

General Base Catalysis, Structure-Reactivity Interactions, and Merging of Mechanisms for Elimination Reactions of (2-Arylethyl)quinuclidinium Ions¹

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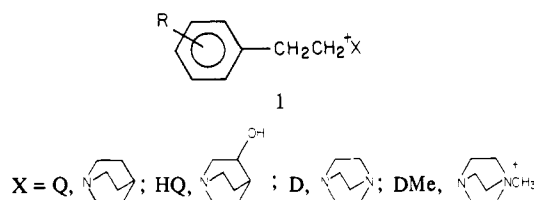
Abstract: Structure-reactivity parameters and interaction coefficients are reported for elimination reactions of *N*-(2-arylethyl)quinuclidinium ions and for 2-arylethyl halides and tosylates in 60% Me₂SO/water at 40 °C, based on direct measurements of Brønsted β values for general base catalysis by oxanion buffers, Hammett ρ values, and β_{1g} for substituted quinuclidines. The Brønsted slopes increase from β = 0.67 for *N*-(2-(*p*-nitrophenyl)ethyl)quinuclidinium ions, which react by an E1cB_{irr} mechanism, to β ~ 0.9 for the reactions of other *N*-(2-arylethyl)quinuclidinium ions by a concerted E2 elimination. There is no detectable interaction between the base catalyst and the leaving group for E1cB elimination, so that the interaction coefficient $p_{xy} = \partial\beta_{1g}/\partial pK_{BH} = \partial\beta/\partial pK_{1g}$ is ~0 for the *N*-(2-(*p*-nitrophenyl)ethyl)quinuclidinium ions. In contrast, values of β_{1g} become less negative with increasing pK_a of the base catalyst for the *p*-cyano and other *N*-(2-arylethyl)quinuclidinium ions, giving a constant value of $p_{xy} = 0.018$ for the E2 elimination reactions of these compounds. The positive p_{xy} coefficient for the *N*-(2-phenylethyl)quinuclidinium ions is confirmed by the observation of less negative values of β_{1g} as the effective basicity of aqueous tetramethylammonium hydroxide is increased by the addition of Me₂SO. An increase in β with poorer leaving groups in the series of 2-(*p*-nitrophenyl)ethyl halides also corresponds to a positive p_{xy} coefficient and an E2 mechanism. The interaction between the leaving group and central atoms is shown by the less negative values of β_{1g} with electron-withdrawing substituents on the β-phenyl group, which corresponds to a negative coefficient $p_{yy} = -\partial\beta_{1g}/\partial\sigma = -\partial\rho/\partial pK_{1g} = -0.09$. A small decrease in β with electron-withdrawing substituents on the β-phenyl group suggests an interaction between the base catalyst and the central atoms that is described by a negative coefficient $p_{xy} = \partial\beta/\partial\sigma = \partial\rho/\partial pK_{BH} = -0.07$. The signs of the p_{yy} and p_{xy} coefficients are consistent with an important component of proton transfer in the transition state. These properties of the E2 elimination reactions of *N*-(2-arylethyl)quinuclidinium ions can be described by a reaction coordinate that is rotated 24° counterclockwise from the *x* coordinate (for proton transfer) on a reaction coordinate-energy diagram that is defined by the observed structure-reactivity parameters. In contrast, β increases with increasing σ for elimination reactions of 2-arylethyl bromides with a positive value of $p_{xy} = 0.07$. This suggests more diagonal character to the transition state on the reaction coordinate diagram. The change from an E1cB to an E2 mechanism is more easily described as a transformation of mechanism than as a change between two coexisting mechanisms.

Extensive studies of structure-reactivity relationships in β-elimination reactions have led to a qualitative understanding of the relationship between the structure of the E2 transition state and changes in reactant structure or reaction conditions.²⁻⁶ These studies have relied heavily upon interpretations of hydrogen and heavy-atom isotope effects and changes in these effects. The results have generally been discussed in terms of the approaches put forth by Bunnett,³ Thornton,^{4,7} and More O'Ferrall.⁵

Elimination reactions have played a central role in the development of the concept that transition states may change by shifting in a direction perpendicular to the reaction coordinate.²⁻⁷ Such changes in transition states are widely ignored by those who interpret all of chemistry in terms of the Polanyi-Bell-Leffler-Hammond-Marcus postulate for movement of the transition state parallel to the reaction coordinate. There are many indications that perpendicular movements of the transition state are important in elimination reactions,²⁻⁷ although some of the evidence is incomplete or conflicting.

Following earlier work from this laboratory on the elimination reactions of *N*-(2-(*p*-nitrophenyl)ethyl)quinuclidinium and *N*-(2-phenylethyl)quinuclidinium ions in water,⁸ we describe here

an examination of the elimination reactions of *N*-(2-arylethyl)quinuclidinium ions, **1**, in 60 vol% (0.28 mol fraction) Me₂SO in



water catalyzed by oxanion bases. This system is well behaved for the classical determination of Brønsted β values from rate constants obtained with increasing concentrations of buffer bases and gives convenient rate constants in a partially aqueous medium for reactions that are too slow to measure in water. These Brønsted slopes probably provide a more direct measure of the amount of proton transfer in the transition state than do hydrogen isotope effects and avoid the ambiguity involved in the interpretation of small isotope effects.⁹ Brønsted coefficients for E2 elimination reactions in ethanol have been reported previously for catalysis by thiophenoxide ions of the reactions of cyclohexyl halides and tosylates¹⁰ and of DDT¹¹ and for catalysis by unbuffered phenoxide ions of the reactions of 2-(*p*-nitrophenyl)ethyl and 2-phenylethyl bromides.¹²

We have determined Brønsted coefficients for the elimination reactions of a series of substituted 2-phenylethyl compounds with quinuclidines or halides as the leaving groups. The results provide measures of the effect of catalyst basicity, β, the effect of leaving

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group basicity, β_{g} , and the effect of substituents at the β -phenyl group, ρ , on the rate and on each other. The results with the substituted quinuclidinium compounds provide a measure of leaving group effects with a constant leaving atom and constant steric effects, which complements previous work with substituted sulfonate leaving groups in the phenylethyl series^{13,14} and in simple alkyl systems.¹⁵⁻¹⁷ The structure-reactivity parameters that have been obtained permit a mapping of transition state structure for these reactions on energy surfaces that are defined in terms of these parameters.^{5,18} Changes in these parameters describe movements of the transition state parallel and perpendicular to the reaction coordinate and define structure-reactivity interaction coefficients that correspond to different orientations of the reaction coordinate and curvatures of the energy surface. The results are generally in agreement with the transition state structures that have been deduced from earlier work, which are based largely upon the interpretations of hydrogen and heavy-atom isotope effects.^{2,4,6,19,20} Furthermore, these studies demonstrate the usefulness of structure-reactivity interactions as a tool for determining the mechanism of elimination reactions and help in describing and understanding what happens when the spectrum of E2 transition states is extended and a change or "merging" to an E1cB mechanism occurs.

Experimental Section

Materials. Inorganic salts were analytical reagent grade and were used without further purification. All other materials were either recrystallized or distilled prior to use, except for hexafluoroacetone sesquihydrate (Aldrich), which was used without further purification. 2-(*p*-Nitrophenyl)ethyl chloride, fluoride, and iodide were generous gifts of Dr. J. Keffe. *N*-(2-(*p*-Nitrophenyl)ethyl)- and *N*-(2-phenylethyl)-quinuclidinium salts⁸ were recrystallized prior to use. 2-(*p*-Nitrophenyl)ethyl bromide and 2-phenylethyl bromide were obtained from Aldrich.

