Nucleophilic Substitution at Sulfur. Effect of Nucleophile and Leaving Group Basicity as Probe of Bond Formation and Breaking

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Abstract: The effect of the basicity of nucleophile and leaving group on the reaction of oxygen nucleophiles with aryl esters of methanesulfinic acid has been investigated. Plotted in a Brønsted fashion, the data give a good linear correlation for the leaving group ($\beta_L = -0.71$), but not for the nucleophile. Here the Brønsted slope changes from a high value ($\beta_N \simeq 0.75$) at the low basicity end (phenoxides) to a low value ($\beta_N \simeq 0$) at the high basicity end (alkoxides and hydroxide). The substituent effect has been determined using as substrates the benzyl esters of arenesulfinic acids, yielding a Hammett ρ of $+1.56$. These results are discussed, together with other ones recently obtained in this and other laboratories. The mechanistic significance of the Brønsted slopes is also critically examined in the light of the more recent theoretical treatments of nucleophilic substitutions. It is concluded that the relation between Brønsted slopes and bond orders at the transition state is far from straightforward and that much of the mechanistic implications commonly based on them, especially those based on isolated β values, are largely unwarranted.

The question whether the direct nucleophilic substitution reaction at the sulfur atom is a one-step concerted process (S$_N$2) or a two-step addition–elimination involving a metastable intermediate (S$_A$N) has been widely investigated in recent years.[2–9] Short of the physical detection of an intermediate,[10] the assignment of a particular reaction to one or the other mechanistic category must rest on indirect evidence which seldom is clear-cut. The least ambiguous indirect evidence is that which can be obtained through exchange experiments of the kind inaugurated by Bender and which resolved the same question for nucleophilic displacement at the carbonyl carbon of carboxylic acid esters.[11] When the results of such experiments are negative, however, the question remains open. This is the case for substitution at sulfur where all attempts in this direction have given negative results,[8,12–14] however well tailored the system was to detect an adduct intermediate, had one been formed.[8,14]

In some special cases the two possible mechanisms may yield different kinetics. This is when the intermediate goes to product *via* a bimolecular reaction (hence involving a second molecule, which may be one of the nucleophilic reagent itself, or of any other species which may be present), rather than *via* a unimolecular expulsion of a leaving group. The involvement of this second molecule may show up in the kinetic law, whose form, however, cannot by itself reveal the *nature* of the intermediate. This was the case of the reaction of sulfenyl halides with amines in benzene, studied in this laboratory, where the intermediate was an adduct or an ion pair.[4] Since in the latter case the reaction could still be a one-step displacement, the question of S$_A$N *vs.* S$_N$2 could not be settled.

Recently, we have started an investigation aimed at resolving this question, based on the evaluation of the Brønsted coefficients for the nucleophile, β_N, and for the leaving group, β_L.[15] The rationale of this approach has been elaborated by Hudson.[16] As the transition state of a nucleophilic substitution implies (partial) donation of an electron pair from the nucleophile to the reaction center, the Brønsted coefficient, β_N, is related to the extent of bond formation of the nucleophile to the reaction center. Similarly for the leaving group, $-\beta_L$ is related to the extent of heterolysis of the bond reaction center to leaving group.

In our first paper we examined the behavior of a dicoordinate sulfur system, that of the aryl esters of triphenylmethanesulfenic acid reacting with aryloxide or hydroxide ions.[15] The result was that for this system β_N is quite small, $+0.25$, while $-\beta_L$ is quite large, 0.97.[17] This was interpreted, in agreement with current views,[16,20,21] as evidence of a very loose, con-

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[1] Thesis, University of Pisa, 1971.

[2] E. Ciuffarin and A. Fava, *Progr. Phys. Org. Chem.*, **6**, 81 (1968).

[3] E. Ciuffarin and G. Guaraldi, *J. Amer. Chem. Soc.*, **91**, 1745 (1969).

[4] E. Ciuffarin and F. Griselli, *ibid.*, **92**, 6015 (1970).

[5] B. M. Trost, W. L. Schinski, and I. B. Mants, *ibid.*, **91**, 4320 (1969).

[6] R. Tang and K. Mislow, *ibid.*, **91**, 5644 (1969).

[7] O. Rogne, *J. Chem. Soc. B*, 727 (1970).

