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Elimination Reactions: Experimental Confirmation of the Predicted Elimination of (β-Cyanoethyl)sulfonium Ions through a Concerted, E2 Mechanism[1]

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Abstract: Extrapolation of the lifetimes of carbanion intermediates formed in the elimination reactions of a series of β-cyanoethyl thioethers with different leaving groups (*J. Am. Chem. Soc.* **1988**, *110*, 5087–5095) predicts that the carbanions will not have a significant lifetime for $pK_{lg} < -2$. General-base catalysis by primary amine buffers and hydroxide anions of the elimination of aryl methyl sulfides ($pK_a < -6.65$) from *S*-aryl-*S*-(2-cyanoethyl)-S-methylsulfonium tetrafluoroborate salts follows Brønsted β values that decrease from 0.75 for 4-methoxyphenyl methyl sulfide to 0.62 for pentafluorophenyl methyl sulfide as the leaving group ($\mu = 1.0$ with KCl, in water or 8.3% Me_2SO/H_2O, 25.0 °C). Values of β_{lg}, obtained from Brønsted-type plots of log k_B against the estimated pK_a values of the leaving groups, decrease from 0.39 to 0.24 with increasing pK_a of the base catalyst. The changes in β and β_{lg} are described by the interaction coefficient $p_{xy} = \partial\beta/\partial pK_{lg} = \partial\beta_{lg}/\partial pK_{BH} = 0.026$. The deuterium isotope effect for proton removal from $Ph\text{-}S^+(Me)\text{-}CH_2CL_2CN$ is $k_H/k_D = 4.4$ and 4.9 for tris(hydroxymethyl)aminomethane and ethylamine buffers, respectively, and there is no detectable protium exchange into the deuterated substrate. The positive p_{xy} coefficient provides evidence for coupling between proton abstraction and leaving group expulsion; it confirms the concerted $A_{xh}D_HD_N$ (E2) mechanism. The values of β and β_{lg} indicate an imbalance in the transition state, in which proton transfer is ahead of leaving group expulsion. The change from a stepwise $A_{xh}D_H + D_N$ (E1cB) mechanism for thiophenoxide leaving groups to a concerted mechanism for sulfide leaving groups is consistent with the notion that the mechanism is determined solely by the lifetime of the carbanion; there is no evidence for the coexistence of stepwise and concerted mechanisms.

Introduction

We are interested in the question of whether the reason that a reaction follows a particular mechanism is simply that this mechanism, among several concurrent mechanisms that could be followed, happens to provide the lowest energy pathway from reactants to products, or whether only one mechanism exists under the conditions of the reaction, i.e. the mechanism is *determined* and *predictable*, depending on whether or not an intermediate species with a significant lifetime can be formed along the reaction path.[2] For substitution at carbon the available data are consistent with the notion that a reaction will be stepwise if it can be; it will become concerted only when substituents or the reaction conditions are changed in such a way that the intermediate species ceases to have a significant lifetime.[3] An intermediate species may be said to have a significant lifetime if it survives for several bond vibrations,[2] which are on the order of 10^{13} s^{-1}. On the other hand, stepwise and concerted reaction paths can take place concurrently in the same solution when one of the component reactions has a low barrier, as in the proton transfer to oxygen during the dehydration step of thiosemicarbazone formation.[4]

Base-catalyzed olefin-forming elimination reactions may proceed through a stepwise mechanism in which the carbanion intermediate has a sufficient lifetime to become diffusionally equilibrated with the bulk solution or through a concerted, one-step mechanism. These mechanisms are described by E1cB and E2, respectively, according to Ingold nomenclature,[5] or by $A_{xh}D_H + D_N$ and $A_{xh}D_HD_N$, according to the recently proposed IUPAC nomenclature,[6] in which A refers to associative and D to dissociative processes. A stepwise mechanism with a short-lived intermediate, such as an ion pair, is designated $E1cB_{ip}$ or $A_{xh}D_H{*}D_N$.

It has been suggested that base-catalyzed elimination reactions might proceed concurrently through concerted ($A_{xh}D_HD_N$) and stepwise ($A_{xh}D_H{*}D_N$) mechanisms,[7] but we are not aware that this possibility has been demonstrated experimentally for reactions with the same stoichiometric composition of the transition state. The appearance of a concerted reaction mechanism requires that the barriers for two separate reactions be combined into a single barrier that is lower than the barriers for the stepwise reaction.[8,9] This is improbable and is inconsistent with the "principle of least nuclear motion"[10] because of the large amount of structural reorganization that must take place in the transition state of a concerted reaction. It will occur only when the advantage from coupling one reaction with the other is more than enough to overcome the increase in ΔG^{*} that arises from combining the activation free energies of the individual steps into a single step.[8] This is likely to occur only when the activation barrier for one of the steps is small, as in proton transfer between electronegative atoms. Therefore, the most common reason that organic reactions proceed through a concerted mechanism may be that an intermediate species becomes so unstable that it reacts with no significant activation barrier, so that the reaction occurs in a single step and is forced to become concerted. It has been suggested that the combination of the two barriers of a stepwise β-elimination reaction into the single barrier of a concerted reaction will be rare,[11] but the reaction *must* become concerted if there is no significant barrier for expulsion of the leaving group from the carbanion.

There is strong experimental evidence that supports a concerted $A_{xh}D_HD_N$ (E2) mechanism for a number of elimination reactions. Most of this evidence is from hydrogen and heavy atom isotope effects,[12] but strong support for a concerted mechanism can also be obtained from the demonstration of an interaction between the effects of substituents in different parts of the molecule on the

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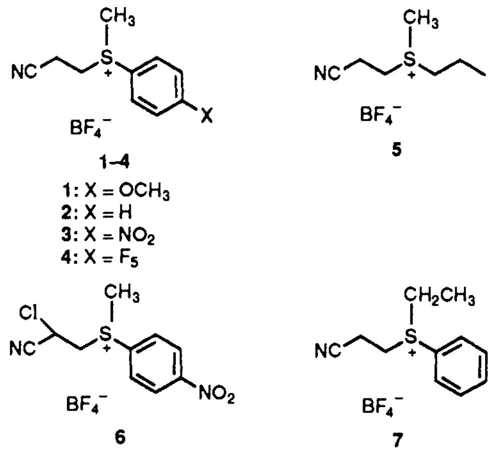
Chart I

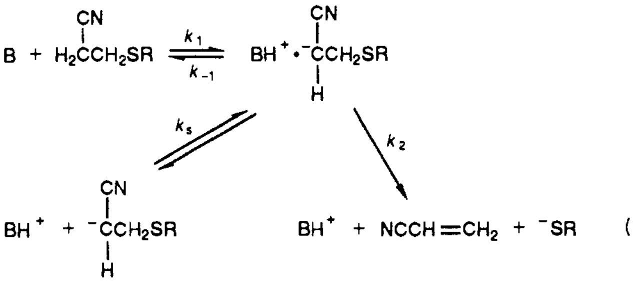


1–4
1: X = OCH$_3$
2: X = H
3: X = NO$_2$
4: X = F$_5$
5
6
7

energy of the transition state.[13] An interaction between substituents on the leaving group that change the Brønsted β value for proton removal and substituents on the base catalyst that change β_{lg} provides evidence for coupling between proton abstraction and leaving group expulsion in a concerted reaction mechanism.[13,14] It is convenient to describe these interactions by shifts in the position of the transition state on an energy contour diagram that is defined by the observed substituent effects.[13-16] The interaction coefficients for the effects of substituents on the base catalyst and on the leaving group in the elimination reactions of *N*-(2-arylethyl)-substituted quinuclidinium ions demonstrate a concerted mechanism for all aryl substituents except for the *p*-nitrophenyl compound, which has no interaction coefficient and was shown to proceed through a stepwise $A_{xh}D_H + D_N$ (E1cB) mechanism.[13,17,18] This reaction series demonstrates the usefulness of interaction coefficients as a means of distinguishing between concerted and stepwise mechanisms, even when the structure of the transition state closely resembles the carbanion intermediate of the $A_{xh}D_H + D_N$ mechanism.