N-(2-(*m*-Chlorophenyl)ethyl)-1,4-diazabicyclo[2.2.2]octanium tosylate, (*m*-ClPhEtD⁺), mp 185–186 °C, was prepared from the tosylate and 1,4-diazabicyclo[2.2.2]octane (Dabco) by the method of Alunni;⁸ the tosylate was prepared from the alcohol.²¹ *N*-(2-(*m*-(Trifluoromethyl)-phenyl)ethyl)-1,4-diazabicyclo[2.2.2]octanium tosylate (*m*-CF₃PhEtD⁺), mp 190–192 °C, was also prepared from the tosylate.⁸ The tosylate was prepared from the alcohol, which was prepared by lithium aluminum hydride reduction of the carboxylic acid.^{22a} The acid was obtained from the nitrile by acid hydrolysis.^{22b} *N*-(2-(*m*-Nitrophenyl)ethyl)-1,4-diazabicyclo[2.2.2]octanium tosylate (*m*-NO₂PhEtD⁺), mp 218–220 °C, was prepared as described above for *m*-CF₃PhEtD⁺, except that the alcohol was obtained by reduction of the commercially available acid with sodium borohydride and aluminum chloride in diglyme.²³ *N*-(2-(*p*-Acetylphenyl)ethyl)-1,4-diazabicyclo[2.2.2]octanium bromide (*p*-AcPhEtD⁺), mp 230–232 °C, was prepared from the bromide according to the procedure of Alunni.⁸ 2-(*p*-Acetylphenyl)ethyl bromide was prepared from phenylethyl bromide by Friedel-Crafts acylation.²⁴ *N*-(2-(*p*-Cyanophenyl)ethyl)-1,4-diazabicyclo[2.2.2]octanium tosylate (*p*-CNPhEtD⁺), mp 240–242 °C, was prepared from the tosylate, which in turn was prepared from the alcohol as described above for analogous compounds. The alcohol was prepared from 2-(*p*-aminophenyl)ethyl alcohol by a Sandmeyer reaction.²⁵ The ¹H NMR (D₂O, 90 MHz)

Table I. Apparent pK_{a} Values in 60 vol % Me₂SO in Water at 25 °C and Ionic Strength 0.30 M (KCl)

acid	pK_{a}	$K_{\text{ass}}, \text{M}^{-1}$
pentafluorophenol	6.0 ^a	
acetic acid	6.3 ^a	~1.0
perfluoro-2-methyl-2-propanol	6.7 ^a	
quinuclidinoneH ⁺	6.9 ^b	
cacodylic acid	8.1 ^b	
DabcoH ⁺	8.5 ^b	
hexafluoroacetone hydrate	8.7 ^a	
quinuclidineH ⁺	10.5 ^b	
acetohydroxamic acid	11.2 ^b	
hexafluoro-2-propanol	11.2 ^a	~4.8
tetrafluoroacetone hydrate	11.2 ^a	
hexafluoro-2-methyl-2-propanol	11.5 ^a	
phenol	11.8 ^a	
trifluoroethanol	14.5 ^b	
ethylene glycol	17.7 ^c	
water	18.3 ^d	~0.8

^a pK_{a} obtained by potentiometric titration. ^b pK_{a} estimated from pH measurements in buffer solutions used for the kinetic runs. ^c Estimated from a plot of $pK_{\text{a}}(\text{water})$ against $pK_{\text{a}}(\text{Me}_2\text{SO}; \text{water})$, based on $pK_{\text{a}} = 15.4$ in water (Ballinger, P.; Long, F. A. *J. Am. Chem. Soc.* 1960, 82, 795–798). ^d $pK_{\text{a}} = -\log \{([\text{H}^+][\text{HO}^-]/[\text{H}_2\text{O}])\}$, where $[\text{H}^+] = 10^{-\text{pH}}$ and $[\text{H}_2\text{O}] = 40 \text{ M}$.

spectra of these salts are characterized by a 16-proton multiplet at δ 3.3, characteristic aromatic absorptions, and a 3-proton singlet at 2.3 for the tosylate salts. The *N*-(2-arylethyl)-4-methyl-1,4-diazabicyclo[2.2.2]octanium salts (ArEtDMe²⁺) were prepared from the ArEtD⁺ salts and methyl iodide in methanol.²² The ¹H NMR spectra of these salts are characterized by a 3-proton singlet at 3.4, a 12-proton singlet at 4.1, 2-proton triplets at 3.2 and 3.9, a 3-proton triplet for the tosylate salts, and characteristic aromatic absorptions.

Me₂SO was first dried over 4 Å molecular sieves and then distilled in vacuo from calcium hydride, while keeping the pot temperature below 45 °C. Sixty percent Me₂SO in water was prepared by adding 0.4 vol of water to a volumetric flask and then filling to the mark at 25 °C. This mixture, determined gravimetrically, corresponds to 0.28 mol fraction Me₂SO.

Kinetics. Kinetics were monitored on a Zeiss PM6 or a Cary 118 spectrophotometer. Reactions were carried out in the presence of a large excess of buffer at ionic strength 0.3 M, maintained with potassium chloride. Cuvettes were temperature equilibrated in the cell compartment of the spectrophotometer for at least 30 min prior to a kinetic run. Reactions with half-lives of less than 30 min were generally followed to completion and plots of $\log(A_{\infty} - A)$ against time were found to obey good pseudo-first-order kinetics. Slower reactions were followed by the method of initial rates with $k_{\text{obs}} = \Delta A / ([\text{S}]_0(\epsilon_{\text{p}} - \epsilon_{\text{s}})\Delta t)$, in which ϵ_{s} and ϵ_{p} are the extinction coefficients of the substrate and product respectively and $[\text{S}]_0$ is the initial substrate concentration.

Apparent extinction coefficients were calculated for the substrates (ϵ_{s}) either from absorbance readings in the buffer solutions used in the kinetic runs or in 0.30 M KCl. Extinction coefficients for the products (ϵ_{p}) were calculated by generating the products in situ by reaction of the substrate in dilute potassium hydroxide. Extinction coefficients for substrates and products were checked for each stock solution. The extinction coefficients for *p*-nitrostyrene and styrene were also determined from solutions of the olefins that were synthesized (*p*-nitrostyrene) or commercially available (styrene). For the reactions of the 2-(*p*-nitrophenyl)ethyl compounds *p*-nitrostyrene formation was monitored at 335 nm ($\epsilon = 0.85 \times 10^4$ in 60 vol% Me₂SO in water); for the reaction of *p*-NO₂PhEtQ⁺ with pentafluorophenol *p*-nitrostyrene formation was monitored at 355 nm ($\epsilon = 0.29 \times 10^4$). Styrene formation from 2-phenylethyl compounds was followed at 260 nm ($\epsilon = 0.86 \times 10^4$). For the reactions of the other substrates, the wavelength at which kinetics were monitored and ($\epsilon_{\text{p}} - \epsilon_{\text{s}}$) are as follows: *m*-ClPhEtD⁺ (260 nm, 0.76×10^4), *m*-ClPhEtDMe²⁺ (260 nm, 0.86×10^4), *m*-CF₃PhEtD⁺ (260 nm, 0.73×10^4), *m*-CF₃PhEtDMe²⁺ (260 nm, 0.74×10^4), *m*-NO₂PhEtD⁺ (260 nm, 0.36×10^3), *m*-NO₂PhEtDMe²⁺ (260 nm, 0.36×10^3), *p*-AcPhEtD⁺ (283 nm, 2.1×10^4), *p*-AcPhEtDMe²⁺ (283 nm, 1.7×10^4), *p*-CNPhEtD⁺ (268 nm, 2.1×10^4), and *p*-CNPhEtDMe²⁺ (268 nm, 1.9×10^4). For the slowest reactions, only ~0.5% reaction was followed, corresponding to an absorbance change of about 0.1. Control experiments for these slow experiments showed no significant change in the absorbance of the buffer or olefin in the absence of substrate or of the substrate in the absence

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of buffer under the same conditions. The reactions of 2-phenylethyl bromide with buffer solutions of hexafluoroacetone, cacodylic acid, and hexafluoro-2-propanol were too slow to follow to completion, but gave linear plots of A against time for at least 6% of the reaction. Since $(\epsilon_p - \epsilon_a)$ is much greater than $(\epsilon_p' - \epsilon_a')$, in which ϵ_a' is the extinction coefficient of any product formed by a direct substitution, the rate constants obtained from the initial part of the reaction give rate constants for the elimination reaction only, although some substitution may also occur.

Measurements of pH were made with an Orion model 701A pH meter and a Radiometer GK 2321C combination electrode. In dilute hydrochloric acid solutions (10^{-2} – 10^{-3} M) of 60% by vol Me_2SO in water, the electrode system responded reversibly to hydrogen ion concentration. The electrode system was standardized at pH 2.00 with 0.01 M hydrochloric acid in the same solvent. Apparent $\text{p}K_a$ values were measured either by titration or from pH measurements of the buffer solutions used in the kinetic runs (Table I). The apparent $\text{p}K_a$ of water in this solvent mixture at ionic strength 0.3 M is defined by $-\log([\text{H}^+][\text{HO}^-]/[\text{H}_2\text{O}])$ and is estimated to be 18.2 ± 0.15 , based on $[\text{H}^+] = 10^{-\text{pH}}$ and $[\text{H}_2\text{O}] = 40$ M. Due to slow electrode response (5–10 min) in dilute potassium hydroxide solutions and pH values that were reproducible to only ± 0.1 unit from day to day, calibrations with standard potassium hydroxide solutions were made after each kinetic run when the hydroxide ion reaction was known to contribute to k_{obsd} .