[8] J. B. Biasotti, and K. K. Andersen, *J. Amer. Chem. Soc.*, **93**, 1178 (1971).

[9] J. L. Kice and J. M. Anderson, *J. Org. Chem.*, 33, 3331 (1968).

[10] C. R. Johnson and J. J. Rigau, *J. Amer. Chem. Soc.*, **91**, 5398 (1969).

[11] M. L. Bender, *ibid.*, 73, 1626 (1951).

[12] C. A. Bunton, *J. Chem. Soc.*, 4754 (1958).

[13] D. R. Christman and S. Oae, *Chem. Ind. (London)*, 1251 (1959).

[14] E. T. Kaiser and O. R. Zaborsky, *J. Amer. Chem. Soc.*, **90**, 4626 (1968).

[15] L. Senatore, E. Ciuffarin, and A. Fava, *ibid.*, **92**, 3035 (1970).

[16] (a) R. F. Hudson, *Chimia*, **16**, 173 (1963); (b) R. F. Hudson and G. Klopman, *J. Chem. Soc.*, 1062 (1962); (c) R. F. Hudson and G. Loveday, *ibid.*, 1068 (1962).

[17] The values reported in our first paper have since been revised. The earlier report[15] was based on pK_a values determined in water while the kinetic experiments had been carried out in aqueous dioxane. While this procedure appears to be, on the whole, sound, as the relative pK_a's depend very little on the solvent,[18] it is not exact. Recent determination of the pK_a of several phenols in 45% aqueous dioxane[19] has allowed the determination of the correct Brønsted coefficients. These are: $\beta_N = 0.24$; $-\beta_L = 0.75$. Although the change, particularly of β_L, is sizable, the overall picture is not fundamentally modified.

[18] (a) J. F. P. J. Dippy, *Chem. Rev.*, **25**, 151 (1939); (b) B. S. M. Petrov and Y. I. Umanskii, *Zh. Fiz. Khim.*, **41**, 1374 (1967); *Chem. Abstr.*, **68**, 69198 (1968); (c) J. E. Leffler and E. Grunwald, "Rates and Equilibria of Organic Reactions," Wiley, New York, N. Y., 1963, p 242.

[19] L. Senatore, E. Ciuffarin, and L. Sagramora, *J. Chem. Soc. B*, 2191 (1971).

[20] W. P. Jencks and M. Gilchrist, *J. Amer. Chem. Soc.*, **90**, 2622 (1968).

Table I. Rate Constants for the Reaction of Sulfinic Esters with Oxygen Nucleophiles[a]

$$X^- + RS(O)Y \longrightarrow RS(O)X + Y^-$$

X^-	$[X^-]$, *M*	R	Y^-	*k*, M^{-1} sec^{-1}
p-CH_3COPhO^-	$1.1\text{–}2.6 \times 10^{-4}$	CH_3	*m*-NO_2PhO^-	$<2.06 \times 10^3$
3,5-Cl_2PhO^-	$1.1\text{–}2.3 \times 10^{-3}$	CH_3	*m*-NO_2PhO^-	$<4.29 \times 10^3$
m-$ClPhO^-$	$0.4\text{–}1.3 \times 10^{-3}$	CH_3	*m*-NO_2PhO^-	1.21×10^4
p-$ClPhO^-$	$0.3\text{–}1.2 \times 10^{-4}$	CH_3	*m*-NO_2PhO^-	1.90×10^4
PhO^-	$0.6\text{–}2.5 \times 10^{-4}$	CH_3	*m*-NO_2PhO^-	3.47×10^4
p-CH_3PhO^-	$0.4\text{–}1.7 \times 10^{-4}$	CH_3	*m*-NO_2PhO^-	8.17×10^4
$CF_3CH_2O^-$	$0.2\text{–}2.9 \times 10^{-5}$	CH_3	*m*-NO_2PhO^-	4.85×10^5
$CH_2ClCH_2O^-$	$0.2\text{–}2.4 \times 10^{-7}$	CH_3	*m*-NO_2PhO^-	5.20×10^5
HO^-	$0.2\text{–}1.0 \times 10^{-5}$	CH_3	*m*-NO_2PhO^-	4.95×10^5
HO^-	$0.6\text{–}100 \times 10^{-6}$	CH_3	*p*-$ClPhO^-$	7.52×10^4
HO^-	$0.1\text{–}1.0 \times 10^{-4}$	CH_3	PhO^-	3.28×10^4
HO^-	$0.1\text{–}1.6 \times 10^{-4}$	CH_3	CH_3PhO^-	1.81×10^4
HO^-	$0.9\text{–}4.7 \times 10^{-2}$	*p*-CH_3Ph	$PhCH_2O^-$	11.2
HO^-	$0.9\text{–}4.7 \times 10^{-2}$	Ph	$PhCH_2O^-$	23.8
HO^-	$0.9\text{–}4.7 \times 10^{-2}$	*p*-ClPh	$PhCH_2O^-$	43.0
HO^-	$0.9\text{–}4.7 \times 10^{-2}$	*m*-ClPh	$PhCH_2O^-$	72.1
HO^-	$0.9\ 4.7 \times 10^{-2}$	*p*-NO_2Ph	$PhCH_2O^-$	363.0