Stirling and co-workers have shown that elimination reactions of nitrile- and sulfone-activated substrates with I$^-$ and Br$^-$ leaving groups are 80-fold and 10–15-fold faster, respectively, than the predicted rates of ionization, and it was suggested that this rate increase arises from a concerted mechanism of elimination with these very good leaving groups.[19] The relatively large kinetic isotope effects of k_H/k_D = 5.0–5.6 with these leaving groups, compared with $k_H/k_D \approx 2$ for compounds with acetate, fluoride, and tosylate leaving groups, may also arise from a concerted elimination if there is less proton removal in the transition state of the concerted compared with the stepwise reaction and there is a maximum in the isotope effect for intermediate amounts of proton transfer. The possibility must be considered that hyperconjugation of the developing negative charge with the I$^-$ and Br$^-$ leaving groups in the transition state for rate-limiting proton removal in a stepwise $A_{xh}D_H{*}D_N$ mechanism[20] could account for these rate increases, but it is not certain that such anionic hyperconjugation causes an increased reaction rate.[21]

The elimination reactions in aqueous solution of a series of β-cyano thioethers with leaving groups in the range of pK_a = −1 to 9.7 have been shown to proceed through stepwise $A_{xh}D_H + D_N$ or $A_{xh}D_H{*}D_N$ (E1cB or E1cB$_{ip}$) mechanisms in earlier work from this laboratory.[22,23] The mechanism was established by several criteria, including the observation of deuterium exchange between the solvent and the thioether, different deuterium isotope effects on the rate of elimination compared with isotope discrimination in the addition of thiol anions to acrylonitrile in the reverse direction, and internal return of the proton that is competitive with leaving-group expulsion. Rate constants for expulsion of the thiolate anion from the carbanion (eq 1) in the range k_2 = 10^{10}–10^{13} s^{-1} were estimated from ratios of k_{-1}/k_s and k_{-1}/k_2 that were determined experimentally and a value of $k_s = 10^{11}$ s^{-1}. These rate constants approach the limit of 2 × 10^{13} s^{-1} for a C–S bond vibration[24] and suggest that less basic sulfur leaving groups would be expelled from the carbanion with no significant barrier. The reaction would then be forced to proceed through a concerted $A_{xh}D_HD_N$ (E2) mechanism because the carbanion would not be stable enough to have a meaningful lifetime. The experiments reported here were carried out to test this prediction.



(1)

Bunting and Moors have shown that a series of (β-cyanoethyl)isoquinolinium ions with leaving groups in the range of pK_a = 2–6 undergo elimination some 1300 times faster than the corresponding thioethers, without hydron exchange with the solvent, and follow β_{lg} = −0.43. Thus, these compounds react either through an $A_{xh}D_H{*}D_N$ mechanism with internal return of the proton or through a concerted $A_{xh}D_HD_N$ mechanism, which may be enforced by the short lifetime of the carbanion.[25]

In this paper, we describe elimination reactions of the acrylonitrile derivatives **1**–**7**. We have measured the effects of catalyst basicity, β, leaving group basicity, β_{lg}, and β-chlorine substitution, ρ, on the rate; we have also measured the interactions between these substituent effects. The changes in the structure–reactivity coefficients correspond to movement of the transition state parallel and perpendicular to the reaction coordinate. The interaction coefficients that describe these changes show that the elimination reactions of compounds **1**–**7** (Chart I) follow a concerted, E2 mechanism, as predicted,[23] but contrary to an earlier suggestion for β-elimination of similar compounds.[26] The results from this study and the previous results of Fishbein and Jencks,[22,23] cover a range of pK_a of ~25 units for the sulfur leaving atom with the same activating group. It is concluded that concurrent stepwise and concerted mechanisms do not occur in this system; the concerted mechanism appears when it is enforced by the absence of a significant lifetime for the carbanion intermediate.

Experimental Section

Materials. The synthesis of the sulfonium salts **1**–**7** was carried out under either nitrogen or argon in glassware that had been dried overnight in the oven and assembled under nitrogen. The reactions were followed by silica gel TLC (Merck 60 F$_{254}$) with 2:3 ethyl acetate/hexanes (v/v) as the mobile phase. The ^{1}H NMR measurements in d_6-Me$_2$SO were carried out with a Varian 300 instrument with TMS as the internal standard. The melting points are uncorrected. Dichloromethane was

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Table I. Proton NMR Shifts[a] and Melting Points of the Sulfonium Salts **1–3** and **5–6**

	mp, °C	λ_{max},[b] nm	^{1}H NMR
1	58–61	250	8.02 (d, 2 H), 7.3 (d, 2 H), 4.0 (m, 2 H), 3.9 (s, 3 H), 3.36 (s, 3 H), 3.15 (m, 1 H), 3.0 (m, 1 H)
2	87–88	266	8.1 (d, 2 H), 7.9 (m, 3 H), 4.05 (m, 2 H), 3.4 (s, 3 H), 3.15 (m, 1 H), 3.0 (m, 1 H)
3	100–102	-	8.55 (d, 2 H), 8.4 (d, 2 H), 4.1 (m, 2 H), 3.35 (s, 3 H), 3.15 (m, 2 H)
			8.1 (m, 2 H), 7.8 (m, 3 H), 4.0 (m, 2 H), 3.4 (s, 3 H)
5	88–89	-	8.15 (m, 2 H), 7.8 (m, 3 H), 4.0 (m, 4 H), 3.15 (m, 1 H), 2.85 (m, 1 H), 1.25 (t, 3 H)
6	~15	225	3.65 (m, 2 H), 3.45 (m, 2 H), 3.22 (t, 2 H), 2.95 (s, 3 H), 1.65 (q, 2 H), 1.0 (t, 3 H)

[a] Spectra in d_6-Me$_2$SO; the chemical shifts are relative to tetramethylsilane. [b] In water at 25 °C.

