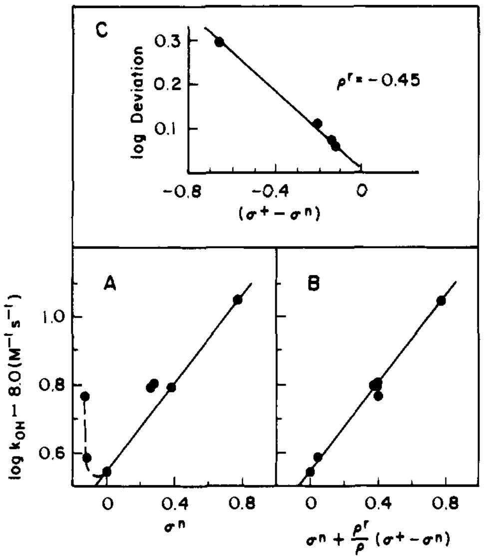
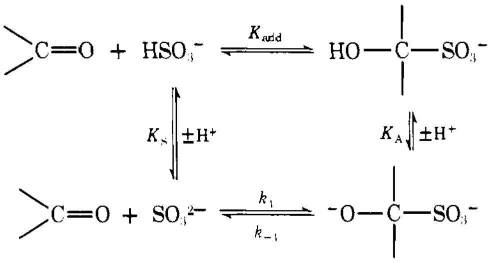


**Figure 1.** (A) Dependence upon $\sigma^n$ of $k_{OH}$ for the specific-base-catalyzed breakdown of acetophenone bisulfites. (B) Dependence of $k_{OH}$ upon $\sigma^n + (\rho^r/\rho)(\sigma^+ - \sigma^n)$. (C) Correlation of the deviations of the points from the solid line in (A) against $(\sigma^+ - \sigma^n)$.

resonance, whereas the coefficient $r^+$ is the ratio of the $\rho$ values for resonance and for polar effects, $\rho^r/\rho$. The coefficient $r^+$ is an unsatisfactory measure of the importance of electron donation by resonance in this reaction because it is *negative*, although the expulsion of bisulfite is certainly aided by electron donation through resonance. The parameter $\rho^r = -0.45$ has the negative sign that is expected for electron donation and provides an unambiguous measure of this resonance contribution. The negative value of $r^+$ is a consequence of the positive sign of $\rho$, which is itself a consequence of the requirement for the loss of a proton from the addition compound in the elimination reaction.

The relationship between the substituent effects on the equilibrium constants and on the rate constants in the two directions may be seen most clearly if the ionization and elimination steps of the breakdown reaction are separated, as shown in eq 4.



(4)

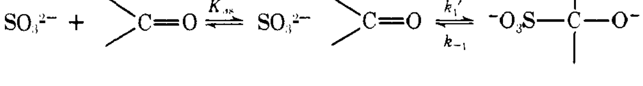
The value of $\rho$ for $K_1 = k_1/k_{-1}$, the equilibrium constant for the addition of sulfite to form the dianion of the addition compound, may be taken as 2.3, based on values of $\rho = 1.2$ for $K_{add}$ and $\rho = 1.1$ for $K_A$. The value of $\rho = 1.1$ for $K_A$ is based on the dissociation constants of substituted trifluoroacetophenone hydrates.[17] The value of $\rho$ for $k_{-1}$ is −0.5, from $\rho = 0.6$ for $k_{OH}$ and $\rho = 1.1$ for $K_A'$. The values of $\rho = -0.5$ for $k_{-1}$, $\rho = 1.8$ for $k_1$, and $\rho = 2.3$ for $K_1$ satisfy the required additivity of $\rho$ values for rate and equilibrium constants according to $\rho_{eq} = \rho_{fwd} - \rho_{rev}$.

The resonance contribution to the substituent effect on $K_1$, $\rho^r = 0.95$, may be taken as essentially the same as that on $K_{add}$, since there is no change in conjugation with the benzene ring in the $K_A$ step. The value of $\rho^r$ for $k_1$ is 0.45, and $\rho^r$ for $k_{OH}$ and for $k_{-1}$ is −0.45. These values show the expected additivity according to $\rho^r{}_{eq} = \rho^r{}_{fwd} - \rho^r{}_{rev}$, within experimental error. However, the values of $r^+$ for the rate and equilibrium constants are not additive, because they represent ratios of $\rho$ values, and cannot be used to compare directly the resonance contributions to substituent effects in the two directions of a reaction.

The reason for the opposite effects on $k_{OH}$ of substituents that act through resonance and through polar effects, as manifested in the opposite signs of $\rho^r$ and $\rho$, is that polar substituents affect both proton removal and sulfite expulsion, but in opposite directions, whereas electron donation by resonance into the developing carbonyl group favors only sulfite expulsion. Since the polar effect on proton removal ($\rho = 1.1$) is larger than that on $k_{-1}$ for sulfite expulsion from the dianion ($\rho = -0.45$), the observed sign of $\rho$ is opposite to that of $\rho^r$.