The observed rate constant was shown to increase linearly with buffer base concentration in buffer solutions of hexafluoro-2-propanol, perfluoro-2-methyl-2-propanol, and 2-methyl-2-propanol, although changes of up to 0.3 pH unit were observed in these solutions (0.85 fraction free base) in the range 0.03–0.24 M [base]. For most reactions, however, no correction to k_{obsd} was necessary because there is no significant contribution to the observed rate from the hydroxide ion reaction. When the hydroxide ion reaction was significant, corrections to k_{obsd} were made according to

$$k_{\text{obsd}}(\text{corr}) = k_{\text{obsd}} - k_{\text{OH}}([\text{OH}^-] - [\text{OH}^-]_0) \quad (1)$$

in which $[\text{OH}^-]$ is the hydroxide ion concentration at the given buffer concentration and $[\text{OH}^-]_0$ is the concentration at the lowest buffer concentration. The corrected rate constants gave second-order rate constants that agreed well with those obtained in experiments in which the hydroxide ion reaction was insignificant.

Results

β -Elimination reactions of *N*-(2-arylethyl)quinuclidinium ions, halides, and tosylates in the presence of oxyanion bases follow the rate law of eq 2, in 60 vol % Me_2SO in water at 40 °C and ionic strength 0.3 M maintained with potassium chloride. Rate con-

$$k_{\text{obsd}} = k_{\text{OH}}[\text{HO}^-] + k_{\text{B}}[\text{B}^-] \quad (2)$$

stants for catalysis by hydroxide ion were obtained directly in dilute solutions of potassium hydroxide. Rate constants for the buffer-catalyzed reactions were obtained from the slopes of plots of k_{obsd} against buffer concentration, generally at four or more buffer concentrations. In buffer solutions in which the hydroxide ion reaction was significant, the observed intercepts were always found to agree with the intercepts calculated from the observed rate constant for hydroxide ion and the measured pH. The reactions of *N*-(2-phenylethyl)quinuclidinium ions catalyzed by the anion of ethylene glycol were followed in ethylene glycol buffer solutions which were prepared by diluting a 1.0 M solution of ethylene glycol containing 0.003 M potassium hydroxide with a solution at the same pH and ionic strength but without ethylene glycol. Rate constants were calculated from the slopes of linear plots of k_{obsd} against ethylene glycol concentration and from an estimated value of 17.4 for the statistically corrected $\text{p}K_a$ of ethylene glycol in 60 vol % Me_2SO in water (Table I). This $\text{p}K_a$ value and, hence, the absolute values of k_{B} for the anion of ethylene glycol are uncertain, but the relative values of k_{B} for compounds with different leaving groups are independent of the choice of $\text{p}K_a$.

In 60 vol % Me_2SO in water, plots of k_{obsd} against buffer concentration show curvilinear behavior at a high fraction free acid concentration in buffer solutions of hexafluoro-2-propanol, acetic acid, and trifluoroethanol. This curvature decreases with decreasing fraction free acid and the plots are linear at low fraction free acid. The curvature is essentially independent of substrate structure and mechanism, including uncharged PhEtBr (E2) and *p*- NO_2 PhEtBr (E2), *p*- NO_2 PhEtQ⁺ cation (E1c_{B_{irr}}), and *p*- NO_2 PhEtDMe²⁺ dication (E1c_{B_{irr}}). This result provides strong

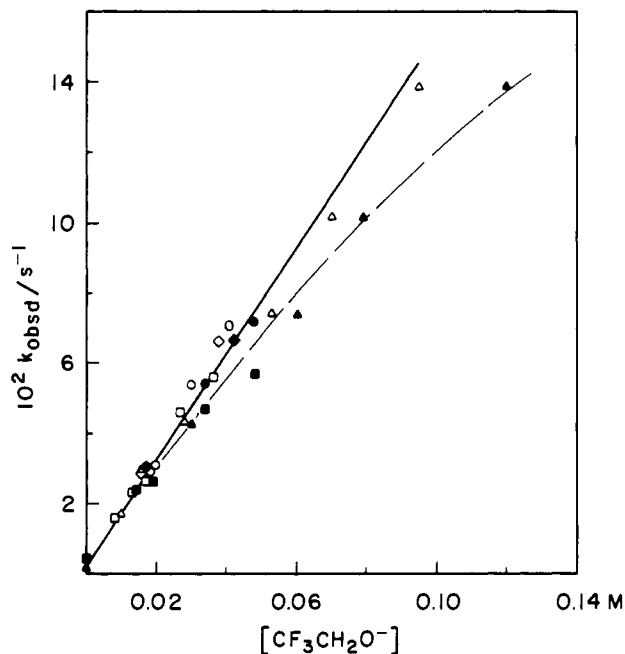
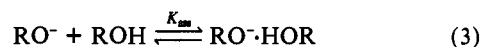


Figure 1. Dependence of k_{obsd} on trifluoroethoxide ion concentration for buffer catalysis of the elimination reaction of 2-(*p*-nitrophenyl)ethyl bromide in 60 vol % Me_2SO in water at 40 °C; $\mu = 0.30$ M (KCl). Fraction of free base: 0.25 (Δ); 0.17 (\circ); 0.14 (\square); 0.10 (\diamond). Closed symbols show uncorrected values and open symbols show values corrected for buffer association using $K_{\text{ass}} = 0.8 \text{ M}^{-1}$.

evidence that this curvature does not represent a change in rate-limiting step and that only a small part of the curvature can be ascribed to a specific medium effect. The curvature is, however, consistent with buffer association, as described by eq 3. Estimated



association constants are summarized in Table I. Hibbert²⁶ has observed buffer association in 70% $\text{Me}_2\text{SO}:\text{H}_2\text{O}$, with phenol buffers. Second-order rate constants were calculated under conditions in which buffer association is not significant (k_{obsd} is linear with buffer concentration), except for trifluoroethoxide ion, for which a small correction was made ($K_{\text{ass}} = 0.8 \text{ M}^{-1}$). Figure 1 shows corrected and uncorrected data for the reaction of *p*- NO_2 PhEtBr catalyzed by trifluoroethoxide ion.

In 20% and 40% $\text{Me}_2\text{SO}:\text{H}_2\text{O}$ mixtures, plots of k_{obsd} against the concentration of acetohydroxamate buffer showed curvilinear behavior for the reaction of *p*- NO_2 PhEtQ⁺. In 40% $\text{Me}_2\text{SO}:\text{H}_2\text{O}$, a plot of k_{obsd} against acetohydroxamate buffer concentration is curvilinear for *p*- NO_2 PhEtQ⁺, but no curvature was observed for the reaction of *p*- NO_2 PhEtD⁺ (Figure 2).

The effect of changing the Me_2SO concentration in $\text{Me}_2\text{SO}:\text{H}_2\text{O}$ mixtures on the observed rate constant for the elimination reactions of PhEtD⁺ and PhEtQ⁺ catalyzed by hydroxide ion is shown in Table II. Rate accelerations of approximately 2×10^7 for PhEtD⁺ and 9×10^7 for PhEtQ⁺ were observed upon changing the solvent from water to 0.84 mol fraction Me_2SO (95 vol % Me_2SO).

As the solvent is changed from water to 60 vol % Me_2SO in water, rate increases of 73- and 3-fold are observed for the reactions of *p*- NO_2 PhEtDMe²⁺ catalyzed by hydroxide ion and by Dabco, respectively (Table III). A comparison of rate constants in water (25 °C) and 60 vol % Me_2SO (40 °C) shows rate increases by factors of 490- and 5.2-fold for reactions of this dication catalyzed by hydroxide ion and by quinuclidine, respectively, and a rate increase of 670-fold for the reaction of uncharged *p*- NO_2 PhEtBr with hydroxide ion (Table III and ref 8). These results are consistent with ground state destabilization in the reaction with hydroxide ion, rather than stabilization of a po-

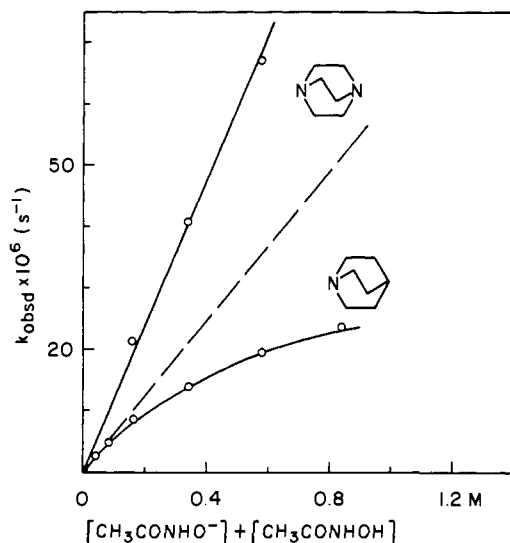


Figure 2. Dependence of k_{obsd} on total acetohydroxamate buffer concentration for the reaction of $p\text{-NO}_2\text{PhEtQ}^+$ and $p\text{-NO}_2\text{PhEtD}^+$ ions in 40 vol % Me_2SO in water at 25 °C; $\mu = 0.30$ M (KCl). Fraction of free acid is 0.68.