[a] Substrate concentration; first six entries, *ca.* 10^{-3} *M;* $0.5\text{–}1 \times 10^{-4}$ *M*, otherwise; temperature, 25°; solvent, water.

certed transition state where bond making (β_N) was lagging far behind bond breaking (β_L). This was unexpected since, whether or not an adduct is formed along the reaction path for nucleophilic substitution, the notion that third-row atoms can easily accept an electron pair, to form at least a partial bond, had crept into everybody's mind. Moreover, a transition state where bond breaking is so much advanced over bond making requires that the reaction center bears a sizable positive charge (with respect to the initial state) which in turn requires a large substituent effect of the substrate, with negative ρ. This conclusion seemed to contradict all available evidence, as no example is known of substitutions at sulfur where electron-releasing substituents favor reaction.[2] Rather, the contrary holds true, even though the effect is usually meager ($\rho \simeq 0$ to $+1.0$).[2]

Rather than questioning the significance of the β values in terms of the extent of bonding at the transition state, we suggested[15] that the particular case under investigation might not be general but might represent a rather extreme case of behavior. In particular, it was suggested that, owing to the bulky triphenylmethyl group in the α position, and its attending enormous steric hindrance effect,[22] extraordinarily long bonds could be expected of nucleophile and leaving group to reaction center at the transition state. In our first paper we also indicated what factors should be probed in order to make the application of the Brønsted relationships more deeply significant and advised that it was necessary "... to verify in a systematic fashion the effect ... of such factors as solvent, steric compression at the reaction center, effective electronegativity of the reaction center, nature of the nucleophilic atom, and leaving group atom." Work along these lines has since been completed in this and other laboratories and published.[7,19,23–28] In this article we report a study of the effect of the basicity of nucleophile and leaving group in the reaction of oxygen nucleophiles with esters of sulfinic acids in water (eq 1). This is a parallel study to our first one,

$$X^- + RS(O)Y \longrightarrow RS(O)X + Y^- \tag{1}$$

$$\begin{aligned} X^- &= ArO^-, RO^-, OH^- \\ Y^- &= ArO^-, RO^- \\ R &= CH_3, Ar \end{aligned}$$

but is complemented by a study of the substituent effect on the substrate. As we shall see these results, considered together with those previously obtained,[15,19,23,24] call for a reassessment of the mechanistic significance of the Brønsted coefficients in nucleophilic substitutions.

Results

The rate of reaction of a number of sulfinic esters with oxygen nucleophiles has been measured in water at 25°. The data are reported in Table I. All reactions were followed under pseudo-first-order conditions with a stopped-flow spectrophotometer at the appropriate wavelength (250–400 nm).

For the reactions of benzyl sulfinic esters, pseudo-first-order conditions were obtained by using a large excess of nucleophile (OH^-). In all other cases borate buffer solutions were used. This buffer was shown not to influence the reaction rate. The concentration of nucleophile was calculated from the pH of the solution and the pK_a of the nucleophile.[29,30] Usually a substrate concentration of $0.5\text{–}1.0 \times 10^{-4}$ *M* was used. However, with phenols as nucleophiles, owing to their larger absorbance, a substrate concentration of *ca.* 10^{-3} *M* was necessary. At this concentration *m*-nitrophenyl methanesulfinate decomposes autocatalytically