The equal numerical values of $\rho^r = +0.45$ and $-0.45$ for the rate constants in the forward and reverse directions suggest that the transition state is approximately midway between reactants and products with respect to the development of resonance. However, the values of $\rho = 1.8$ for $k_1$ and $\rho = -0.5$ for $k_{-1}$ suggest that the charge development on the central carbon atom in the transition state more closely resembles that in the dianionic addition compound than that in acetophenone; in terms of the change in charge that is "seen" by the substituent the addition reaction has proceeded some 1.8/2.3 = 80% toward the addition compound in the transition state. This is an example of *imbalance* of the extent to which polar and resonance effects are manifested in the transition state. This behavior is the opposite of what has been observed for the dehydration of benzaldehyde carbinolamines[18] and the ionization of nitroalkanes,[19,20] for which the development of resonance stabilization lags behind other processes in the transition state.

The apparent imbalance in the sulfite reaction may be attributed, at least in large part, to a simple electrostatic effect that is caused by the proximity of the sulfite dianion to the substituent in the transition state. The transition state contains two additional negative charges provided by the sulfite dianion that will be stabilized by electron-withdrawing substituents on the acetophenone and will, therefore, increase the observed value of $\rho$. To a first approximation, this direct electrostatic effect will be independent of small differences in the amount of C–S bond formation and loss of conjugation with the carbonyl group. If we assume that the transition state is midway between reactants and products with respect to polar as well as resonance effects of substituents, then the values of $\rho$, in the absence of the electrostatic effect, are 0.5 and −0.5 for $k_1'$ and $k_{-1}$, respectively. The rate constant $k_1'$ is a first-order rate constant for the addition reaction starting with an encounter complex or "reaction complex"[21] in which the electrostatic effect has already been manifested.



Since $k_1(\text{obsd}) = k_1'/K_{as}$, the value of $\rho$ for the electrostatic effect on $K_{as}$ for the formation of this complex is 1.8 − 0.5 = 1.3. This is not an unreasonable value for the effect of two negative charges in view of the values of $\rho = 1.1$ and 0.49 for the ionization of substituted trifluoroacetophenone hydrates[17] and phenylacetic acids,[22] respectively.

**Benzyl Halides.** There is no reason that polar and resonance effects cannot act in opposite directions in one-step as well as in two-step reactions.[8] The open circles in Figure 2 show Hammett plots, based on $\sigma^n$ and the rate constants determined by Hudson and Klopman,[23] for the reactions of $p$-MeO, H, and $p$-MeCO benzenethiolate anions with substituted benzyl bromides in methanol. U-Shaped curves of this kind, with a minimum at the unsubstituted compound, are commonly observed for the reactions of benzyl halides with anionic nucleophiles;[23-27] the rate minimum is, of course, also present in correlations with $\sigma$ or $\sigma^+$. There are three explanations for this behavior and for the curvature that is observed in almost all Hammett correlations of the reactions of benzyl halides.[25,27-41]

(1) There is a change in *mechanism* from $S_N2$ to $S_N1$ or an ion-pair mechanism on going from electron-withdrawing to electron-donating substituents.[28,29,39]

(2) There is a change in the *structure* of the transition state for a single mechanism with a differing balance of bond formation and cleavage, such that electron-donating substituents cause a shift to a transition state with more positive charge development on the central carbon atom.[23,27,30-39,41]

(3) Different *substituents* act to stabilize the transition state with a differing balance of polar and resonance effects (a two-interaction mechanism[11]).

It is probable that all three of these mechanisms contribute to the observed behavior of some reactions of benzyl halides under some conditions, but most workers have favored explanations 1 and 2. We wish to examine the hypothesis that much, or most, of the curvature in structure-reactivity correlations for these reactions may be accounted for by explanation 3. The solid circles in Figure 2 show that a linear rather than a U-shaped correlation is obtained if the rate constants are plotted according to eq 2 with $\rho = 1.35$ ($p$-MeOPhS$^-$), 1.06 (PhS$^-$), and 0.86 ($p$-MeCOPhS$^-$), and $\rho^r = -1.3$. The value of $\rho^r$ was determined from a plot against $(\sigma^+ - \sigma^n)$ of the deviations from correlations with $\rho\sigma^n$ (analogous to Figure 1C). We conclude that, although some contribution of explanations 1 and 2 cannot be excluded, the data can be satisfactorily accounted for by explanation 3 with opposite signs of $\rho$ and $\rho^r$. Again, the values of $r^+ = \rho^r/\rho$ are negative, although electron donation by resonance certainly stabilizes the transition state.

The fact that qualitatively similar behavior is observed for a large number of different reactions of benzyl halides with nucleophiles of a given charge type in different solvents is consistent with explanation 3 and is difficult to explain according to (1) and (2), because it would be expected that a change in mechanism or transition-state structure would occur at a different point or not at all with different reactions and conditions. In most cases substituents that act only by a polar effect exhibit a positive $\rho$ with anionic nucleophiles and a negative $\rho$ with uncharged nucleophiles and in solvolysis, whereas substituents that donate electrons by resonance exhibit a positive deviation from the correlation line for polar substituents that gives rise to upward curvature for the $p$-$CH_3$ and $p$-$CH_3O$ substituents. In particular, the reactions of 4-substituted benzyl chlorides with thiosulfate in 60% acetone follow two different U-shaped Hammett plots for the 3-H and 3-$NO_2$ series of compounds, rather than the single smooth curve that would be expected from a gradually changing transition-state structure.[25] The rising left limbs of both curves are caused by the faster rates for the $p$-$CH_3O$ and $p$-$CH_3$ substituents that provide electron donation by resonance.