Table II. Catalysis by Hydroxide Ion of the Elimination Reactions of N -(2-Phenylethyl)quinuclidinium and N -(2-Phenylethyl)-1,4-diazabicyclo[2.2.2]octanium Ions in Me_2SO :Water Mixtures^a

mol % Me_2SO	H_-^b	$10^5 k_{\text{obsd}}, \text{s}^{-1}$	
		PhEtQ ⁺	PhEtD ⁺
0	12.00	0.000044 ^c	0.00035 ^c
14.5	13.77	0.0033	0.016
28.3	15.35	0.109	0.34
38.6	16.35	1.18	3.21
43.8	16.87	4.0	10.2
59.6	18.42	45	91
70.3	19.52	335	662
77.4	20.20	1000	2000
83.6	21.02	4000	7900

^a At 40 °C and ionic strength 0.01 M, $(\text{Me})_4\text{N}^+\text{OH}^-$. ^b Reference 41. ^c At ionic strength 1.0 M (KCl); k_{obsd} at $\text{KOH} = 0.01$ M was calculated from the reported second-order rate constant.⁸

larizable transition state, as the cause of the rate increases brought about by Me_2SO .

Table III summarizes the second-order rate constants and reaction conditions for the substrates investigated in this work.

The Brønsted plot for general base catalysis of the elimination reaction of $p\text{-NO}_2\text{PhEtQ}^+$ by oxyanions is consistent with a slope of $\beta = 0.68$, shown by the solid line in Figure 3, for catalysts of pK_a 6–12. A value of $\beta = 0.68$ is also given by the average of the β values for two carbonyl hydrates (0.62), three quinuclidines (0.74), two phenoxides (0.65), and two tertiary alkoxides (0.71). The Brønsted plot for $p\text{-NO}_2\text{PhEtDMe}^{2+}$ is indistinguishable from that in Figure 3 and gives a value of $\beta = 0.66$ with $\beta = 0.63$ for two hydrates and $\beta = 0.74$ for three quinuclidines. The more basic oxyanion catalysts show downward curvature from Brønsted plots, which is similar for proton removal from carbon and for nucleophilic reactions and has been attributed to a solvation effect.²⁷ The Brønsted plots can also be described by curves (dashed line, Figure 3), but we believe that the average slope of $\beta = 0.68$ described here represents a reasonable value based on different classes of the less basic catalysts, for which solvation effects are less important. These β values are based on pK_a values in the same solvent.

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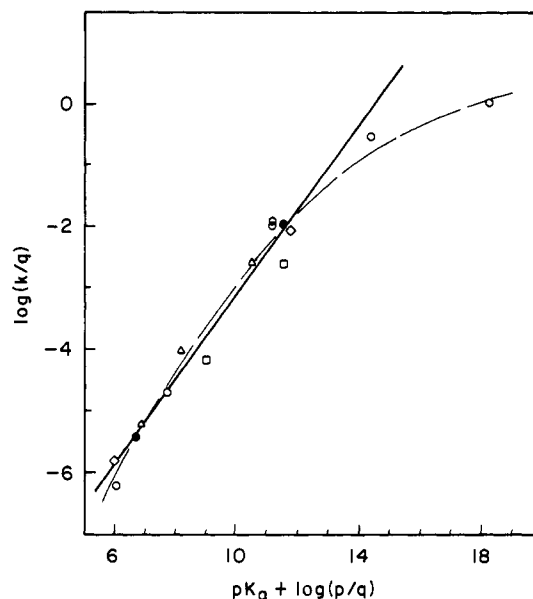


Figure 3. Brønsted plot for the reaction of $p\text{-NO}_2\text{PhEtQ}^+$ catalyzed by oxyanions and substituted quinuclidinium ions in 60 vol % Me_2SO in water at 40 °C; $\mu = 30$ M (KCl). Oxyanions (O), tertiary hydrates (□), phenoxides (◇), tertiary alcohols (●), and quinuclidines (Δ).

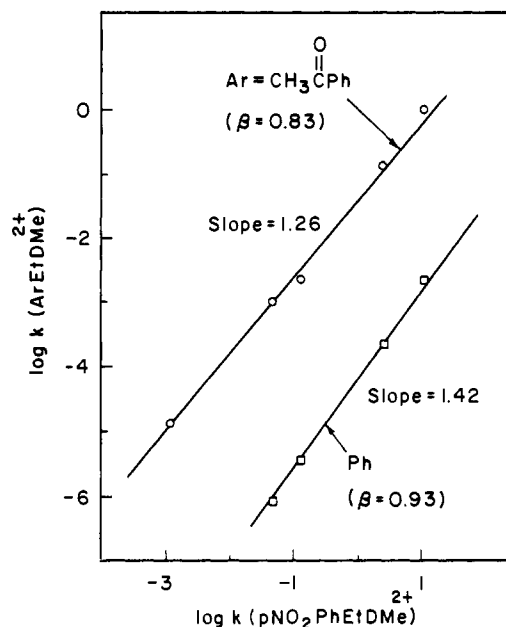


Figure 4. Plot of $\log k$ for ArEtDMe^{2+} compounds against $\log k$ for $p\text{-NO}_2\text{PhEtDMe}^{2+}$ in 60 vol % Me_2SO in water at 40 °C; $\mu = 0.30$ M (KCl). $\text{Ar} = p\text{-AcPh}$ (O) and Ph (□).

Similar Brønsted plots were obtained for the elimination reactions of other 2-arylethyl derivatives, but fewer rate constants were determined for the slow reactions of less reactive compounds with weak bases (Table III; plots not shown). Because of the curvature of the Brønsted plots with the more basic catalysts, Brønsted coefficients for other substrates were calculated from plots of $\log k$ for a given substrate against $\log k$ for $p\text{-NO}_2\text{PhEtDMe}^{2+}$, as illustrated in Figure 4. Plots of $\log k$ for $p\text{-AcPhEtDMe}^{2+}$ and for PhEtDMe^{2+} against $\log k$ for $p\text{-NO}_2\text{PhEtDMe}^{2+}$ give slopes of 1.26 and 1.42 that correspond to values of $\beta = 0.83$ and 0.93, respectively. The Brønsted β values obtained in this manner are summarized in Table IV. These values are not exact, but the data establish the direction of the changes in β and the value of $\beta = 0.68$ for the N -(2-(p -nitrophenyl)ethyl)quinuclidinium compounds with less basic catalysts, and it is certain that the values of β are larger than 0.68 for the other N -(2-arylethyl)quinuclidinium compounds.

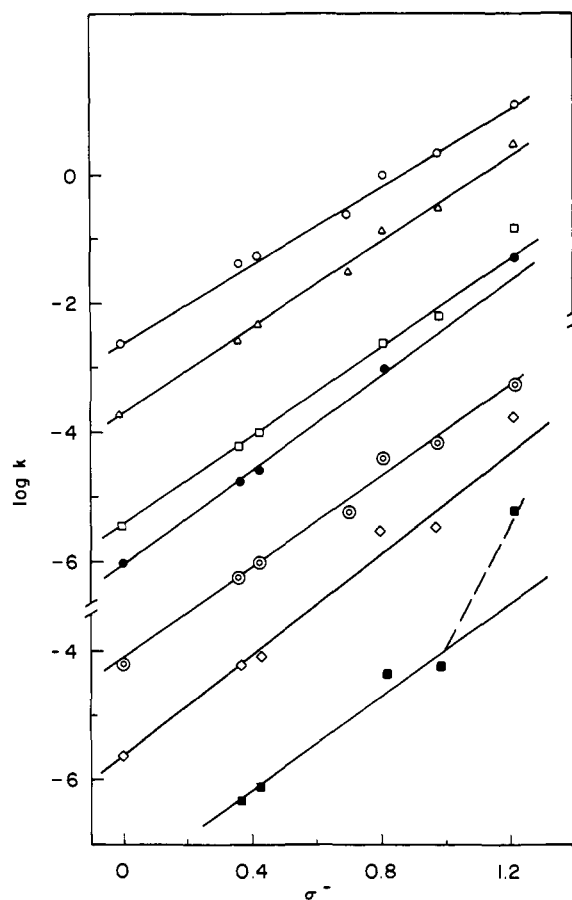


Figure 5. Hammett plots for the β -elimination reactions of ArEtDMe^{2+} and ArEtD^+ ions catalyzed by oxyanions in 60 vol % Me_2SO in water at 40°C ; $\mu = 0.30\text{ M}$ (KCl). The top four lines are for ArEtDMe^{2+} ions and the catalysts in descending order are: hydroxide, trifluoroethoxide, hexafluoroisopropoxide, and the anion of tetrafluoroacetone hydrate. The bottom three lines are for ArEtD^+ and the catalysts in descending order are: hydroxide, trifluoroethoxide, and hexafluoroisopropoxide ions.