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(21) (a) T. C. Bruice and S. Benkovic, "Bioorganic Mechanism," Vol. IV, W. A. Benjamin, New York, N. Y., 1966, Chapter 1; (b) M. J. Gregory and T. Bruice, *J. Amer. Chem. Soc.*, **89**, 4400 (1967); (c) F. Pietra, *Quart. Rev., Chem. Soc.*, **23**, 504 (1969); (d) S. J. Benkovic and P. A. Benkovic, *J. Amer. Chem. Soc.*, **88**, 5504 (1966); (e) R. F. Hudson, "Structure and Mechanism in Organo Phosphorus Chemistry," Academic Press, London, 1965; (f) L. H. Sommer, "Stereochemistry, Mechanism, and Silicon," McGraw-Hill, New York, N. Y., 1964.

(22) A. Fava and A. Iliceto, *J. Amer. Chem. Soc.*, **80**, 3478 (1958).

(23) E. Ciuffarin and L. Senatore, *J. Chem. Soc. B*, 1680 (1970).

(24) E. Ciuffarin, L. Senatore, and M. Isola, *ibid.*, 2187 (1971).

(25) O. Rogne, *J. Chem. Soc., Perkin Trans. 2*, 472 (1972).

(26) O. Rogne, *J. Chem. Soc. B*, 1855 (1971).

(27) E. Ciuffarin, L. Senatore, and M. Isola, *J. Chem. Soc., Perkin Trans. 2*, 468 (1972).

(28) E. Ciuffarin and G. Guaraldi, *J. Org. Chem.*, **35**, 2006 (1970).

(29) G. B. Barlin and D. D. Perrin, *Quart. Rev., Chem. Soc.*, **20**, 75 (1966).

(30) A. B. Fersht and W. P. Jencks, *J. Amer. Chem. Soc.*, **92**, 5442 (1970).

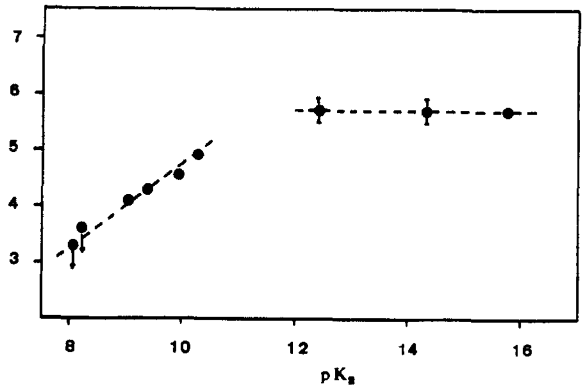

Figure 1. Brønsted plot for the reaction of oxygen nucleophiles with *m*-nitrophenyl methanesulfinate as a function of the basicity of the nucleophile. The nucleophiles in order of increasing pK_a are: *p*-CH_3COPhO^-, 3,5-Cl_2PhO^-, *m*-$ClPhO^-$, *p*-$ClPhO^-$, PhO^-, *p*-CH_3PhO^-, $CF_3CH_2O^-$, $CH_2ClCH_2O^-$, and HO^-.

so that the substrate solution had to be used immediately. However, both fresh and partially hydrolyzed solutions have the same rate constant. Fast hydrolysis in concentrated solution is due to acid catalysis by sulfinic acid. The higher the substrate concentration the shorter the time necessary to form sulfinic acid in concentration sufficiently high to catalyze fast decomposition. This was tested by adding varying amounts of sulfinic acid to a solution of *m*-nitrophenyl methanesulfenate.

All reactions were linear up to 90% completion. The precision of the rate data can be estimated to be within ±4% maximum error except for the reactions of *m*-nitrophenyl methanesulfinate with *p*-acetoxyphenolate, 3,5-dichlorophenolate, 2-chloroethoxide, and 2,2,2-trifluoroethoxide. The reactions with *p*-acetoxyphenolate and 3,5-dichlorophenolate cannot go to completion, the excess of nucleophile notwithstanding, since the pK_a of the nucleophile is lower than that of the leaving group. An equilibrium is established, and consequently the rate values corresponding to the nucleophilic attack are lower than those reported in Table I. The rate constants for 2-chloroethoxide and 2,2,2-trifluoroethoxide are also affected by large errors since the reaction with ethoxide was only a minor portion of the total rate which included the alkaline hydrolysis. The reported constants are affected by a maximum error estimated to be *ca.* ±0.2 log *k* unit.