The positive $\rho$ value for the reactions of benzyl halides with anionic nucleophiles, which is responsible for the U-shaped curves that are usually observed for these reactions, has been attributed to a later transition state with more bond formation for such nucleophiles.[27] However, it can also be accounted for by a simple electrostatic effect resulting from the addition of a net negative charge to the transition state that is "seen" by polar substituents, as suggested above for the addition of sulfite to substituted acetophenones and elsewhere for a number of nucleophilic reactions.[20,34,42,43] The observed $\rho$ values are comparable to the value of $\rho = 1.1$ for the development of a negative charge upon the ionization of trifluoroacetophenone hydrates.[17] Positive $\rho$ values have also been found for the reactions of $ArCH_2CH_2Cl$ with $I^-$,[44] and of 4-substituted 1-bicyclo[2.2.2]octamethyl tosylates with benzenethiolate anion, in which the reaction center is well insulated from the substituent, and were attributed to a simple electrostatic effect in the latter reaction.[43]

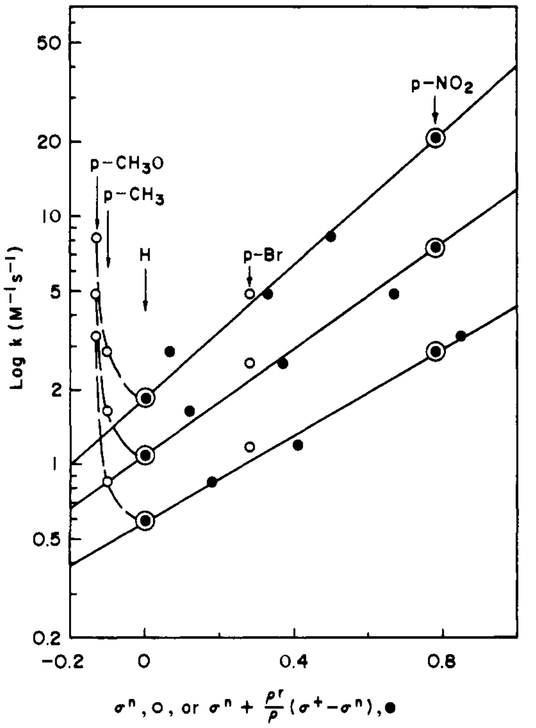


**Figure 2.** Hammett correlations of the rates of reactions of substituted benzyl bromides with $p$-$CH_3OPhS^-$ (top line), $PhS^-$ (center line), and $p$-$CH_3COPhS^-$ (bottom line).[23] Open circles: correlation with $\sigma^n$. Closed circles: correlation with $\sigma^n + \rho^r/\rho\ (\sigma^+ - \sigma^n)$.

**Table II.** Substituent Effects for the Attack of Substituted Anilines on Substituted Benzyl Chlorides[a]

| substituted aniline | $-\rho$[b] | $-\rho^r$[c] | $r^+ = \rho^r/\rho$ |
|---|---|---|---|
| $p$-$OCH_3$ | 0.2 | 1.8 | 9 |
| $p$-$CH_3$ | 0.3 | 1.9 | 6.3 |
| H | 0.5 | 1.8 | 3.6 |
| $p$-Cl | 0.6 | 1.9 | 3.2 |
| $m$-Cl | 0.8 | 2.0 | 2.5 |

[a] In ethanol, from ref 35. [b] Based on data for benzyl chloride and $p$-nitrobenzyl chloride. [c] Based on the deviation of the point for $p$-methoxybenzyl chloride from the line defined by benzyl chloride and $p$-nitrobenzyl chloride.

The advantage of using $\rho^r$ (eq 2) rather than $r^+$ (eq 1) as a measure of electron donation by resonance is illustrated in a different way by the reactions of substituted anilines with a series of substituted benzyl chlorides in ethanol.[35] The positive deviations in a plot against $\sigma^n$ of the points for the $p$-$CH_3O$, $p$-$CH_3$, and $p$-Cl compounds (Figure 3) may be attributed to resonance stabilization of the transition state. Values of $r^+$ ranging from 2.5 to 9 are required to account for the positive deviations of the points for the $p$-$CH_3O$ compound according to eq 1, whereas the deviations are accounted for by a single value of $\rho^r = -1.9 \pm 0.1$ (Table II, Figure 3, inset). This value of $\rho^r$ implies an almost constant amount of resonance stabilization in the series, whereas the use of $r^+$ as a measure of resonance stabilization would lead to the unlikely conclusion that there is more than a threefold variation in the amount of electron donation by resonance as the structure of the aniline is varied. The second-order kinetics of these reactions, the regular decrease in $\rho$ for substituted anilines with electron donation on the benzyl chlorides (including the $p$-$CH_3O$ and