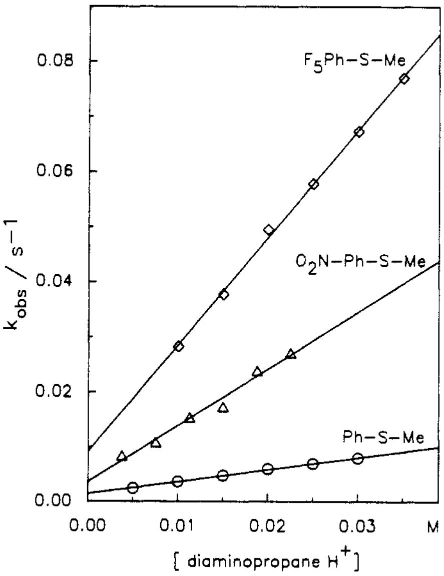

Figure 1. The dependence of k_{obs} on the concentration of the diaminopropane monocation catalyst ($BH_2^{2+}/BH^+ = 9$) for elimination from acrylonitrile adducts in water at 25 °C, μ = 1 M (KCl), of methyl phenyl sulfide (○), methyl *p*-nitrophenyl sulfide (△), and methyl pentafluorophenyl sulfide (◇).

distilled from P_2O_5 under nitrogen and 1,2-dichloroethane was distilled from calcium hydride. The sulfides were prepared according to a literature procedure.[22]

Compounds **1**, **2**, and **5–7** were synthesized by the following method. A 1.5-fold molar excess of trimethyloxonium tetrafluoroborate or triethyloxonium tetrafluoroborate was added to a solution of 0.8 M sulfide in CH_2Cl_2, and the mixture was stirred at room temperature. After 24 h (14 days for $NCCH_2CH_2S$-*n*-Pr gave 67% reaction by NMR), absolute ethanol was added to remove the excess methylating agent, and the volatile materials were removed under reduced pressure. The residue was dissolved in 5–10 mL of glass-distilled water, and the solution was extracted twice with ethyl acetate; the aqueous phase was then lyophilized. The residue, which was usually >95% pure by NMR, was recrystallized from absolute ethanol. Compound **7** was stored in 0.5 M aqueous HBF_4 at −15 °C; it was found to decompose in the absence of acid.

A typical procedure for the synthesis of **3** and **4** is as follows: To a bright yellow solution of methyl 4-nitrophenyl sulfide (3.0 g, 0.018 mol) and 1-iodopropionitrile (10.0 g, 0.055 mol) in 15 mL of dry 1,2-dichloroethane was added silver tetrafluoroborate (3.2 g, 0.016 mol) in small portions. The solution became dark brown immediately. The round-bottom flask was wrapped in aluminum foil and stirred at room temperature for 9 days. Trifluoroethanol was added and the solution was stirred at room temperature for 0.5 h. After gravity filtration, the organic solvents were removed with a rotary evaporator to yield a dark liquid that crytallized upon standing. The product **3** was recrystallized twice from absolute ethanol to yield **3**, mp 100–102 °C. The pentafluorothiophenol adduct **4** was not stable as a solid and was not isolated. Purification was accomplished by dissolving **4** in distilled water and extracting three to four times with ethyl acetate. The aqueous layer was stored at −15 °C. The physical and spectral characteristics of these compounds are summarized in Table I.

Kinetics. Kinetic measurements were carried out with a Perkin-Elmer Lambda 4B spectrophotometer at 25.0 ± 0.1 °C. The ionic strength was kept constant at 1.0 M with KCl. Measurements of pH were made with a Orion Model 701A pH meter and a Radiometer GK 2321C combination electrode standardized at pH 7.00 and 4.00 or 10.00.

Rate constants were obtained under pseudo-first-order conditions by observing the appearance of the sulfide product. The monitoring wavelengths were as follows: methyl *p*-nitrophenyl sulfide, 352 nm; methyl phenyl sulfide, 254 nm; *p*-methoxyphenyl methyl sulfide, 220 nm; methyl *n*-propyl sulfide, 214 or 215 nm; ethyl phenyl sulfide, 254 nm. Methyl *p*-nitrophenyl sulfide was identified as the product from the reaction of the sulfonium salt **6** with ethylamine buffer by chromatography on a C_{18} reverse-phase HPLC column with 20% CH_3CN/80% water containing 0.0025 M tetrabutylammonium phosphate (PIC A) to 70% CH_3CN/30% 0.0025M PIC A. First-order rate constants were obtained from semilogarithmic plots of $A_\infty - A_t$ against time, which were linear for 2–4 half-lives, and from the relationship $k_{obs} = \ln 2/t_{1/2}$. Second-order rate constants were obtained from the slopes of plots of k_{obs} against base concentration with at least five buffer concentrations. The endpoint for reactions of **5** was calculated from ΔA at 5 $t_{1/2}$ (A_5) and the approximate halflife, according to $A_\infty = A_0 + 1.03(A_5 - A_0)$, because the addition of amines to the acrylonitrile product at the monitoring wavelength caused a slow decrease of the end-point absorbance. Second-order rate constants for catalysis by hydroxide ion were obtained from values of k_{obs} extrapolated to zero buffer concentration and the average activity of hydroxide ion calculated from all of the observed pH values. The activity of hydroxide ion at a measured pH value was obtained from eq 2 in pure water and eq 3 in 8.3% Me$_2$SO.[22]

$$[OH^-] = 10^{(pH_{obs} - 14)} \tag{2}$$

$$[OH^-] = 0.73 \times 10^{(pH_{obs} - 14)} \tag{3}$$

The reactions were initiated by adding 0.08–0.10 mL of stock solutions of the sulfonium salts in water or Me$_2$SO to thermostated cuvettes containing the buffer, and inverting the cuvettes two to three times. The substrate concentrations in the final mixtures were as follows: **1**, 1.5 × 10^{-4} M; **2**, **3**, **6**, and **7**, 1 × 10^{-4} M; **4**, 2.2 × 10^{-4} M; and **5**, 5.1 × 10^{-4} M. The stock solutions for **7** were prepared just before each run as follows: 2 mL of the solution containing **7** was placed in a test tube with a stirring bar and cooled in an ice-water bath. Aqueous sodium bicarbonate was injected into the solution from a syringe with rapid magnetic stirring until the pH reached 5.8. The solution was then filtered with suction through a 0.45 μm filter into another cold test tube. The volume of this solution that gave an endpoint near A = 1.0 was determined; this absorbance corresponds to ~10^{-4} M substrate in the kinetic runs.

The second-order rate constants and their errors were calculated by a least-squares fit of the data. The values of Brønsted β, β_{lg}, the interaction coefficients, and the errors in these parameters were calculated according to the least squares method of Deming,[27a] modified for computer applications,[27b] assuming an error of ±0.05 in the pK_a values. This program yields the experimental error of the parameters as opposed to some least-squares programs that give the error of fit of the data to an equation.

Results

The kinetics of the elimination reactions of the sulfonium salts **1–7** at 25 °C and 1 M ionic strength, maintained with KCl, in water or 8.3% Me$_2$SO in water (v/v) were followed spectrophotometrically under pseudo-first-order conditions, as described in the Experimental Section. The reactions were found to obey the rate law described by eq 4. Typical data are shown in Figure 1. The second-order rate constants, collected in Tables II and III, were obtained from the slopes of such plots and were reproducible within ±5%. The rate constants for catalysis of elimination by hydroxide ion were obtained by extrapolation of the observed rate constants to zero buffer concentration. In some cases, amine

$$k_{obs} = k_{HO^-}[HO^-] + k_B[B] \tag{4}$$

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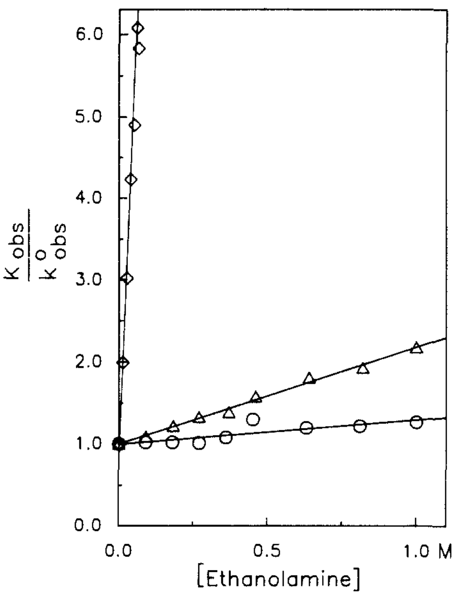