Each rate constant was computed from the plot of the pseudo-first-order rate constant *vs.* the nucleophile concentration. Each plot contains three or more experimental points.

Table II is a summary of the Brønsted coefficients for the entering and leaving group, and the substituent effect on the reaction center calculated from the data of Table I. The last two lines of the table report unpublished data relative to the leaving-group effect.[31]

Discussion

Analyzing the data of Table I by means of the appropriate linear free energy relations, the values of β and ρ are obtained which are summarized in Table II. The more interesting result is that concerning the Brønsted treatment of the nucleophile, which yields a nonlinear correlation (Figure 1). At the lower end, where the basicity of the nucleophiles (phenoxides) is of the same order as that of the group being displaced, the slope is maximum ($\beta_N \simeq 0.75$), while at the high basicity end (alkoxides and hydroxide) the slope is virtually zero. On the other hand, the Brønsted plot for the leaving group and the Hammett plot for the substrate are linear: $\beta_L = -0.71$ ($r = 0.9999$) and $\rho = 1.56$ ($r = 0.9971$), respectively.

Table II. Brønsted Coefficients and Values for the Reaction of Sulfinic Esters with Oxygen Nucleophiles

$$X^- + RS(O)Y \longrightarrow RS(O)X + Y^-$$

X^-	R	Y^-	β_N	ρ	$-\beta_L$
X–PhO^-[a]	CH_3	*m*-NO_2PhO^-	≃0.75		
RO^-[b]	CH_3	*m*-NO_2PhO^-	≃0.0		
HO^-	CH_3	X–PhO^-[c]			0.71
HO^-	X–Ph[d]	$PhCH_2O^-$		1.56	
HO^-	Ph	RO^-[e]		3.21[g,h]	
HO^-	Ph	X–$PhCH_2O^-$[f]		0.97[h]	

[a] X = *p*-CH_3CO, 3,5-Cl_2, *m*-Cl, *p*-Cl, H, *p*-CH_3. [b] R = CF_3CH_2, CH_2ClCH_2, H. [c] X = *m*-NO_2, *p*-Cl, H, *p*-CH_3. [d] X = *p*-NO_2, *m*-Cl, *p*-Cl, H, *p*-CH_3. [e] R = CH_3, C_2H_5, *n*-C_3H_7, *i*-C_4H_9, *i*-C_3H_7, *sec*-C_4H_9, $PhCH_2$. [f] *p*-NO_2, *m*-Cl, *p*-Cl, H, *p*-CH_3, *p*-CH_3O. [g] ρ^*. [h] Reference 31.

Postponing the discussion on the significance of the curvature of the β_N plot until later, it is interesting to observe that, at least for the more basic nucleophiles, where the Brønsted slope is close to zero, the picture emerging from these experiments on tricoordinated sulfur substrates is closely similar to that which was derived for dicoordinated sulfur in our earlier report.[15] Interpreted in the same fashion, this picture would indicate a transition state with little bond formation and a great deal of bond breaking, only compatible with a concerted (SN2) mechanism. There is, however, a contradiction: in our first paper[15] it was noted that such a loose transition state required that the reaction center be more *positive* in the transition state than in the initial state, which in turn required a structural effect on the substrate characterized by a *negative* value of the Hammett ρ. A similar consequence should be expected for tricoordinated sulfur. However, the data do not support this expectation as the ρ value, +1.56, is positive and relatively high for a substitution at sulfur.[32,33]

This conflict and the consideration of various recent pieces[12,19,24] of evidence concerning Brønsted correlations in nucleophilic substitutions of sulfur substrates suggest a reexamination of the significance of the Brønsted slopes in terms of extents of bond formation and rupture.

A factor of general importance, which makes the absolute value of the Brønsted slopes of little significance, is the effect of solvent. In a recent paper,[34] it has been shown that a change in solvent composition may cause a large change in the β value, while at the

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(31) V. Caciagli, unpublished data.

(32) O. Rogne, *J. Chem. Soc. B*, 1294 (1968).