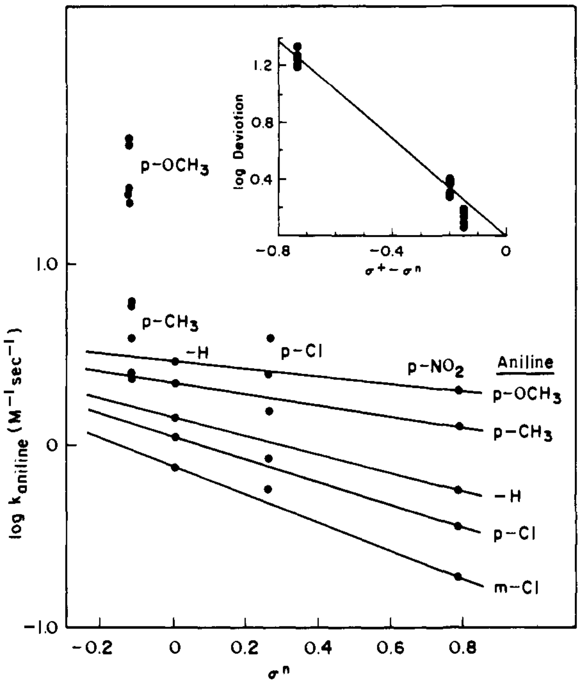


Figure 3. Dependence of the rate of aminolysis of substituted benzyl chlorides by a series of substituted anilines upon $\sigma^n$.[35] Inset: correlation with ($\sigma^+ - \sigma^n$) of the deviation of the points in the $\sigma^n$ plots.

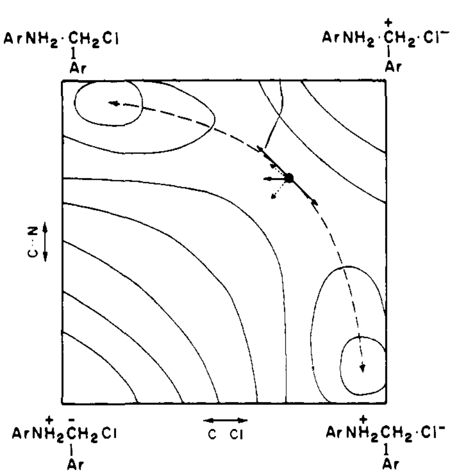


Figure 4. Reaction coordinate-energy contour diagram for the reaction of substituted benzyl chlorides with substituted anilines, with separate axes for C-N and C-Cl bond cleavage and formation. The arrows show how the transition state might be expected to move to the left with electron-donating substituents that increase the energy of the aniline, as the resultant of motions parallel and perpendicular to the reaction coordinate.

$p$-$CH_3$ compounds),[35] and the correlations shown in Figure 3 support the interpretation of the structure-reactivity data according to eq 2, rather than a change in mechanism with changing substituents.

**Structure-Reactivity Interactions.** Although a variable combination of polar and resonance effects, as described by $\rho$ and $\rho^r$, can account for the greater part of the observed curvature in structure-reactivity correlations of displacement reactions on benzyl halides, there is evidence that changes in transition-state structure also occur and can cause changes in the slopes of structure-reactivity correlations.

It is evident in Figure 3 that there is a decreasing sensitivity of the reaction to polar substituents on the benzyl chloride as the aniline becomes more basic, with $\rho$ changing from −0.8 for $m$-chloroaniline to −0.2 for $p$-methoxyaniline (Table II). This is evidence for the operation of explanation 2 above, a change in transition-state structure, with a decrease in positive charge development on the central carbon atom in the transition state as the nucleophile becomes more basic. Similar behavior has been observed for other reactions of benzyl halides with nucleophiles.[23,45] The result for the aniline reaction can be described according to[20]

$$p_{xy'} = \frac{\partial \rho_b}{-\partial \sigma_{an}} = \frac{\partial \rho_{an}}{-\partial \sigma_b} \qquad (5)$$

and a plot of $\rho_b$ (for the benzyl chloride) against $-\sigma_{an}$ (for the aniline) is linear with a slope of $p_{xy'} = 0.95$. As required by eq 5 there is also an increase in the sensitivity of the rate to the basicity of the aniline ($\beta_{nuc}$ or $-\rho_{an}$) with electron-withdrawing substituents on the benzyl halide (increasing $\sigma_b$).[35] The value of $\rho_{an}$ changes from −0.59 for $p$-$CH_3OPhCH_2Cl$ to −1.55 for $p$-$NO_2PhCH_2Cl$ and a plot of $\rho_{an}$ against $-\sigma_b$ gives a value of $p_{xy'} = 0.93$. This coefficient may be normalized[46] to an approximate value of $p_{xy'} = 0.045$, using limiting values of $\rho_b = -4.95$ for the solvolysis of $\alpha$-methylbenzyl chlorides (in 80% aqueous acetone)[47] and $\rho_{an} = -4.20$ for the protonation of anilines (in ethanol).[8] Some, but certainly not all, of this interaction coefficient can be accounted for by a simple electrostatic interaction between the substituents on the aniline and on the benzyl chloride; the maximum electrostatic contribution to $p_{xy'}$ is $\lesssim 0.024$.[20,48] There must, therefore, be a change in transition-state structure with changing substituents on the reactants.