Figure 2. Comparison of the amount of buffer catalysis of elimination from acrylonitrile adducts with different leaving groups, at 25 °C, μ = 1 M (KCl). The value of k_{obs}/k^o_{obs} is k_{obs} at a given buffer concentration divided by k_{obs} extrapolated to zero buffer concentration. Catalysis by ethanolamine buffer (BH^+/B = 9) of elimination from acrylonitrile adducts of methyl pentafluorophenyl sulfide (◇) (in water) and pentafluorothiophenol (○) (8.3% Me_2SO in water v/v),[22] and the fumaronitrile adduct of pentafluorothiophenol (△) (8.3% Me_2SO in water v/v).[22]

buffer concentrations of up to 1 M (0.35 M for diamines) were used. The replacement of KCl with amine hydrochlorides caused a increase in the observed pH, which was ≤0.07 units at the highest buffer concentration.

Figure 2 shows that there is a dramatic increase in the effects of buffers on the observed rate constants for elimination from acrylonitrile adducts of thioethers, compared with elimination of thiolate anions from acrylonitrile and fumaronitrile adducts. Thiolate expulsion has been shown to be partly rate determining in the elimination of acrylonitrile derivatives, while proton transfer is mostly rate determining in the elimination reactions of fumaronitrile derivatives.[22,23] The increase in the buffer effects shows that proton transfer becomes kinetically more significant with the less basic thioethers as the leaving groups.

The isotope effects for the general-base-catalyzed elimination were determined with the same reagents and with alternating cuvettes containing the protium and deuterium adducts. Figure 3 shows plots of k_{obs} against base concentration in such experiments. The isotope effects for elimination of **2** catalyzed by ethylamine and tris(hydroxymethyl)aminomethane (Tris) buffers were found to be k_H/k_D = 4.9 and 4.4, respectively. The isotope effect for elimination catalyzed by hyroxide ion, obtained by extrapolation to zero concentration of ethylamine and tris(hydroxymethyl)aminomethane buffers, was found to be k_H/k_D = 4.6 ± 0.6. The reactions of the deuterated adducts in H_2O were found to follow first-order kinetics for more than 3 half-lives. This shows that there is no detectable exchange of protium for deuterium during the elimination.

Rate constants for the elimination reactions were determined in water (Table II) and in 8.3% Me_2SO in water (v/v) (Table III). The rate constants and β value for the reaction of **2** were found to be the same in the two solvents, within experimental error.

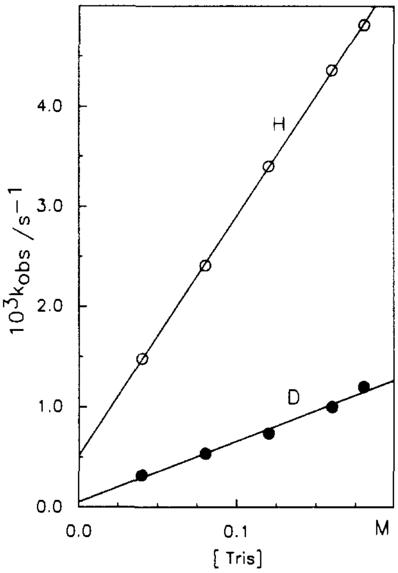

Figure 3. The deuterium isotope effect for elimination of methyl phenyl sulfide from $NCCL_2CH_2S^+(Me)Ph$ catalyzed by Tris buffer at 25.0 °C and μ = 1 M.

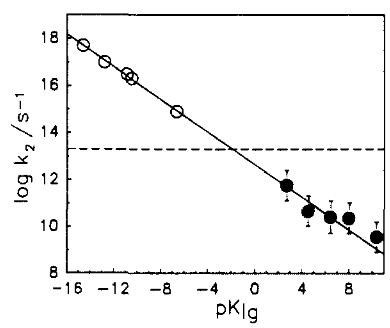

Figure 4. Correlation of the estimated lifetimes of the carbanions against the pK_a of the leaving group for acrylonitrile adducts. The dashed line corresponds to a single C–S bond vibration frequency[24] of 2 × 10^{13} s^{-1}. The solid symbols are estimated rate constants for carbanions formed from acrylonitrile adducts of thiols[23] and the open symbols are extrapolated rate constants for adducts of aliphatic and aromatic sulfides.

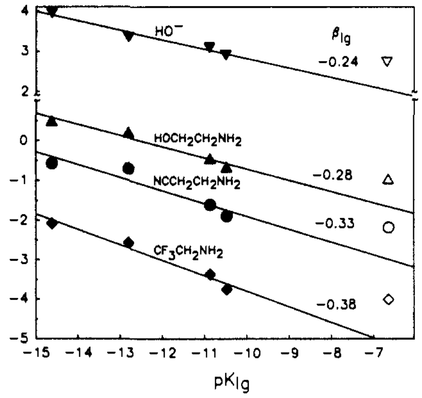

Figure 5. Brønsted type plot for elimination from acrylonitrile adducts of aryl methyl sulfides (solid symbols) and methyl *n*-propyl sulfide (open symbols) catalyzed by hydroxide anion and by primary amines.

Discussion

The elimination reactions of β-cyanoethyl thioethers must become concerted when the rate constant for expulsion of the leaving group from the carbanion becomes so large that there is no longer a barrier for leaving group expulsion. Figure 4 shows a correlation of the estimated values of log k_2 for leaving-group expulsion from the carbanion that is formed in elimination reactions of β-cyanoethyl thioethers, against the pK_a of the conjugate acid of the leaving group.[22,23] The line is drawn with a slope of β_{lg} = −0.35 that was obtained from the difference between the observed values of β_{lg} = −0.54 for the base-catalyzed elimination of thiol anions from a series of acrylonitrile adducts, for which leaving group expulsion is largely (but not entirely) rate limiting, and a value of β_{lg} = −0.19 for formation of the carbanion intermediate from three fumaronitrile adducts with leaving groups of

Table II. Rate Constants for β-Elimination Reactions of (β-Cyanoethyl)sulfonium Salts in Water at 25.0 °C and Ionic Strength 1 M (KCl)