(33) Although ρ and β have been derived for different substrates, there is little doubt that the two values are compatible. That the organic residue does not make any important difference can be granted without question, as ρ itself proves that there can be no important charge delocalization. Neither does the difference in the leaving group (phenoxide *vs.* benzyl oxide) appear to be important since the substitution proves to be very susceptible to the basicity of the leaving group when the latter is a strong base also (Table II and ref 31).

(34) L. J. Stangeland, L. Senatore, and E. Ciuffarin, *J. Chem. Soc., Perkin Trans. 2*, 852 (1972).

same time having little effect on the rate. The most dramatic example reported is that of benzenesulfonyl chloride reacting with pyridines, which affords $\beta = 0.43$ in water but $\beta = 0.79$ in aqueous dioxane, while the rate changes by very small factors in the two solvent media.[34] While the effect of solvent has not yet been fully investigated and its significance is uncertain at present, such enormous variation seems hardly abscribable to changes in transition state structure, particularly in view of the minor rate change. In any case, because of this solvent effect, a given value of β in a given solvent cannot be confidently related to the extent of bond formation and breaking or, more generally, to the structure of the transition state.

Finally, still another factor must be considered which appears to have been neglected in previous discussions. This is the fact that in a nucleophilic substitution

$$\mathrm{N{:}} + \mathrm{C\text{-}L} \longrightarrow \mathrm{N\text{-}C} + \mathrm{L{:}}$$

where C is the reaction center and N: and L: are nucleophile and leaving group, respectively, any structural change in the nucleophile which affects its basicity will affect the N–C as well as the C–L bond orders at the transition state, though in opposite directions.[35] The rate change resulting from the combination of these perturbations of bond orders, and which contributes to the overall β value, may be a rate decrease, a rate increase, or no change at all, according to the structure of the transition state, *i.e.*, the values of $n_{\mathrm{N-C}}$ and $n_{\mathrm{C-L}}$. For example, a transition state where $n_{\mathrm{N-C}} \ll n_{\mathrm{C-L}}$, a structural change which makes the nucleophile less basic, would increase $n_{\mathrm{N-C}}$ but would more strongly decrease $n_{\mathrm{C-L}}$, thus yielding an overall decrease of total bond order and contributing a rate decrease that may be quite steep. In other words, the overall value of β_{N} can be relatively high even though there may be little N–C bond formation.

As far as the leaving group is concerned in a transition state of this structure, *i.e.*, rather reactant-like, making the leaving group more electronegative (less basic) would increase the C–L bond order more that it decreases the N–C bond order, thus contributing a rate increase. Conceivably this situation may yield a large $-\beta_{\mathrm{L}}$ value, even though the stretching and charging of the C–L bond may be small at the transition state. Thus, this type of reactant-like transition state may well yield sizable β_{N} and $-\beta_{\mathrm{L}}$ values, contrary to the expectations based on accepted theories.[36]

Conversely, for a transition state characterized by $n_{\mathrm{N-C}} \gg n_{\mathrm{C-L}}$, the effect just discussed would operate in the opposite direction, while for a "central" transition state, $n_{\mathrm{N-C}} \simeq n_{\mathrm{C-L}}$, the bond order changes tend to cancel each other completely, and the β's should have values relatively independent of the "tightness" of the transition state.

The discussion above should have made clear that if the β values *per se* do not provide a reliable criterion for judging the detailed structure of a S$_{\mathrm{N}}$2 transition state, much the less they provide a reliable criterion for distinguishing between the S$_{\mathrm{N}}$2 and the S$_{\mathrm{A}}$N pathways.[38]

We believe that β values cannot be readily translated into mechanistic information and think that much of the mechanistic inferences made on the basis of *single* β_{N} and β_{L} values have little significance, if any. This includes our previous discussion,[15] no less than numerous other ones concerning sulfur as well as other reaction centers.[21] For a fitting illustration of this contention and the futility of interpretations based on single β values in terms of bond formation, reference can be made to our own work,[24] the reaction of *p*-nitrophenyl triphenylmethanesulfenate with amines. Here the following β_{N} values were found for different classes of amines (in parentheses): 0.58 (primary aliphatic amines); 0.75 (secondary heterocyclic amines); 0.84 (pyridines); 1.5 (anilines). It would seem naive at best to attempt an interpretation of these values merely in terms of changes of bond formation at the transition state.