It is convenient to illustrate these changes in transition-state structure on a reaction-coordinate-energy contour diagram with separate axes for N-C and C-Cl bond formation and cleavage and an energy surface in the third dimension (Figure 4). Such diagrams were first used by Hughes, Ingold, and Shapiro to describe changes in transition-state structure in this type of reaction[31] and have been utilized more recently for this[27,33,38,39,49] and other[20,50] classes of reactions. An increase in basicity of the aniline increases the energy of the upper relative to the lower edge of the diagram. If the reaction coordinate is diagonal there will then be a tendency for the position of the transition state to slide downhill toward the lower left corner (perpendicular to the reaction coordinate, an "anti-Hammond" effect) and to shift uphill toward the upper left corner (parallel to the reaction coordinate, a "Hammond effect"), so that there is a net shift to the left and away from the carbenium ion intermediate in the upper right corner. This corresponds to the observed increase in $\rho_b$. Conversely, an electron-withdrawing substituent on the benzyl chloride will increase the energy of the upper right relative to that of the lower left corner so that a transition state on a diagonal reaction coordinate will tend to slide downhill, perpendicular to the reaction coordinate, toward the lower left corner. This will give a shift in the direction of more N-C bond formation and a more negative $\rho_{an}$, as observed. These two changes are complementary and are described by a positive interaction coefficient, $p_{xy'}$, of eq 5.

There is other evidence that substituents on the benzyl halide can shift the position of the transition state along the diagonal axis, toward or away from the carbenium ion intermediate, so that explanation 2 as well as explanation 3 can contribute to curvature in Hammett correlations.[31,38,39] The reaction of pyridine with benzyl bromides in dry acetone follows a U-shaped Hammett plot with a minimum rate for the $p$-nitro compound and a rate increase for 2,4-dinitrobenzyl bromide;[30] this upward curvature is not caused by electron donation by resonance.[51] Similarly, the increasing chloride isotope effects in the series $p$-nitro, unsubstituted, and $p$-methoxybenzyl chlorides reacting with methoxide and with benzenethiolate anions suggest that there is a shift in transition-state structure in the direction of increased C–Cl cleavage with electron-donating substituents on the benzyl halide.[26]

The solvolysis of benzyl compounds exhibits an increase in the $\alpha$ secondary deuterium isotope effect with electron-donating substituents on the benzene ring that is evidence for a shift toward a transition state that more closely resembles the carbenium ion.[52,53] The observed Grunwald–Winstein $m_{GW}$ values decrease with electron-withdrawing substituents for the solvolysis of benzyl brosylates in ethanol–water mixtures[52] with a slope of $-dm_{GW}/d\sigma = 0.17-0.21$, but the $m_{GW}$ values decrease much more sharply for the solvolysis of benzyl chlorides in trifluoroethanol–ethanol mixtures[36,54] with a slope of $-dm_{GW}/d\sigma^+ = 1.0-1.3$. This result can be accounted for according to the extended Grunwald–Winstein equation

$$\log\left(\frac{k}{k_0}\right) = mY + lN$$

in which $Y$ and $N$ are the ionizing power and nucleophilicity of the medium, respectively, and $m$ and $l$ are parameters describing the sensitivity of a reaction to $Y$ and $N$.[37,55] The nucleophilicity of the solvent, $N$, changes much more rapidly than the ionizing power, $Y$, in trifluoroethanol–ethanol mixtures compared with ethanol–water mixtures and Kaspi and Rappoport have shown that the proportionality constant $a$ in the relationship $N = aY + b$ is $-0.85$ and $-0.071$, respectively, for these two solvent mixtures.[36] The large change in the observed $m_{GW}$ values in trifluoroethanol–water mixtures therefore suggests that there is an increase in the amount of nucleophilic attack in the transition state with electron-withdrawing substituents on the benzyl derivative. Kaspi and Rappoport's equation[36] $m = m_{GW} - al$ for the two solvent mixtures gives

$$l = (m_E - m_T)/0.78 \tag{6}$$

and

$$m = m_E + 0.071l \tag{7}$$

in which $m_E$ and $m_T$ are the observed Grunwald–Winstein values, $m_{GW}$, in the two solvent mixtures. Solution of these equations gives values of $m$ which decrease slightly and values of $l$ which increase sharply with electron-withdrawing substituents (Table III). These values are far from exact, in view of the curvature in the Grunwald–Winstein plot for trifluoroethanol–ethanol mixtures and other approximations in the calculations, but they do suggest that there is a progressive increase in the amount of bond formation to the attacking solvent molecule in the transition state with electron-withdrawing substituents. This, and the smaller decrease in $m$, corresponds to movement of the transition state toward the lower left corner in Figure 4. The observed increase in selectivity for ethanol–trifluoroethanol in the series *p*-methyl-, unsubstituted, and *m*-fluorobenzyl chlorides, as measured by product analysis, provides further evidence for such a shift in the transition state.[54] Harris and co-workers have reached a similar conclusion from a comparison of the solvolysis rates of benzyl chlorides in ethanol–water and in trifluoroethanol–water mixtures.[56]