leaving group	catalyst (pKa)	buffer ratio: $[BH^+]/[B]$	[buffer], M	k_B, $M^{-1}\,s^{-1}$	β
An-S-Me	ethylamine (10.97)[a]	19	$(0.9–1.3) \times 10^{-3}$	1.7	
	ethanolamine (9.76)[b]	9	0.01–0.06	0.22	
	1,3-diaminopropane(H+) (9.24)[c]	9	0.01–0.036	0.11	
	2-chloroethylamine (8.81)[d]	9	0.009–0.075	0.042	
	Tris (8.37)[c]	4	0.02–0.2	0.016	0.75 ± 0.01
	cyanoethylamine (8.17)[e]	4	0.02–0.2	0.013	
	ethylenediamine(H+) (7.42)[a]	4	0.02–0.07	6.20×10^{-3}	
	trifluoroethylamine (5.84)[f]	2.33	0.06–0.3	1.8×10^{-4}	
	cyanomethylamine (5.55)[d]	1.5	0.04–0.16	1.5×10^{-4}	
	HO^-			815	
Ph-S-Me	ethylamine	19	$(0.4–1.2) \times 10^{-2}$	2.51	
	ethanolamine	9	0.01–0.06	0.35	
	1,3-diaminopropane(H+)	9	0.005–0.03	0.2	
	2-chloroethylamine	9	0.020–0.071	0.075	
	Tris	4	0.04–0.2	0.028	0.71 ± 0.01
	cyanoethylamine	4	0.02–0.20	0.025	
	glycine ethyl ester (7.83)[a]	4	0.04–0.16	0.018	
	ethylenediamine(H+)	4	0.02–0.07	0.012	
	trifluoroethylamine	2.33	0.06–0.3	4.3×10^{-4}	
	cyanomethylamine	1.5	0.16–0.36	4.2×10^{-4}	
	HO^-			1260	
F_5Ph-S-Me	ethanolamine	9	0.013–0.067	3.15	
	1,3-diaminopropane(H+)	9	0.01–0.035	1.95	
	2-chloroethylamine	9	0.009–0.077	0.86	
	Tris	4	0.04–0.16	0.33	0.62 ± 0.01
	cyanoethylamine	4	0.018–0.18	0.27	
	ethylenediamine(H+)	4	0.02–0.07	0.15	
	trifluoroethylamine	2.33	0.101–0.253	8.3×10^{-3}	
	cyanomethylamine	1.5	0.08–0.40	7.3×10^{-3}	
	HO^-			9000	
^{n}Pr-S-Me	ethylamine	19	0.0039–0.014	0.98	
		19	0.0039–0.014	0.89	
	ethanolamine	9	0.01–0.06	0.11	
	1,3-diaminopropane(H+)	9	0.005–0.03	0.074	
	2–chloroethylamine	9	0.0203–0.071	0.020	0.76 ± 0.01
	Tris	4	0.0174–0.174	0.011	
	cyanoethylamine	4	0.02–0.20	6.6×10^{-3}	
	ethylenediamine(H+)	4	0.02–0.07	3.2×10^{-3}	
	trifluoroethylamine	2.33	0.121–0.303	9.9×10^{-5}	
	HO^-			544	
4-NO_2Ph-S-Me from compound **6**	ethanolamine	9	0.01–0.06	1.13	
	1,3-diaminopropane(H+)	9	0.01–0.0325	0.66	
	2-chloroethylamine	9	0.02–0.08	0.26	
	Tris	4	0.0174–0.174	0.11	
	cyanoethylamine	4	0.02–0.18	0.084	
		4	0.1–0.16	0.067	
	glycine ethyl ester	4	0.09–0.19	0.051	0.71 ± 0.01
		4	0.04–0.16	0.048	
	ethylenediamine(H+)	4	0.02–0.07	0.049	
	trifluoroethylamine	2.33	0.03–0.303	1.4×10^{-3}	
	cyanomethylamine	1.5	0.16–0.36	1.2×10^{-3}	
	HO–			11,970	

[a] Jencks, W. P.; Gilchrist, M. J. *J. Am. Chem. Soc.* **1968**, *90*, 2622. [b] Page, M. I.; Jencks, W. P. *J. Am. Chem. Soc.* **1972**, *94*, 8818. [c] Reference 22. [d] Cox, M. M.; Jencks, W. P. *J. Am. Chem. Soc.* **1981**, *103*, 572. [e] Fox, J. P.; Jencks, W. P. *J. Am. Chem. Soc.* **1974**, *96*, 1435. [f] St. Pierre, T.; Jencks, W. P. *J. Am. Chem. Soc.* **1968**, *90*, 3817.

$pK_a < 6.5$.[22] The value of $\beta_{lg} = -0.19$ was obtained from a correlation of rate constants instead of equilibrium constants, but the large value of $\beta = 0.9$ for general-base catalysis of this reaction suggests that proton transfer is rate limiting and is almost complete in the transition state; the value of $\beta_{lg} = -0.19$ is close to the value of $0.5 \times 0.5 = 0.25$ that is expected for substituents on a group that is separated by two carbon atoms from the negative charge.[22,28] Similar values of β_{lg} have been reported for the proton-removal step in several other elimination reactions.[13,29]

The correlation in Figure 4 is certainly not exact; the "rate constants" of $>10^{13}\ s^{-1}$ have no meaning because they are larger than the frequency of a C–S bond vibration and it is possible that the correlation becomes nonlinear as the pK_a of the leaving group decreases. However, it does suggest that the lifetime of the carbanion is likely to become insignificant with leaving groups that are much weaker bases than the thiol anions that were examined previously. The calculated line in Figure 4 intersects the horizontal line that corresponds to a C–S vibration frequency[24] of $2 \times 10^{13}\ s^{-1}$ at $pK_{lg} = -2$, which suggests that when the pK_a of the leaving group is lower than ~ -2 the carbanion will not have a significant lifetime. The pK_a of protonated dimethyl sulfide has been estimated to be -7.0, according to the X acidity function.[30] Therefore, this correlation suggests that there should be no significant barrier for the expulsion of all of the sulfide leaving groups examined in this study after the proton is removed from the (β-cyanoethyl)sulfonium salts, so that the elimination reactions are expected to be concerted. The pK_a of -7.0 for protonated dimethyl sulfide corresponds to a decrease in pK_a of -17.3 units

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(29) Fedor, L. R.; Glove, W. P. *J. Am. Chem. Soc.* **1971**, *93*, 985–989.

(30) Bagno, A.; Scorrano, G.; More O'Ferrall, R. A. *Rev. Chem. Inter.* **1987**, *7*, 313–352.

Table III. Rate Constants for β-Elimination Reactions of (β-Cyanoethyl)sulfonium Salts in 8.3% Me_2SO/Water (v/v) at 25.0 °C and Ionic Strength 1 M (KCl)

leaving group	catalyst	buffer ratio: $[BH^+]/[B]$	[buffer], M	k_B, $M^{-1}\,s^{-1}$	β
Ph-S-Me	ethylamine	19	(1.8–3.5) × 10^{-3}	2.27	
	ethanolamine	9	0.01–0.06	0.41	
	1,3-diaminopropane(H+)	9	0.005–0.03	0.22	
	2-chloroethylamine	9	0.011–0.066	0.091	0.72 ± 0.02
	Tris	4	0.017–0.173	0.029	
	trifluoroethylamine	2.33	0.030–0.30	4.8 × 10^{-4}	
	HO^-			710	
4-NO_2Ph-S-Me	ethanolamine	9	0.011–0.064	1.61	
	1,3-diaminopropane(H+)	9	(0.38–2.3) × 10^{-2}	1.03	
	2-chloroethylamine	9	0.01–0.061	0.32	
	Tris	4	0.018–0.14	0.16	
	cyanoethylamine	4	0.081–0.81	0.20	0.68 ± 0.02
	ethylenediamine(H+)	4	0.02–0.07	0.056	
	trifluoroethylamine	2.33	0.018–0.28	2.7 × 10^{-3}	
	cyanomethylamine	1.5	0.08–0.40	2.1 × 10^{-3}	
	HO^-			2297	
Ph-S-Et	ethylamine	19	(0.65–1.5) × 10^{-3}	3.03	
	ethanolamine	9	0.011–0.064	0.21	
	1,3-diaminopropane(H+)	9	0.005–0.030	0.11	0.77 ± 0.02
	2-chloroethylamine	9	0.010–0.061	0.027	
	Tris	4	0.019–0.186	0.015	
	cyanoethylamine	4	0.081–0.81	0.019	
	HO^-			600	

when a methyl group is added to the sulfur atom of a thiol. This gives calculated values of pK_a = −6.7, −10.5, −10.9, −12.8, and −14.6 for protonated $CH_3CH_2CH_2SMe$, p-$CH_3OPhSMe$, PhSMe, p-NO_2PhSMe, and F_5PhSMe, respectively, if it is assumed that ΔpK is the same for aliphatic and aromatic thiols. These pK values correspond to extrapolated "rate constants" of 8 × 10^{14} s^{-1} for $CH_3CH_2CH_2SMe$ and 2 × 10^{16} to 5 × 10^{17} s^{-1} for the aryl methyl sulfide leaving groups (Figure 4). These extrapolations suggest that there is no significant restoring force for a C–S bond vibration in any of the carbanions that are formed by proton removal, so that the reaction cannot proceed by a stepwise mechanism with a carbanion intermediate.