Hammett plots utilizing σ^- constants are shown in Figure 5 for the elimination reactions of ArEtD^+ and ArEtDMe^{2+} catalyzed by oxyanion bases; ρ values are given in Table V. Values of β_{1g} obtained from plots of $\log k$ against $\text{p}K_{1g}$ are summarized in Table VI (plots not shown).

Discussion

Mapping the Transition State. Structure-reactivity parameters, such as Brønsted's β , ρ , and β_{1g} , provide some measure of the distribution of charge in a transition state, and changes in these parameters provide a measure of changes in this charge distribution. It is convenient to map these properties of the transition state on a reaction coordinate diagram in which the x and y axes are defined by experimental parameters, such as β for proton transfer and β_{1g} for bond-breaking of the leaving group, and the Gibbs energy is indicated by contour lines.^{5,18,29} The locations of the transition states for the reactions examined here are described on such a diagram in Figure 6, in which the contour lines have been omitted.

The Brønsted β values for catalysis by oxyanions of the β -elimination reactions of N -(2-arylethyl)quinuclidinium ions and of 2-arylethyl halides and tosylates are summarized in Table IV. These β values provide a comparatively straightforward measure of charge development in the catalyzing base that complements other measurements of the amount of proton transfer in the transition state, such as the primary hydrogen isotope effect and the secondary solvent deuterium isotope effect.^{2,9,30,31} The large

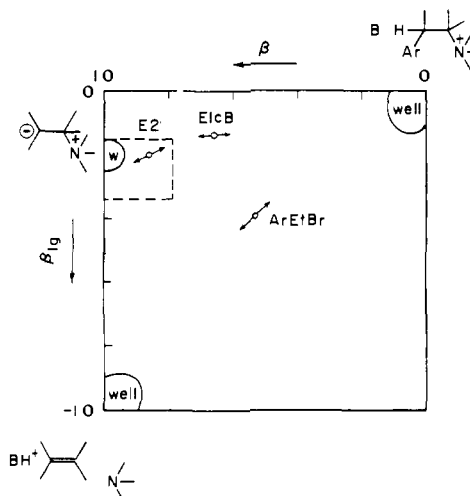


Figure 6. Reaction coordinate energy diagram for β -elimination reactions of (2-arylethyl)quinuclidinium ions and bromides catalyzed by oxyanions. Proton transfer along the x axis is defined by β and C-N bond cleavage along the y axis is defined by β_{1g} . The energy contours are omitted. The range of transition state structures as defined by the observed variations of the structure-reactivity parameters is shown by the dashed lines for E2 elimination reactions of the quinuclidinium ion substrates.

values of $\beta > 0.66$ that are observed for the reactions of N -(2-arylethyl)quinuclidinium ions indicate a large amount of proton transfer in the transition state. They are consistent with a previous conclusion that the small to moderate primary β -deuterium isotope effects in the range $k_{\text{H}}/k_{\text{D}} = 2.6$ – 4.2 and the solvent deuterium isotope effects of $k_{\text{OD}^-}/k_{\text{OH}^-} = 1.6$ – 1.7 for the elimination reactions of the closely related (2-arylethyl)trimethylammonium ions catalyzed by hydroxide ion represent a proton that is more than half-transferred in the transition state.^{4,31} The values of $k_{\text{OD}^-}/k_{\text{OH}^-} = 1.79$ for the elimination reaction of (2-phenyl)trimethylammonium ion and $k_{\text{OD}^-}/k_{\text{OH}^-} = 1.57$ for 2-phenylethyl bromide correspond to β values of 0.92 and 0.70, respectively, based on a limiting ratio of 1.88 for the isotope effect.³¹ These values can be compared with the directly determined Brønsted β values of 0.93 and 0.48 for PhEtDMe^{2+} and PhEtBr (Table IV). Strong bases show a downward deviation from the Brønsted plot (Figure 3) that has been attributed to a requirement for partial desolvation before proton abstraction.²⁷ Desolvation will be more difficult for stronger bases (negative β) and will decrease the observed Brønsted slope. There may also be a decrease in β from a change in transition state structure, but any such decrease must be small if the large values of $k_{\text{OD}^-}/k_{\text{OH}^-}$ can be taken as a measure of the amount of proton transfer in the transition state. There is also good agreement between the observed Brønsted slope of $\beta = 0.68$ for catalysis of the elimination reaction of $p\text{-NO}_2\text{PhEtD}^+$ by substituted quinuclidines in water and the value of $\beta = 0.63$ calculated from the secondary solvent isotope effect of $k_{\text{OD}^-}/k_{\text{OH}^-} = 1.55$ for this reaction.⁸ The β values give no indication of a change in the amount of proton transfer to the catalyzing base in the transition state as the solvent is changed from water to 60% Me_2SO . These parameters and the primary isotope effect of $k_{\text{H}}/k_{\text{D}} = 4.65$ for (2-phenylethyl)trimethylammonium ion^{32a} suggest that moderately large primary isotope effects can be observed for reactions in which the proton is extensively transferred in the transition state. These results are consistent with the view that proton tunneling contributes significantly to the hydrogen isotope effects in these reactions.^{32a}

However, the primary isotope effect for catalysis by hydroxide ion of elimination reactions of two (2-arylethyl)trimethyl-

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(32) (a) Kaldor, S. B.; Saunders, W. H., Jr. *J. Am. Chem. Soc.* **1979**, *101*, 7594–7599. (b) Brown, K. C.; Romano, F. J.; Saunders, W. H., Jr. *J. Org. Chem.* **1981**, *46*, 4242. Miller, D. J.; Saunders, W. H., Jr. *J. Org. Chem.* **1981**, *46*, 4247.

(29) Jencks, W. P. *Chem. Rev.* **1972**, *72*, 705–718.

(30) Melander, L. "Isotope Effects on Reaction Rates"; Ronald Press: New York, 1960; pp 24–32.

Table III. Experimental Data and Conditions for the β -Elimination Reactions of *N*-(2-Arylethyl)quinuclidinium Ions, Halides, and Tosylates in 60 vol % Me₂SO in Water at 40 °C and Ionic Strength 0.30 M (KCl)