There is conflicting evidence as to whether changes in transition-state structure occur in simple displacement reactions on methyl compounds,[38,57-59] but it is probable that such changes are smaller than in displacements on benzyl compounds if they occur at all. Ingold et al. pointed out that when the carbenium ion intermediate in the upper right corner of the diagram of Figure 4 is of high energy, as in the case of a methyl compound, there will be a steep barrier perpendicular to the reaction coordinate.[31] This imposes a sharp curvature perpendicular to the reaction coordinate that is expected to inhibit movement of the transition state on the energy surface, compared with the shallower curvature of the surface for benzyl compounds. When this curvature is sufficiently steep, motion of the transition state perpendicular to the reaction coordinate may be neglected and the reaction may be described according to the two-dimensional reaction-coordinate-energy diagram that is usually used in applications of Hammond's postulate. When it is less steep and the transition state moves perpendicular to the reaction coordinate, as in the reactions of benzyl compounds, the two-dimensional "Hammond postulate" description is an oversimplification and the reaction may be adequately described only by a three-dimensional diagram such as Figure 4.

**Table III.** Calculated Values of the Grunwald–Winstein Parameters $m$ and $l$ for the Solvolysis of Benzyl Derivatives in Ethanol–Water and Trifluoroethanol–Ethanol Mixtures[a]

| benzyl derivative | $m_E$ | $m_T$ | $m$ | $l$ |
|---|---|---|---|---|
| *p*-$CH_3$- | 0,48[b] | 0.47[c] | 0.47 | 0 |
| H- | 0.42[d] | 0.04[c] | 0.44 | 0.48 |
| *m*-F- | 0.35[b] | −0.30[c] | 0.41 | 0.83 |
| *m*-CF- | 0.30[d] | −0.58[b] | 0.37 | 1.1 |
| *p*-$NO_2$- | 0.28[d] | −0.86[b] | 0.38 | 1.5 |

[a] Calculated from eq 6 and 7. [b] Calculated from $-dm_E/d\sigma = 0.19$ and $-dm_T/d\sigma^+ = 1.15$. [c] For benzyl chlorides.[36,54] [d] For benzyl brosylates.[52] Winstein et al. report values of $m_{GW} = 0.425$ for benzyl chloride and $m_{GW} = 0.394$ for benzyl tosylate.[55]

It is commonly assumed that the total bond order to a central carbon atom remains constant during a reaction. When this is the case it may be reasonable to describe structure–reactivity behavior of displacement reactions on a methyl group in terms of only the bonds that are being formed and broken and with a two-dimensional reaction-coordinate diagram. However, in benzyl compounds account must be taken of electron donation to the central carbon atom from the benzene ring and its substituents, perpendicular to the bonds that are forming and breaking, so that the sum of the bond orders to the attacking and leaving atoms can change without changing the total bond order to the central carbon atom. Changes in this perpendicular bonding can be described by a diagram such as Figure 4, but not by a simple two-dimensional reaction coordinate–energy profile, and must be taken into account in considerations of the structure–reactivity behavior of these reactions.

The rate constants on the right-hand side of Figure 2 show that for the more reactive thiol anions there is a *larger* selectivity for substituents on the benzyl bromide and, conversely, for the more reactive benzyl bromides there is a larger sensitivity toward the nucleophilicity of the attacking thiol anion.[22] There has been much discussion of the "reactivity-selectivity principle" (RSP)[58,60] and these results might be taken as an example of a "failure" of this principle.

In fact, the data are consistent with the behavior that is expected from the reaction-coordinate diagram of Figure 4 and the above discussion. The sign of the structure–reactivity coefficient $p_{xy'} = \partial\rho_b/-\partial\sigma_{nuc} = \partial\rho_{nuc}/-\partial\sigma_b$ and the directions of the shifts in the position of the transition state with changing structure are the same as for the aniline series, so that the properties of the transition state are very similar for these two related reactions according to these criteria. The different sign of $\rho$ in the two reactions may be attributed to a simple, constant electrostatic effect resulting from the introduction of an additional negative charge into the transition state in the thiol anion reaction, as suggested above for other reactions of anionic nucleophiles. We suggest that the "reactivity-selectivity principle" is an oversimplification because it takes into account only one of the several factors that influence changes in transition-state structure.

It is also considered a failure of the RSP if no changes in structure–reactivity parameters and the position of the transition state are observed when the reactivity of the reactants is changed. Such changes depend on the direction of the reaction coordinate and the curvatures parallel and perpendicular to the reaction coordinate in the diagram of Figure 4, and no change will be observed if (a) there is a cancellation of the vectors for movement parallel and perpendicular to the reaction coordinate so as to produce no net movement in one direction[20,33,39] or (b) the curvatures are sufficiently steep as to give no significant shift of the transition state with a given change in structure, as noted above. For example, the absence of a change in the value of $\beta_{nuc}$ for the alkylation of pyridines over a range of $10^8$ in reaction rate[59] and the large shifts in transition-state structure in the benzyl halide series are consistent with the expected steep upward curvature perpendicular to the reaction coordinate in the direction of carbenium ion formation in the former reaction and a much smaller curvature that reflects the smaller barrier for formation of the carbenium ion in the latter reaction.

Thus, we believe that all reactions should not be expected to follow the "RSP" and that the RSP should be abandoned as a general principle. Changes in structure-reactivity relationships that do not follow the RSP do not represent failures of reactions to follow rational structure-reactivity principles, but rather provide useful information from which differences in the properties of transition states and their surrounding energy surfaces may be inferred for different classes of reactions.