Nature of the Transition State. The dependence of the observed rate constants on the basicity of the leaving group, which increases as the strength of the catalyzing base decreases (Figure 5), provides the strongest direct experimental evidence in support of a concerted reaction mechanism. Figure 5 shows a correlation of log k with the calculated pK_a of the leaving group, with slopes of β_{lg} in the range of −0.24 to −0.38 for catalysis of the elimination of aryl sulfide leaving groups by hydroxide ion and three primary amines. The rate constants for the aliphatic sulfide show a positive deviation from this correlation; the dependence on the pK_a of the leaving group corresponds to that expected for an aryl sulfide of pK_a = −10.

These values of β_{lg} provide evidence that there is significant bond cleavage to the leaving group in the transition state because they are more negative than the values of β_{lg} = −0.19 for rate-limiting deprotonation of three arylthiol adducts of fumaronitrile[22] and β_{lg} = −0.18 for the deprotonation of N-[2-(p-nitrophenyl)ethyl]quinuclidinium ions.[13,31] They are also more negative than the values of β_{lg} in the range of −0.17 to −0.26 for the concerted elimination reactions of (2-arylethyl)quinuclidinium ions.[13]

The *change* in β_{lg} from −0.28 to −0.38 with decreasing base strength of the catalyst, from pK_a 9.8 to 5.8, provides even stronger evidence for a concerted reaction mechanism because it shows that the reaction with a more weakly basic catalyst involves a larger amount of bond breaking to the leaving group. This is the behavior that is expected for a reaction in which proton removal and leaving group expulsion are concerted. It has been observed for the elimination reactions of N-(2-arylethyl)quinuclidinium ions, but is not expected and is not observed for rate-limiting deprotonation of N-(2-(p-nitrophenyl)ethyl)quinuclidinium ions in a stepwise elimination reaction.[13] This shows that it does not arise from hyperconjugation with the leaving group in a stepwise reaction mechanism.

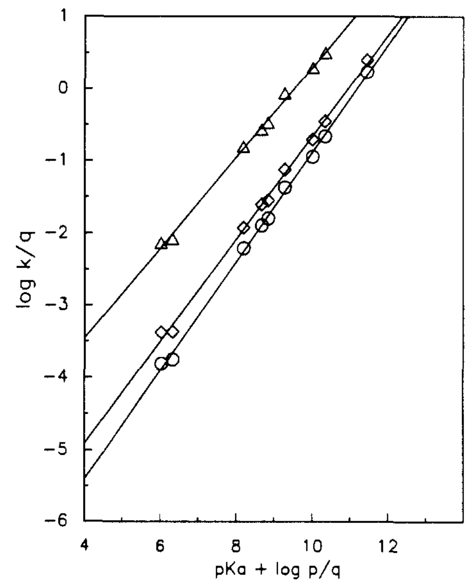

Figure 6. Statistically corrected Brønsted plots for catalysis of elimination from acrylonitrile adducts by primary amine buffers for (Δ) methyl pentafluorophenyl sulfide (β = 0.62), (◇) methyl phenyl sulfide (β = 0.7), and (○) p-anisyl methyl sulfide (β = 0.75) as the leaving groups.

Figure 6 shows representative Brønsted plots for general-base catalysis of the elimination reactions by substituted primary amines. The slopes are in the range β = 0.75–0.62 and decrease with increasing leaving group ability of the aryl sulfide. These values are considerably smaller than the value of β = 0.9 for rate-limiting proton abstraction from thiol adducts of fumaronitrile in a stepwise elimination reaction; they are also smaller than the value of β = 0.9 for the much slower concerted elimination reactions of N-(2-arylethyl)quinuclidinium ions, which have poorer leaving groups and less activation for proton abstraction.[13] The relatively small values of β are consistent with a concerted reaction mechanism in which departure of the leaving group is coupled

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(31) Alunni, S.; Jencks, W. P. *J. Am. Chem. Soc.* **1980**, *102*, 2052–2060.

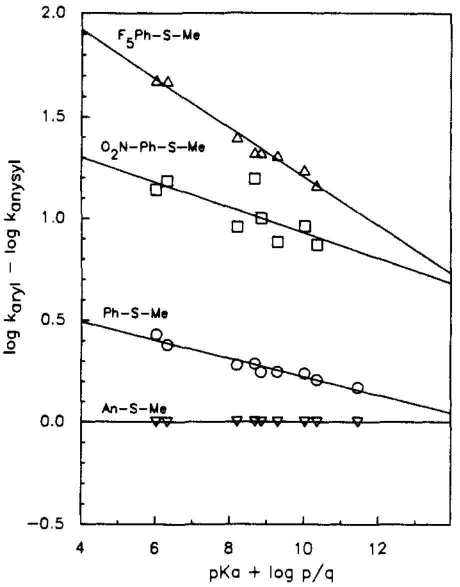

Figure 7. Ratios of the rate constants for elimination of different sulfide leaving groups plotted against the statistically corrected pK_a of the buffer bases.

with proton removal and less proton transfer is required in order to reach the transition state.

Again, the *change* in β with decreasing pK_a of the leaving group provides the strongest evidence for a coupled, concerted mechanism of elimination. The decrease in β with increasing leaving ability of the leaving group is most clearly shown by the correlation of the ratios of rate constants for different leaving groups with the pK_a of the base catalyst, as shown in Figure 7. If there were no change in β with the different leaving groups the lines in this figure would be parallel, with slope 0. Figure 8A shows the increase in β from 0.62 to 0.75 with increasing pK_a of the four aryl sulfide leaving groups. There is a deviation for the aliphatic sulfide leaving group, which would be smaller if the rate constant rather than the pK_a for the leaving group were used in the correlation.

This increase in β with increasing basicity of the leaving groups is described by $\partial\beta/\partial pK_{lg} = 0.028$. The increase in β_{lg} with increasing pK_a of the catalyst is shown in Figure 8B and is described by $\partial\beta_{lg}/\partial pK_{BH} = 0.024$. Both of these changes correspond to the same interaction coefficient, p_{xy}, according to eq 5.[16] The slopes

$$p_{xy} = \partial\beta/\partial pK_{lg} = \partial\beta_{lg}/\partial pK_{BH} \qquad (5)$$

in Figure 8 do not differ significantly and we conclude that the elimination reactions of this series of compounds exhibit coupling between proton removal and leaving-group expulsion in the transition state that is described by an interaction coefficient of $p_{xy} = 0.026$.