catalyst	fraction base	$k_B, M^{-1} s^{-1}$	catalyst	fraction base	$k_B, M^{-1} s^{-1}$
2-Phenylethyl Bromide					
HO ⁻		100×10^{-4}	(CF ₃) ₂ COHO ⁻	0.47, 0.53, 0.34	$0.17 \times 10^{-4} b$
CF ₃ CH ₂ O ⁻	0.17, 0.14, 0.11	$93 \times 10^{-4} a, b$	(CH ₃) ₂ As(O)O ⁻	0.52	0.21×10^{-4}
(CF ₃) ₂ CHO ⁻	0.83	8.3×10^{-4}	(CF ₃) ₂ (CH ₃)CO ⁻	0.82	6.5×10^{-4}
(CF ₂ H) ₂ COHO ⁻	0.66	1.6×10^{-4}			
2-(<i>p</i> -Nitrophenyl)ethyl Bromide					
HO ⁻		1.8	(CF ₃) ₂ COHO ⁻	0.66, 0.47	$14.6 \times 10^{-4} b$
HO ⁻		$2.69 \times 10^{-3} d$	(CH ₃) ₂ As(O)O ⁻	0.52	11.2×10^{-4}
CF ₃ CH ₂ O ⁻	0.25, 0.17, 0.14, 0.11	$1.51^{a, b}$	CH ₃ CONHO ⁻	0.45	99×10^{-3}
(CF ₃) ₂ CHO ⁻	0.83, 0.58, ^a 0.24 ^a	0.125 ^b	CH ₃ COO ⁻	0.84	0.37×10^{-4}
EtO ⁻		0.92 ^c	(CF ₃) ₂ (CH ₃)CO ⁻	0.82	85×10^{-3}
(CF ₂ H) ₂ COHO ⁻	0.86, 0.60, 0.66	$26 \times 10^{-3} b$			
<i>N</i> -(2-(<i>p</i> -Nitrophenyl)ethyl)-4-methyl-1,4-diazabicyclo[2.2.2]octanium Bromide, Iodide					
HO ⁻		$117 \times 10^{-1}, 0.16^e$	CH ₃ COO ⁻	0.84, 0.33, 0.17	$0.17 \times 10^{-4} a, b$
HO ⁻		$23.8 \times 10^{-3} d$	CH ₃ CONHO ⁻	0.70, 0.45	142×10^{-3}
CF ₃ CH ₂ O ⁻	0.25, 0.17, 0.11	$29 \times 10^{-1} a, b$	(CF ₃) ₂ (CH ₃)CO ⁻	0.82	140×10^{-3}
(CF ₃) ₂ CHO ⁻	0.83	141×10^{-3}	quinuclidine	0.50	32×10^{-3}
(CF ₂ H) ₂ COHO ⁻	0.86	50×10^{-3}	Dabco	0.50	24×10^{-4}
(CF ₃) ₂ COHO ⁻	0.67, 0.54	$13.3 \times 10^{-4} b$	Dabco	0.50	$0.79 \times 10^{-3} e$
(CH ₃) ₂ As(O)O ⁻	0.51	8.8×10^{-4}	3-ketoquinuclidine	0.50	0.85×10^{-4}
<i>N</i> -(2-Phenylethyl)-4-methyl-1,4-diazabicyclo[2.2.2]octanium Bromide, Iodide					
HO ⁻		22×10^{-4}	(CF ₃) ₂ CHO ⁻	0.84	0.036×10^{-4}
HOCH ₂ CH ₂ O ⁻		0.015 ^f	(CF ₂ H) ₂ COHO ⁻	0.84	0.0093×10^{-4}
CF ₃ CH ₂ O ⁻	0.17, 0.13, 0.25	$2.0 \times 10^{-4} a, b$			
<i>N</i> -(2-Phenylethyl)-1,4-diazabicyclo[2.2.2]octanium Bromide					
HO ⁻		0.65×10^{-4}	CF ₃ CH ₂ O ⁻	0.17, 0.25, 0.13	$0.023 \times 10^{-4} a, b$
HOCH ₂ CH ₂ O ⁻		$4.6 \times 10^{-4} f$			
<i>N</i> -(2-Phenylethyl)quinuclidinium Bromide					
HO ⁻		0.20×10^{-4}	CF ₃ CH ₂ O ⁻	0.25	$0.0051 \times 10^{-4} a$
HOCH ₂ CH ₂ O ⁻		$1.1 \times 10^{-4} f$			
<i>N</i> -(2-Phenylethyl)-3-hydroxyquinuclidinium Bromide					
HO ⁻		0.35×10^{-4}	CF ₃ CH ₂ O ⁻	0.17	$0.0103 \times 10^{-4} a$
<i>N</i> -(2-(<i>p</i> -Nitrophenyl)ethyl)-1,4-diazabicyclo[2.2.2]octanium Bromide					
HO ⁻		153×10^{-2}	(CF ₃) ₂ CHO ⁻	0.84	1.8×10^{-2}
CF ₃ CH ₂ O ⁻	0.17	$48 \times 10^{-2} a$			
<i>N</i> -(2-(<i>p</i> -Nitrophenyl)ethyl)-3-hydroxyquinuclidinium Bromide					
HO ⁻		123×10^{-2}	CF ₃ CH ₂ O ⁻	0.17, 0.13	$40 \times 10^{-2} a, b$
<i>N</i> -(2-(<i>p</i> -Nitrophenyl)ethyl)quinuclidinium Bromide					
HO ⁻		87×10^{-2}	CH ₃ COO ⁻	0.84	0.012×10^{-4}
CF ₃ CH ₂ O ⁻	0.17, 0.13	$29 \times 10^{-2} a, b$	(CF ₃) ₂ (CH ₃)CO ⁻	0.73	112×10^{-4}
(CF ₃) ₂ CHO ⁻	0.76	104×10^{-4}	(CF ₃) ₃ CO ⁻	0.77	0.041×10^{-4}
	0.23	$104 \times 10^{-4} a$	3-ketoquinuclidine	0.50	0.062×10^{-4}
(CF ₃) ₂ COHO ⁻	0.23	0.69×10^{-4}	Dabco	0.50	1.99×10^{-4}
(CF ₂ H) ₂ COHO ⁻	0.275	25×10^{-4}	quinuclidine	0.50	32×10^{-4}
(CH ₃) ₂ As(O)O ⁻	0.50	0.41×10^{-4}	C ₆ H ₅ O ⁻	0.50	92×10^{-4}
CH ₃ CONHO ⁻	0.70	119×10^{-4}	C ₆ F ₅ O ⁻	0.49	0.015×10^{-4}
<i>N</i> -(2-(<i>p</i> -Acetylphenyl)ethyl)-4-methyl-1,4-diazabicyclo[2.2.2]octanium Tosylate, Iodide					
HO ⁻		103×10^{-2}	(CF ₃) ₂ CHO ⁻	0.81	$22 \times 10^{-4} a$
CF ₃ CH ₂ O ⁻	0.21	$14 \times 10^{-2} a$	(CF ₃) ₂ COHO ⁻	0.76	21×10^{-4}
(CF ₂ H) ₂ COHO ⁻	0.70	7.9×10^{-4}		0.61	0.134×10^{-4}
<i>N</i> -(2-(<i>p</i> -Acetylphenyl)ethyl)-1,4-diazabicyclo[2.2.2]octanium Tosylate					
HO ⁻		110×10^{-3}	(CF ₃) ₂ CHO ⁻	0.76	0.47×10^{-4}
CF ₃ CH ₂ O ⁻	0.21	$86 \times 10^{-4} a$	(CF ₃) ₂ COHO ⁻	0.81	$0.43 \times 10^{-4} a$
(CF ₂ H) ₂ COHO ⁻	0.70	0.26×10^{-4}		0.61	0.0014×10^{-4}
2-(<i>p</i> -Nitrophenyl)ethyl Propyl Sulfide					
HO ⁻		7.8×10^{-2}			
<i>N</i> -(2-(<i>m</i> -(Trifluoromethyl)phenyl)ethyl)-1,4-diazabicyclo[2.2.2]octanium Tosylate					
HO ⁻		27×10^{-4}	(CF ₃) ₂ CHO ⁻	0.81	0.0076×10^{-4}
CF ₃ CH ₂ O ⁻	0.21	$0.84 \times 10^{-4} a$			
<i>N</i> -(2-(<i>m</i> -(Trifluoromethyl)phenyl)ethyl)-4-methyl-1,4-diazabicyclo[2.2.2]octanium Tosylate, Iodide					
HO ⁻		52×10^{-3}	(CF ₃) ₂ CHO ⁻	0.83	0.96×10^{-4}
CF ₃ OH ₂ O ⁻	0.21	$45 \times 10^{-4} a$	(CF ₂ H) ₂ COHO ⁻	0.84	0.24×10^{-4}
<i>N</i> -(2-(<i>m</i> -(Chlorophenyl)ethyl)-1,4-diazabicyclo[2.2.2]octanium Tosylate					
HO ⁻		17.7×10^{-4}	(CF ₃) ₂ CHO ⁻	0.81	0.0046×10^{-4}
CF ₃ CH ₂ O ⁻	0.21	$0.63 \times 10^{-4} a, b$			
<i>N</i> -(2-(<i>m</i> -(Chlorophenyl)ethyl)-4-methyl-1,4-diazabicyclo[2.2.2]octanium Tosylate, Iodide					
HO ⁻		41×10^{-3}	(CF ₃) ₂ CHO ⁻	0.83	0.62×10^{-4}
CF ₃ CH ₂ O ⁻	0.21	$26 \times 10^{-4} a$	(CF ₂ H) ₂ COHO ⁻	0.84	0.18×10^{-4}