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## References and Notes

(1) Supported in part by grants from the National Science Foundation (BM471-01501) and the National Institute of General Medical Sciences of the National Institutes of Health (GM20888).
(2) P.R.Y. was partially supported by a fellowship (CA 05356) from the National Cancer Institute of the National Institutes of Health.
(3) Hine, J. "Structural Effects on Equilibria in Organic Chemistry", Wiley: New York, 1975; Chapter 3.
(4) Brown, H. C.; Okamoto, Y. *J. Am. Chem. Soc.* **1958**, *80*, 4979-4987.
(5) Taft, R. W., Jr.; Ehrenson, S.; Lewis, I. C.; Glick, R. E. *J. Am. Chem. Soc.* **1959**, *81*, 5352-5361.
(6) Hoefnagel, A. J.; Wepster, B. M. *J. Am. Chem. Soc.* **1973**, *95*, 5357-5366.
(7) Taft, R. W., Jr.; Lewis, I. C. *J. Am. Chem. Soc.* **1958**, *80*, 2436-2443. **1959**, *81*, 5343-5352.
(8) Ehrenson, S.; Brownlee, R. T. C.; Taft, R. W. *Prog. Phys. Org. Chem.* **1973**, *10*, 1-80.
(9) Yukawa, Y.; Tsuno, Y. *Bull. Chem. Soc. Jpn.* **1959**, *32*, 965-971, 971-981.
(10) Yukawa, Y.; Tsuno, Y.; Sawada, M. *Bull. Chem. Soc. Jpn.* **1966**, *39*, 2274-2286.
(11) Leffler, J. E.; Grunwald, E. "Rates and Equilibria of Organic Reactions," Wiley: New York, 1963; p 192.
(12) Young, P. R.; Jencks, W. P. *J. Am. Chem. Soc.* **1977**, *99*, 8238-8248.
(13) Yukawa and Tsuno considered an equation of the same form as eq 2, but preferred eq 1 and have utilized $r$ (or $r^+$) as a measure of the contribution of the resonance effect to structure-reactivity correlations.[9,10]
(14) Stewart, T. D.; Donnally, L. H. *J. Am. Chem. Soc.* **1932**, *54*, 2333-2340.
(15) Young, P. R.; Jencks, W. P. *J. Am. Chem. Soc.* **1977**, *99*, 1206-1214.
(16) Young, P. R.; Jencks, W. P. *J. Am. Chem. Soc.* **1978**, *100*, 1228-1235.
(17) Stewart, R.; Van Der Linden, R. *Can. J. Chem.* **1960**, *38*, 399-406.
(18) Funderburk, L. H.; Jencks, W. P. *J. Am. Chem. Soc.* **1978**, *100*, 6708-6714.
(19) Bordwell, F. G.; Boyle, W. J., Jr. *J. Am. Chem. Soc.* **1972**, *94*, 3907-3911. Kresge, A. J. *Can. J. Chem.* **1974**, *52*, 1897-1903.
(20) Jencks, D. A.; Jencks, W. P. *J. Am. Chem. Soc.* **1977**, *99*, 7948-7960.
(21) Hassid, A. I.; Kreevoy, M. M.; Liang, T.-M. *Faraday Symp. Chem. Soc.* **1975**, *10*, 69.
(22) Jaffé, H. H. *Chem. Rev.* **1953**, *53*, 191-261.
(23) Hudson, R. F.; Klopman, G. *J. Chem. Soc.* **1962**, 1062-1067.
(24) Bennett, G. M.; Jones, B. *J. Chem. Soc.* **1935**, 1815-1819. Baker, J. W.; Nathan, W. S. *Ibid.* **1936**, 236-241. Miller, W. T., Jr.; Bernstein, J. *J. Am. Chem. Soc.* **1948**, *70*, 3600-3604. Sugden, S.; Willis, J. B. *J. Chem. Soc.* **1951**, 1360-1363. Fuchs, R.; Nisbet, A. *J. Am. Chem. Soc.* **1959**, *81*, 2371-2373.
(25) Fuchs, R.; Carlton, D. M. *J. Org. Chem.* **1962**, *27*, 1520-1523.
(26) Grimsrud, E. P.; Taylor, J. W. *J. Am. Chem. Soc.* **1970**, *92*, 739-741.
(27) Thorstenson, T.; Eliason, R.; Songstad, J. *Acta Chem. Scand., Ser. A* **1977**, *31*, 276-280.
(28) Okamoto, Y.; Brown, H. C. *J. Org. Chem.* **1957**, *22*, 485-494. Hill, J. W.; Fry, A. *J. Am. Chem. Soc.* **1962**, *84*, 2763-2769. Aronovitch, H.; Pross, A. *Tetrahedron Lett.* **1977**, 2729-2732.
(29) Graczyk, D. G.; Taylor, J. W.; Turnquist, C. R. *J. Am. Chem. Soc.* **1978**, *100*, 7333-7339.
(30) Baker, J. W.; Nathan, W. S. *J. Chem. Soc.* **1935**, 1840-1844.