This coupling is also presumably responsible for the decrease in β for general-base catalysis in the concerted compared with the stepwise elimination reactions. Departure of the leaving group increases the acidity of the H–C bond and facilitates proton abstraction; this results in a decrease in β. On the other hand, the values of β_{lg} in the range −0.24 to −0.38 for the concerted reaction are less negative than the values of $\beta_{lg} = \sim -0.54$ for leaving-group expulsion from the carbanion intermediate in the stepwise reaction, in spite of the large driving force from the fully developed negative charge of the anion. This might be interpreted as an indication that the primary, difficult process in most concerted elimination reactions is proton removal; leaving-group expulsion may then occur in a concerted fashion because the carbanion intermediate has no barrier for decomposition.

The decrease in β in the concerted reaction is responsible for the large increase in buffer catalysis for the concerted compared with the stepwise reaction (Figure 2). The large value of $\beta = 0.9$ for the stepwise reaction results in relatively large rate constants for catalysis by hydroxide ion, so that catalysis by buffer bases is less significant. The small isotope effects in the range $k_H/k_D = 4$–5 for carbanion formation[22,23] in the stepwise reactions may be attributed to the asymmetric, late, transition state of a strongly unfavorable proton transfer reaction, with $\beta = 0.9$. The concerted reactions presumably proceed through a more central, symmetrical transition state for proton transfer, with $\beta = 0.62$–0.75, and might be expected to show larger isotope effects because of the maxima in isotope effects that are sometimes observed when $\Delta G°$ for the reaction is not far from 0.[32] However, the observed isotope effects of $k_H/k_D = 4.4$–4.9 show no increase compared with those for the stepwise reactions. It is possible that a tendency for the isotope effect to increase in the more symmetrical transition state is offset by coupling of the motions of the proton and the leaving heavy atom in the transition state of the concerted reaction, which increases the effective mass of the hydron and decreases the observed isotope effect.[33]

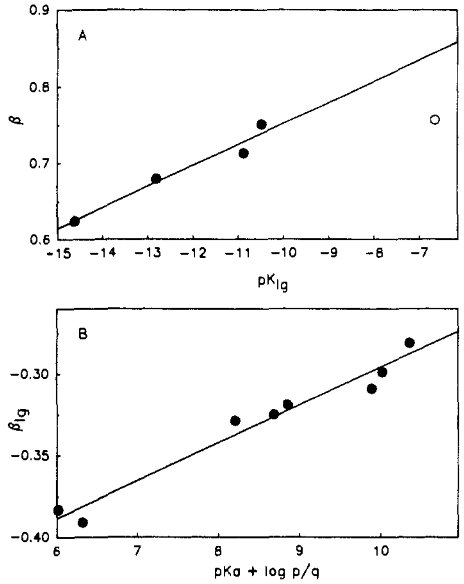

Figure 8. A. Dependence of the Brønsted β for primary amine catalysts on the estimated pK_a of the leaving groups for elimination of aryl methyl sulfides (●) and methyl *n*-propyl sulfide (○). B. Dependence of β_{lg} on the pK_a of the base catalyst for elimination of aryl methyl sulfides.

The change in β occurs with a change in substituents that are far removed from the site of ionization; it is not caused by a Hammond effect on the proton abstraction step of a stepwise reaction. There is no change in β in the stepwise elimination reactions of *N*-(2-(*p*-nitrophenyl)ethyl)quinuclidinium ions with changing substituents on the leaving group; however, changes in β with changing substituents on the leaving group and a significant p_{xy} coefficient are observed in the concerted elimination reactions of other *N*-(2-arylethyl)quinuclidinium ions.[13] There is no change in β with changing substituents close to the site of ionization in the amine-catalyzed ionization of 1-aryl-1-nitroethanes.[34]

A change in β with a change in substituents on the leaving groups can result from an electrostatic interaction between the catalyst and the reactant, without a change in transition state structure, but this change is in the opposite direction to the observed p_{xy} coefficient. An electrostatic interaction between an electron-donating substituent on the alcohol and an electron-withdrawing substituent on the phenyl ring for the interconversion of substituted 1-phenylethyl alcohols and ethers with different alcohols at equilibrium corresponds to a negative p_{xy} coefficient of −0.10.[35] If an electrostatic interaction is significant in the reactions described here the observed p_{xy} coefficient of 0.026 is an underestimate.

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(32) More O'Ferrall, R. A. In *Proton Transfer Reactions*; Caldin, E., Gold, V. Eds.; Chapman and Hall: London, 1975; pp 201–262.

(33) Katz, A. M.; Saunders, W. H. *J. Am. Chem. Soc.* **1969**, *91*, 4469–4472. Kaldor, S. B.; Saunders, W. H. *J. Am. Chem. Soc.* **1979**, *101*, 7594–7599.

(34) Bordwell, F. G.; Boyle, W. J., Jr. *J. Am. Chem. Soc.* **1972**, *94*, 3907–3911; **1975**, *97*, 3447–3452.

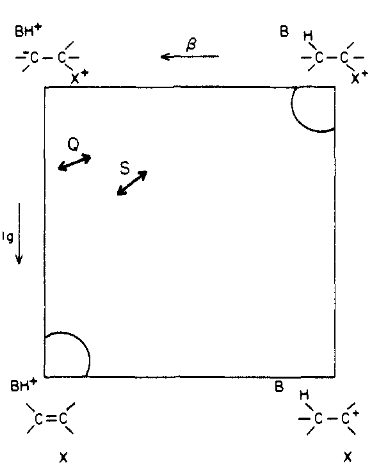

Figure 9. Reaction-coordinate energy contour diagram for concerted elimination reactions of (β-arylethyl)quinuclidinium ions, Q, and (β-cyanoethyl)sulfonium ions, S. The coordinates are defined by the observed values of β and β_{lg}; the contour lines are omitted.

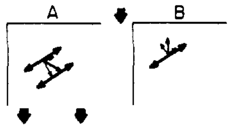

Figure 10. Sections of energy contour diagrams to show how substituents that change the energy of reactants or intermediates can cause changes in the position of the transition state by movements parallel and perpendicular to the reaction coordinate: Part A shows that an electron-withdrawing substituent in the leaving group stabilizes the products at the bottom of the diagram (heavy arrows). The transition state moves *toward* the perturbation perpendicular to the reaction coordinate and *away* from the perturbation parallel to the reaction coordinate, to give decreases in β and in β_{lg}. Part B shows that an electron-withdrawing substituent at the β-position stabilizes the carbanion intermediate in the upper left corner of the diagram. The transition state moves *toward* the perturbation perpendicular to the reaction coordinate. There is a small movement *away* from the perturbation parallel to the reaction coordinate because the reaction coordinate has a large horizontal component. The net movement is predominantly toward the top of the diagram, to increase β_{lg}.