Table III (Continued)

catalyst	fraction base	$k_B, M^{-1} s^{-1}$	catalyst	fraction base	$k_B, M^{-1} s^{-1}$
<i>N</i> -(2-(<i>m</i> -Nitrophenyl)ethyl)-1,4-diazabicyclo[2.2.2]octanium Tosylate					
HO ⁻		153×10^{-4}			
<i>N</i> -(2-(<i>m</i> -Nitrophenyl)ethyl)-4-methyl-1,4-diazabicyclo[2.2.2]octanium Tosylate, Iodide					
HO ⁻		22×10^{-2}	CF ₃ CH ₂ O ⁻	0.21	29×10^{-3a}
<i>N</i> -(2-(<i>p</i> -Cyanophenyl)ethyl)-1,4-diazabicyclo[2.2.2]octanium Tosylate					
HO ⁻		19×10^{-2}	(CF ₃) ₂ COHO ⁻	0.69	0.0016×10^{-4}
CF ₃ CH ₂ O ⁻	0.21	93×10^{-4a}	(CF ₃ H) ₂ COHO ⁻	0.70	0.27×10^{-4}
(CF ₃) ₂ CHO ⁻	0.50 ^a	0.52×10^{-4a}			
	0.85	0.55×10^{-4}			
	0.55 ^a	0.58×10^{-4a}			
<i>N</i> -(2-(<i>p</i> -Cyanophenyl)ethyl)-4-methyl-1,4-diazabicyclo[2.2.2]octanium Tosylate, Iodide					
HO ⁻		1.9	(CF ₃) ₂ COHO ⁻	0.58	0.21×10^{-4}
CF ₃ CH ₂ O ⁻	0.21	28×10^{-2a}		0.38	0.22×10^{-4}
(CF ₃) ₂ CHO ⁻	0.55, ^a 0.85, 0.50 ^a	54×10^{-4b}	(CF ₃ H) ₂ COHO ⁻	0.70	14.1×10^{-4}
2-Phenylethyl Tosylate					
HO ⁻		5.0×10^{-4}			
2-(<i>m</i> -Chlorophenyl)ethyl Tosylate					
HO ⁻		48×10^{-4}			
2-(<i>m</i> -(Trifluoromethyl)phenyl)ethyl Tosylate					
HO ⁻		81×10^{-4}			
2-(<i>m</i> -Nitrophenyl)ethyl Tosylate					
HO ⁻		18×10^{-3}			
2-(<i>p</i> -Cyanophenyl)ethyl Tosylate					
HO ⁻		0.118			
2-(<i>p</i> -Nitrophenyl)ethyl Chloride					
EtO ⁻		0.079 ^c	(CF ₃ H) ₂ COHO ⁻	0.77	13.0×10^{-4}
HO ⁻		33×10^{-2}	CH ₃ CONHO ⁻	0.64	44×10^{-4}
(CF ₃) ₂ CHO ⁻	0.78	68×10^{-4}	CF ₃ CH ₂ O ⁻	0.17	16×10^{-2a}
2-(<i>p</i> -Nitrophenyl)ethyl Fluoride					
EtO ⁻		0.02 ^c	(CF ₃ H) ₂ COHO ⁻	0.77	1.6×10^{-4}
HO ⁻		80×10^{-3}	MeCONHO ⁻	0.64	5.9×10^{-4}
(CF ₃) ₂ CHO ⁻	0.77	8.1×10^{-4}	CF ₃ CH ₂ O ⁻	0.17	29×10^{-3a}
2-(<i>p</i> -Nitrophenyl)ethyl Tosylate					
HO ⁻		55×10^{-2}	MeCONHO ⁻	0.64	
CF ₃ CH ₂ O ⁻	0.17	25×10^{-2a}	(Me) ₂ As(O)O ⁻	0.54	0.50×10^{-4}
(CF ₃) ₂ CHO ⁻	0.74	95×10^{-4}	(CF ₃) ₂ COHO ⁻		1.12×10^{-4}
(CF ₂ H) ₂ COHO ⁻	0.77	20×10^{-4}			

^a Corrected for buffer association as described in the text. ^b Average value of data collected at more than one buffer ratio. Values at various buffer ratios always agreed to within 15%. ^c In ethanol at 30 °C; [EtO⁻] = $(5 \times 10^{-3}) - (20 \times 10^{-3})$ M. ^d Reference 8; in water at 25 °C; $\mu = 1.0$ (KCl). ^e In water at 40 °C; $\mu = 0.30$ (KCl). ^f See text.

Table IV. Apparent Brønsted β Values for Catalysis by Oxyanions of the β -Elimination Reactions of (2-Arylethyl)quinuclidinium Ions, Halides, and Tosylates in 60 vol % Me₂SO in Water at 40 °C and Ionic Strength 0.30 M (KCl).

substrate	β^a	substrate	β^a
<i>p</i> -NO ₂ PhEtDMe ²⁺	0.66	<i>p</i> -CH ₃ COPhEtD ⁺	1.05, 0.99 ^b
<i>p</i> -NO ₂ PhEtD ⁺	0.67 ^b	<i>p</i> -CNPhEtD ⁺	1.1, 1.0 ^b
<i>p</i> -NO ₂ PhEtQ ⁺	0.70, 0.69 ^c	<i>p</i> -NO ₂ PhEtF	0.76
<i>p</i> -CNPhEtDMe ²⁺	0.87, 0.84 ^d	<i>p</i> -NO ₂ PhEtCl	0.67
<i>p</i> -CH ₃ COPhEtDMe ²⁺	0.86, 0.83 ^d	<i>p</i> -NO ₂ PhEtBr	0.55 ^e
<i>m</i> -CF ₃ PhEtDMe ²⁺	0.91	<i>p</i> -NO ₂ PhEtOTs	0.68
<i>m</i> -ClPhEtDMe ²⁺	0.91	PhEtBr	0.48 ^e
PhEtDMe ²⁺	0.93		

^a β calculated from plots of $\log k(\text{ArEtX})$ against $\log k(\text{p-NO}_2\text{-PhEtDMe}^{2+})$ for which $\beta = 0.66$, based on rate constants for HO⁻, CF₃CH₂O⁻, (CF₃)₂CHO⁻, and (CF₂H)₂C(OH)O⁻, which provide a common data set. ^b Based on rate constants for HO⁻, CF₃CH₂O⁻, and (CF₃)₂CHO⁻. ^c Ten catalysts used in correlation (see Table III). ^d Based on rate constants for HO⁻, CF₃CH₂O⁻, (CF₃)₂CHO⁻, (CF₂H)₂COHO⁻, and (CF₃)₂COHO⁻. ^e Based on rate constants for HO⁻, CF₃CH₂O⁻, (CF₃)₂CHO⁻, (CF₂H)₂COHO⁻, (CF₃)₂COHO⁻, (CH₃)₂As(O)O⁻, and (CF₃)₂(CH₃)CO⁻.

ammonium ions in mixtures of Me₂SO and water exhibits a maximum of k_H/k_D near 35 mol % Me₂SO, which is close to the solvent composition of the experiments reported here.^{32b} Isotope effect maxima are expected to occur when the proton is half-

Table V. Hammett ρ Values for β -Elimination Reactions of *N*-(2-Arylethyl)quinuclidinium Ions Catalyzed by Oxyanions in 60 vol % Me₂SO in Water at 40 °C and Ionic Strength 0.30 M (KCl)^a

catalyst	ρ	
	ArEtD ⁺	ArEtDMe ²⁺
HO ⁻	3.5, ^a 3.9 ^b	3.3, ^b 3.0 ^a
CF ₃ CH ₂ O ⁻	3.9, ^a 4.3 ^b	3.5, ^b 3.3 ^a
(CF ₃) ₂ CHO ⁻	3.6 ^c	3.4, ^b 3.3 ^a
(CF ₂ H) ₂ COHO ⁻		3.6, ^b 3.6 ^a

^a Based on rate constants for all compounds except *p*-nitro, which reacts by an E1cB mechanism. ^b Based on rate constants for the unsubstituted, *m*-chloro, *m*-trifluoromethyl, and *p*-acetyl compounds, so that the comparisons can be made using a common data set (excluding the *p*-nitro compound which reacts by an E1cB mechanism). ^c Based on rate constants for the *m*-chloro, *m*-trifluoromethyl, *p*-cyano, and *p*-acetyl compounds.

transferred in the transition state for proton transfer between identical atoms and with 0.38 transfer for reaction of an oxygen base with a carbon acid.^{9,30,32b} Thus, there is a major discrepancy between an interpretation of 0.5 or 0.38 proton transfer based on the isotope effect maximum and the larger amount of proton transfer in the transition state that is indicated by the Brønsted slopes and secondary solvent isotope effects. There is also a discrepancy between the constant amount of proton transfer to