(31) Hughes, E. D.; Ingold, C. K.; Shapiro, U. G. *J. Chem. Soc.* **1936**, 225-236.
(32) Swain, C. G.; Langsdorf, W. P., Jr. *J. Am. Chem. Soc.* **1951**, *73*, 2813-2819.
(33) Thornton, E. R. *J. Am. Chem. Soc.* **1967**, *89*, 2915-2927.
(34) Harris, J. C.; Kurz, J. L. *J. Am. Chem. Soc.* **1970**, *92*, 349-355.
(35) Ballistreri, F. P.; Maccarone, E.; Mamo, A. *J. Org. Chem.* **1976**, *41*, 3364-3367.
(36) Kaspi, J.; Rappoport, Z. *Tetrahedron Lett.* **1977**, 2035-2038.
(37) Schadt, F. L.; Bentley, T. W.; Schleyer, P. v. R. *J. Am. Chem. Soc.* **1976**, *98*, 7667-7674.
(38) Albery, W. J.; Kreevoy, M. M. *Adv. Phys. Org. Chem.*, **1978**, *16*, 87-157.
(39) Harris, J. M.; Shafer, S. G.; Moffatt, J. R.; Becker, A. R. *J. Am. Chem. Soc.*, following paper in this issue.
(40) Willi, A. V.; Ho, C.-k.; Ghanbarpour, A. *J. Org. Chem.* **1972**, *37*, 1185-1189.
(41) Hammond, G. S.; Reeder, C. E.; Fang, F. T.; Kochi, J. K. *J. Am. Chem. Soc.* **1958**, *80*, 568-573.
(42) Hine, J. *J. Am. Chem. Soc.* **1959**, *81*, 1126-1129. Koehler, K.; Skora, R.; Cordes, E. H. **1966**, *88*, 3577-3581. Funderburk, L.; Aldwin, L.; Jencks, W. P. *ibid.* **1978**, *100*, 5444-5459.
(43) Holtz, H. D.; Stock, L. M. *J. Am. Chem. Soc.* **1965**, *87*, 2404-2409.
(44) Baddeley, G.; Bennett, G. M. *J. Chem. Soc.* **1935**, 1819-1821.
(45) Radhakrishnamurti, P. S.; Panigrahi, G. P. *Bull. Chem. Soc. Jpn.* **1970**, *43*, 81-84.
(46) The coefficient $p_{xy'}$ is normalized, for the overall equilibrium and to convert $\sigma$ to a standard scale based on log $K$, by multiplying by $1/\rho_{an}\rho_b$.[20]
(47) Tsuno, Y.; Kuguyama, Y.; Sawada, M.; Fujii, T.; Yukawa, Y. *Bull. Chem. Soc. Jpn.* **1975**, *48*, 3337-3346.
(48) Hine, J. *J. Am. Chem. Soc.* **1972**, *94*, 5766-5771. See also footnote 26 of ref 18.
(49) Lowry, T. H.; Richardson, K. S. "Mechanism and Theory in Organic Chemistry," Harper and Row: New York, 1976; Chapter 5. Shiner, V. S.; Seib, R. C. *J. Am. Chem. Soc.* **1976**, *98*, 862-864.
(50) See, for example, More O'Ferrall, R. A. *J. Chem. Soc. B* **1970**, 274-277. Jencks, W. P. *Chem. Rev.* **1972**, *72*, 705-718.
(51) An alternative explanation has been proposed (Streitwieser, A. "Solvolytic Displacement Reactions," McGraw-Hill: New York, 1962; p 28) but lacks support from other experimental evidence.
(52) Shiner, V. J., Jr.; Rapp, M. W.; Pinnick, H. R., Jr. *J. Am. Chem. Soc.* **1970**, *92*, 232-233.
(53) Koshy, K. M.; Robertson, R. E. *Can. J. Chem.* **1974**, *52*, 2485-2490.
(54) da Roza, D. A.; Andrews, L. J.; Keefer, R. M. *J. Am. Chem. Soc.* **1973**, *95*, 7003-7009.
(55) Winstein, S.; Grunwald, E.; Jones, H. W. *J. Am. Chem. Soc.* **1951**, *73*, 2700-2707.
(56) Harris, J. M.; Mount, D. L.; Smith, M. R.; Neal, W. C., Jr.; Dukes, M. D.; Raber, D. J. *J. Am. Chem. Soc.* **1978**, *100*, 8147-8156.
(57) Lewis, E. S.; Vanderpool, S. H. *J. Am. Chem. Soc.* **1977**, *99*, 1946-1949. **1978**, *100*, 6421-6425.
(58) Giese, B. *Angew. Chem., Int. Ed., Engl.* **1977**, *16*, 125-136.
(59) Arnett, E. M.; Reich, R. *J. Am. Chem. Soc.* **1978**, *100*, 2930-2931.
(60) See, for example, Ritchie, C. D. *Acc. Chem. Res.* **1972**, *5*, 348-354. Kemp, D. S.; Casey, M. L. *J. Am. Chem. Soc.* **1973**, *95*, 6670-6680. Johnson, C. D. *Chem. Rev.* **1975**, *75*, 755-765. Pross, A. *Adv. Phys. Org. Chem.* **1977**, *14*, 69-132. McLennan, D. J. *Tetrahedron* **1978**, *34*, 2331-2342.