Greater significance might have, rather than the β values themselves, their variation with respect to certain variables *under carefully controlled conditions.* Such would be the variation of β_{N} as a function of a structural change at the leaving group, and, *vice versa*, the variation of β_{L} as a function of a structural variation of the nucleophile, or the variation of β_{N} and β_{L} as a function of a structural change at the reaction center. Such data are largely unavailable as yet, very laborious, and in most cases extremely difficult to obtain, and perhaps will turn out to be of little use, at least in discerning between S$_{\mathrm{N}}$2 and S$_{\mathrm{A}}$N. This is the case of the recent work by Rogne[26] proving that, in the reaction of arenesulfonyl chloride with amines, the value of β_{N} increases steadily with increasing the electronegativity of the reaction center. This is certainly more informative than a single value of β_{N}; however, the same trend may be expected whether the mechanism is S$_{\mathrm{N}}$2 or S$_{\mathrm{A}}$N (first step rate determining), and consequently the experiments cannot differentiate the two mechanisms.

It is in light of the above discussion that the curvature of our Brønsted plot should be considered (Figure 1). First of all, although both at the high and at the low basicity ends the slope is affected by large errors due to experimental difficulties (discussed in the Results section), there is no doubt that the sensitivity of the reaction to the basicity of the nucleophile becomes virtually nil as its basicity becomes much greater than that of the group being displaced ($\Delta \mathrm{p}K_{\mathrm{a}} = 6$). A curvature in the Brønsted plot is by no means novel. In particular, Jencks and coworkers have disclosed a very marked curvature for the reaction of carboxylic acid derivatives with a set of oxygen nucleophiles similar to our own.[30] Their interpretation invokes a gradual change of the structure of the transition state, which becomes progressively "early" along the reaction coordinate, as the nucleophile basicity increases, so that at the high basicity end little charge is transferred to the reaction center from the nucleophile.

A similar explanation could apply to our case as well. However, irrespective of whether it is correct, this ex-

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(35) J. C. Harris and J. L. Kurtz, *J. Amer. Chem. Soc.*, **92**, 349 (1970).

(36) Interpretations of the significance of β_{L} values diverging from the generally accepted ideas have already been suggested.[19,37]

(37) (a) G. W. Jameson and J. M. Lawlor, *J. Chem. Soc. B*, 53 (1970); (b) T. C. Bruice and M. F. Mayahi, *J. Amer. Chem. Soc.*, **82**, 3067 (1960); (c) A. J. Kirby and W. P. Jencks, *ibid.*, **87**, 3209 (1965); (d) ref 20, footnote 27b.

(38) Another factor which, specifically for substitution at sulfur, would make questionable any meaning which might be given to the absolute value of the Brønsted slopes, is that the relation between sulfur and hydrogen basicity is unknown. This difficulty, however, can in principle be circumvented, as this relation is experimentally accessible. That values of β_{N} as high as 1.5 have been found[24] shows that it cannot be taken for granted that the coefficient relating sulfur and hydrogen basicities may be close to unity.

planation can be accommodated within the framework of either the S_N2 or the S_AN mechanism, and therefore is not useful to differentiate them.

However, this interpretation attributes to the pK_a change the capacity of doing much more than merely perturb the transition state structure (and provide a probe for the structure itself). Thus, if the explanation were correct, it would by itself deny any value to the β's as probes of transition state structures. Then one could not without contradiction utilize the Brønsted slopes approach[30] and at the same time propose this explanation.[30] On the other hand, in this interpretation is not clear why in some cases is the Brønsted plot linear while in other cases it is curved. It is difficult to admit that a given pK_a in certain cases merely perturbs while in other ones it drastically changes the transition state structures. Also which features of the reaction cause such varying response remain obscure.

Even though we are unable to provide a comprehensive answer to these questions we feel not inclined to accept without reserve the interpretation in terms of bond-order changes. Rather, we would like to indicate the possibility that the observed curvatures merely arise from the fact that points relative to a certain group of nucleophiles may belong to a regression line different from that of another group.

That this is a likely possibility is obvious from the consideration of much experimental evidence, including our own. For example, in the already cited reaction of amines with *p*-nitrophenyl triphenylmethanesulfenate,[24] if the results of aromatic and aliphatic primary amines are taken together, a curved plot would obtain with slopes of 1.5 and 0.58 at the two extremes. Separately, however, the two sets of primary amines define reasonably straight lines. The case of our oxygen nucleophiles *could* be analogous insofar as the set of nucleophiles involve aromatic and aliphatic oxides.