It is useful to illustrate the structure–reactivity behavior of concerted elimination reactions on an energy contour diagram such as that shown in Figure 9,[15,16] in which the x and y coordinates are defined by the observed values of β and β_{lg}, respectively (the contour lines are not shown in Figure 9). The transition states for elimination from the sulfonium ions, S, differ from those for elimination from (β-arylethyl)quinuclidinium ions, Q,[13] in that the value of β is smaller, $-\beta_{lg}$ is slightly larger, and the reaction coordinate is more diagonal. The transition states of both reactions have a large amount of carbanion character, which places them in the upper left quadrant of the diagram. This means that these reactions, like most $\mathrm{A_{xh}D_HD_N}$ (E2) elimination reactions, show "imbalance" because there is more proton abstraction than leaving-group departure in the transition state. The sulfonium ions appear to be a little closer to a fully coupled, "synchronous" reaction, which would be near the diagonal line between reactants and products. The elimination reactions of β-arylethyl halides also appear to be in this category.[13] An increase in diagonal character, or coupling, is suggested by the increase in the p_{xy} coefficient from 0.018 for the (arylethyl)quinuclidinium compounds, to 0.026 for the (cyanoethyl)sulfonium ions. The predominantly horizontal direction of the reaction coordinate at the transition state reflects the predominant role of proton abstraction in the activation process.

Electron-withdrawing substituents that decrease the $\mathrm{p}K_a$ of the leaving sulfide increase the energy of the sulfonium ions at the top of the diagram, compared with the sulfide at the bottom; this is indicated by the heavy arrows at the bottom of Figure 10A. The position of the transition state will then tend to slide downhill toward the position of lower energy, perpendicular to the reaction coordinate, and to move uphill toward the position of higher energy, parallel to the reaction coordinate. This produces a movement toward the right side which corresponds to the observed decrease in β with decreasing $\mathrm{p}K_a$ of the leaving group and to the positive p_{xy} coefficient. The transition state for proton abstraction in a stepwise $\mathrm{A_{xh}D_H + D_N}$ (E1cB) mechanism would be on a horizontal reaction coordinate and would not be expected to show a significant increase in β when the energy at the bottom of the diagram is decreased. The more horizontal reaction coordinate for elimination from the quinuclidinium compounds gives less movement to the right, in accord with the smaller coupling and p_{xy} coefficient for this reaction.[13]

The differences between the behavior of (β-arylethyl)quinuclidinium and (β-cyanoethyl)sulfonium ions can be illustrated by the same diagram. The (β-cyanoethyl)sulfonium ions have a much better activating group to stabilize proton removal and a much better leaving group, compared with the (β-arylethyl)quinuclidinium ions. The better leaving group will decrease the energy of the species at the bottom of the diagram, as shown by the heavy arrows in Figure 10A. This will tend to shift the position of the transition state toward the right, to decrease β, and toward the lower part of the diagram, to increase $-\beta_{lg}$. This is consistent with the observed decrease in β from ~0.9 (0.86–1.1) to ~0.7 (0.62–0.75) and the increase in $-\beta_{lg}$ from 0.27 (0.25–0.33) to 0.31 (0.28–0.38) for the sulfonium compared with the quinuclidinium compounds.

Stabilization of the carbanion structure by the CN group of the (cyanoethyl)sulfonium ions, compared with the aryl group of the quinuclidinium compounds, lowers the energy of the upper left corner of the diagram. This will tend to shift the position of the transition state toward the top of the diagram, perpendicular to the reaction coordinate, and toward the right side of the diagram, parallel to the reaction coordinate, as shown in Figure 10B. The movement toward the right will augment the decrease in β that is brought about by the better leaving group, while the movement toward the top will oppose the downward movement brought about by the better leaving group. The decrease in $-\beta_{lg}$ from the movement upward is not enough to overcome the movement downward that is caused by the better leaving group in the sulfonium compounds, but it may account for the smaller change in $-\beta_{lg}$ than in β for the two reaction series.

The increase in coupling that is described by the increase in the p_{xy} coefficient from 0.018 for the (arylethyl)quinuclidinium ions to 0.026 for the (cyanoethyl)sulfonium ions is a third-derivative effect; the p_{xy} coefficient is a second derivative of log k with respect to a structural parameter, such as $\mathrm{p}K_a$ or σ, and a change in p_{xy} is a third derivative.[36] It is possible that the change in p_{xy} in these reactions arises from an edge effect. The reaction coordinate for the quinuclidinium ions may have more horizontal character because it is closer to the top edge of the diagram; a reaction coordinate that is very close to the top edge is not likely to have a large amount of diagonal character. More diagonal character is likely when the reaction coordinate moves down from the top, and when it approaches the center of the diagram it is likely to be close to diagonal, as in the coupled concerted elimination reactions of arylethyl halides.[13]

Other Matters. There is a small, but inconclusive, increase in β from 0.68 to 0.71 for **6** compared with **3** on the addition of a β-Cl atom. A significant increase in β would correspond to a positive value of the coefficient $p_{xy'} = \partial\beta/\partial\sigma$. A positive $p_{xy'}$ coefficient corresponds to a reaction coordinate with a large vertical component in Figure 9, but it can also be caused by an electrostatic interaction between polar substituents on the base catalyst and on the substrate.[13,16,35]

There is a small decrease of 30–40% in the second-order rate

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constants for the elimination reactions of the β-Cl compound **6** compared with **3** (Tables II and III). This is opposite to the observed effect on the stepwise $A_{xh}D_H + D_N$ elimination reactions of thioethers, in which the large increase in the acidity of the carbon acid upon β-Cl substitution results in an increase in rate by $\sim 10^4$ compared with the corresponding acrylonitrile compounds.[22] CPK models of **3** and **6** suggest that the large chlorine atom causes steric hindrance to free rotation of the leaving group. The proton is accessible to the base but the steric effect prevents the substrate from assuming an anti geometry for concerted elimination, thus decreasing the observed rate of elimination. The steric influence of the β-Cl substitution appears to be negligible for syn elimination, so that the absence of an increase in rate suggests that concerted anti elimination is strongly favored in this system. A destabilizing steric interaction between a bulky β-substituent and the leaving group in the anti-transition state was suggested to lead to an increase in syn elimination and a decrease in the rates of elimination from *N*-(2-substituted-2-phenethyl)-trimethylammonium ions.[37]

Methyl *n*-propyl sulfide is expelled from the corresponding (β-cyanoethyl)sulfonium ion faster than is predicted by the rate constants for elimination of aryl methyl sulfides from the corresponding (β-cyanoethyl)sulfonium ions (Figure 5). This could arise from differences in either the reactivity or the estimated pK_a values of the alkyl and aryl compounds. If resonance stabilization is significant for thiophenolate anions and not for aryl sulfides, the decrease in the reference values of pK_a could account for at least part of the deviation in Figure 5. However, calculations have been reported that indicate that resonance stabilization is not important for phenoxide anions.[38] Examination of space-filling CPK molecular models suggests that hindrance to free rotation in the transition state may decrease the rate constants for elimination of methyl aryl sulfides from the corresponding sulfonium ions and account for the relatively slow reactions of these compounds.

The rate constants for catalysis by strong bases of elimination from the methyl phenyl sulfide and ethyl phenyl sulfide adducts are very similar, but weaker bases react several fold faster with the methyl phenyl sulfide adduct (Table III); the difference corresponds to a slightly larger value of $\beta = 0.81$ for the ethyl compared with $\beta = 0.72$ for the methyl compound. This result suggests that elimination may occur with several different conformations of the transition state and that steric hindrance to free rotation of the ethyl group inhibits elimination from one or more of the conformations that react with a relatively small value of β.

The values of log k for catalysis by hydroxide ion show negative deviations of 0.63, 0.42 and 0 unit from the Brønsted plots for catalysis by amine bases of the elimination reactions with p-anisyl methyl sulfide, methyl phenyl sulfide, and methyl pentafluorophenyl sulfide, respectively. These deviations presumably reflect the "hydroxide ion anomaly".[39]

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