Admittedly, this is *not* an explanation; it merely puts the curvature of the Brønsted plot under a different perspective. However, in this perspective it no longer appears as a strange phenomenon but, though unexplained, as a familiar one: that different sets of nucleophiles lie on different regression lines.

Experimental Section

Materials. Reagent grade sodium hydroxide, hydrochloric acid, and borax were used without further purification. All commercial phenols, *i.e.*, *p*-Cl, *m*-Cl, H, 3,5-Cl_2, and *p*-CH_3, have been purified by repeated sublimations and had good melting points. *p*-Acetylphenol was kindly provided by Professor P. Da Re and purified by sublimation, mp 110°. 2-Chloroethanol and 2,2,2-trifluoroethanol were commercial products which were carefully fractionated.

Sulfinyl Chlorides. All sulfinyl chlorides necessary for the preparation of the sulfinic esters were prepared according to the literature[39] except for the methanesulfinyl chloride which was prepared as follows.

Methyl disulfide (5-10 g) and acetic acid (1:2, mole ratio) were dissolved in dry methylene chloride (25-30 ml). A *slow* dry chlorine current was bubbled into the solution while stirring and keeping the temperature at −10°. The solution becomes at first red and then the color turns yellow. The reaction is thus completed and the excess chlorine is rapidly stripped (together with acetyl chloride, hydrochloric acid, and the solvent) with a water pump in order to avoid chlorination of the organic moiety. (A fast chlorine current produces polychlorination too.) The product is then distilled under vacuum, bp 56-59 (40 mm), $n^{25}{}_D$ 1.500-1.501.[39]

Sulfinic Esters. Benzyl sulfinic esters were prepared according to general procedures.[40] A solution of the appropriate sulfinyl chloride was slowly added to alcohol and pyridine in stoichiometric amounts at 0° while stirring. Stirring was continued for about 45 min. The reaction mixture was then washed with water, 0.5 *N* HCl, water, sodium hydrogen carbonate (1% in water), and water, in rapid sequence to avoid hydrolysis of the sulfinic esters which is particularly fast in acid or basic media. After drying over anhydrous sodium sulfate, the ethereal solution was concentrated and cooled at −25°. Sometimes an oil was obtained which was recrystallized (at −25°) from a mixture of ethyl ether-petroleum ether.

Methanesulfinic esters were prepared from methanesulfinyl chloride, the appropriate phenol, and pyridine as described above. However, because of their high hydrolysis rate, their work-up was as follows. The pyridine hydrochloride was filtered off. Evaporation of the solvent usually yielded oils upon which various purification procedures were tried unsuccessfully (column and thick layer chromatography, molecular distillation, and recrystallizations). The only way to obtain crystalline products is the use of highly purified reagents and solvents in the preparation procedure. In such a way recrystallization at low temperature (−25°) from ethyl ether-petroleum ether (1:1) yields crystalline solids. The esters were then repeatedly recrystallized until ir spectroscopy (absence of phenol) and elemental analysis indicated a purity of 99% or better. The esters can be kept for extended periods of time at low temperature in a dry atmosphere. All esters are liquid at room temperature and cannot be distilled without decomposition. Therefore melting and boiling points were not measured.

Kinetic Methods. Boric acid-borate buffers have been prepared according to Bates.[41] pH measurements were performed with a Metrohm Herisau pH meter equipped with XL glass electrode.

The solutions of *m*-nitrophenyl methanesulfenate were prepared with thermostated water at 25° and used immediately (within 5 min). The total concentration of nucleophile was at least ten times that of the substrate and varied within large limits 1×10^{-3}-0.5 *M*, according to the particular reaction conditions (ratio of reaction, pK_a of the nucleophile, presence of buffer).

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(39) I. B. Douglass, B. S. Farah, and E. G. Thomas, *J. Org. Chem.*, **26**, 1996 (1961).

(40) A. H. Wraggs, J. S. Fadyen, and T. S. Stevens, *J. Chem. Soc.*, 3604 (1958).

(41) R. G. Bates, "Determination of pH," Wiley, New York, N. Y., 1963, pp 160-161.