Table VI. Values of β_{1g} and $p_{yy'}$ Interaction Coefficients for the Elimination of *N*-(2-Arylethyl)quinuclidinium Ions Catalyzed by Oxyanions in 60 vol % Me₂SO in Water at 40 °C and Ionic Strength 0.3 M (KCl)^a

aryl group	β_{1g}				
	HO ⁻	CF ₃ CH ₂ O ⁻	(CF ₃) ₂ CHO ⁻	(CF ₂ H) ₂ COHO ⁻	(CF ₃) ₂ COHO ⁻
<i>p</i> -NO ₂ Ph	-0.15, -0.13 ^b	-0.13, -0.12 ^b	-0.13 ^c	-0.15 ^c	-0.15 ^c
<i>p</i> -CNPh	-0.17	-0.25	-0.34	-0.29	-0.36
<i>p</i> -CH ₃ COPh	-0.16	-0.21	-0.29	-0.25	-0.33
<i>m</i> -NO ₂ Ph	-0.20				
<i>m</i> -CF ₃ Ph	-0.22	-0.29	-0.35		
<i>m</i> -ClPh	-0.23	-0.27	-0.36		
Ph	-0.26, -0.24 ^b	-0.33, -0.31 ^b			
$p_{yy'}$ ^d	-0.097	-0.099	-0.060		

^a pK_{1g} in water at 25 °C and $\mu = 1.0$ M (KCl). Leaving groups *N*-methyl-Dabco ($pK_a = 3.0$) and Dabco ($pK_a = 8.9$). ^b Leaving groups *N*-methyl-Dabco, Dabco, quinuclidinol ($pK_a = 10.1$), and quinuclidine ($pK_a = 11.5$). ^c Leaving groups *N*-methyl-Dabco and quinuclidine. ^d Excluding the *p*-NO₂ compound. These values of $p_{yy'}$ are equal within the experimental error limits.

the base in water and 60% Me₂SO that is indicated by the Brønsted slopes and the changing amount of proton transfer indicated by the isotope effect maximum. Evidently these parameters are measuring different properties of the transition state. This discrepancy might be related in part to the complex nature of the proton abstraction from carbon in these reactions. If electron delocalization from carbon lags behind other processes the electron density on carbon in the transition state may be large enough to balance that of the base, so that there is little motion of the proton in a symmetric vibration. Electron delocalization is known to lag behind proton removal in the ionization of nitroalkanes and similar behavior is expected, to a lesser extent, in the ionization of other carbon acids.³³

The values of $\beta_{1g} = -0.12$ to -0.36 for the reactions of *N*-(2-arylethyl)quinuclidinium ions (Table VI and ref 8) indicate a small to moderate amount of C-N bond cleavage in the transition states of these reactions. These results and the large Brønsted β values place the transition states of these reactions in the upper left quadrant of the reaction coordinate diagram (Figure 6). The values of β_{1g} are consistent with the relatively small nitrogen isotope effects, in the range 0.9–1.4%, for the elimination of (2-arylethyl)trimethylammonium ions catalyzed by ethoxide ion.⁶ Values of $\beta_{1g} = -0.25$ and -0.31 can be estimated for the reactions in ethanol of (2-phenylethyl)dimethylanilinium ions from $\rho = 1.07$ ³⁴ and 1.3 ,³⁵ respectively, and $\rho = 4.20$ for the equilibrium ionization of anilines in the same solvent.³⁶

The Hammett ρ values are large, in the range 3.0–4.3 (Table V), and are consistent with the large amount of C-H cleavage and small amount of C-N cleavage that are indicated by the values of β and β_{1g} , respectively. They are in agreement with previously reported values of $\rho = 3.77$ and 3.0 for the elimination reactions of (2-arylethyl)ammonium ions catalyzed by ethoxide and *tert*-butoxide ions, respectively.³⁷

These structure-reactivity parameters and the location of the transition states of these reactions in the upper left quadrant of Figure 6 agree with most previous conclusions regarding the charge distribution in the transition states for elimination reactions of (2-arylethyl)ammonium ions.^{2,4,6,8,19,20,31}

Change in Rate-Determining Step. Following the observation by Alunni that the rate of elimination from *N*-(2-(*p*-nitrophenyl)ethyl)quinuclidinium ions increases nonlinearly with increasing buffer concentration,⁸ Keeffe established that these reactions follow a stepwise E1cB mechanism by demonstrating a change in rate-determining step with increasing buffer concentration, a large inverse solvent deuterium isotope effect for the initial reaction rate, and hydrogen-deuterium exchange into the

Table VII. The Effect of Increasing Amounts of Me₂SO in Me₂SO:Water Mixtures on the Partitioning of the Carbanion Intermediate for the Elimination of *N*-(2-(*p*-Nitrophenyl)ethyl)quinuclidinium Ions Catalyzed by Acetohydroxamate Ion at 25 °C and Ionic Strength 0.3 M (KCl)

vol % Me ₂ SO	k_{-1}/k_2	vol % Me ₂ SO	k_{-1}/k_2
0	85 ^a	40	3.6
20	17	60	<1

^a Reference 38.

substrate.³⁸ A change in rate-determining step is also observed with increasing concentration of acetohydroxamate buffer in 40% Me₂SO for *p*-NO₂PhEtQ⁺, but not for *p*-NO₂PhEtD⁺ (Figure 2). The linear increase in the rate with increasing buffer concentration for the latter compound shows that the curvature observed for *p*-NO₂PhEtQ⁺ is not caused by buffer association or a specific medium effect.

The change in rate-determining step for the E1cB mechanism occurs because proton removal, k_1 , is rate determining at low buffer concentration but k_2 (eq 4) becomes rate determining as the buffer concentration is increased and the carbanion intermediate returns rapidly to reactants as the $k_{-1}[BH]$ step becomes fast. The addition of organic solvents increases the rate of leaving



group expulsion from the zwitterionic intermediate, k_2 , and is likely to decrease k_{-1} as BH becomes less acidic, so that the change in rate-determining step occurs at higher buffer concentrations than in water.^{38b} The values of k_{-1}/k_2 for *p*-NO₂PhEtQ⁺ were calculated from the observed nonlinear dependence of k_{obsd} on buffer concentration and decrease from a value of 85 in water³⁸ to <1 in 60% Me₂SO (Table VII). The ratio k_{-1}/k_2 also decreases as the leaving group becomes less basic, with a slope of $\beta_{1g} = -0.5$ in aqueous solution.^{38b} A ratio of $k_{-1}/k_2 = 0.2$ was calculated for *p*-NO₂PhEtD⁺ in 40% Me₂SO from this value of β_{1g} and the ratio $k_{-1}/k_2 = 3.6$ for *p*-NO₂PhEtQ⁺ in this solvent, which explains why there is no significant curvature with the better leaving group (Figure 2).

The Interaction between the Base Catalyst and the Leaving Group. A structure-reactivity parameter, such as β or ρ , is a first derivative of $\log k$ with respect to a structural property, such as $\beta = \partial \log k / \partial pK_{\text{BH}}$, and defines the position of the transition state on one coordinate of a reaction coordinate diagram, such as Figure 6. A changing structure-reactivity parameter corresponds to a changing position of the transition state on the diagram. If the transition state is at a saddle point of this energy diagram, the movement of the transition state with changing reactant structure can be explained qualitatively and described quantitatively by assuming a linear perturbation of the energy surface by the change

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in energy of the reactant.^{5,7,18,29} The amount and direction of the movement depend on the curvatures of the surface parallel and perpendicular to the reaction coordinate and the direction of the reaction coordinate.^{7,18,39}

These changes in transition state structure may be described formally by interaction coefficients, such as p_{xy} (eq 5). The p_{xy}

$$p_{xy} = \partial\beta_{1g}/\partial pK_{BH} = \partial\beta/\partial pK_{1g} \quad (5)$$

coefficient describes a change in β_{1g} with changing basicity of the catalyst which is identical with the change in the Brønsted β with changing basicity of the leaving group. Since β and β_{1g} are first derivatives, these interaction coefficients are second derivatives of $\log k$. These coefficients depend on the curvatures of the surface and the direction of the reaction coordinate and, if three of them are known from experiment, they can be used to calculate both the curvatures and the direction.¹⁸

A stepwise E1cB reaction that involves only proton transfer or C-N bond cleavage in the transition state can be described by a reaction coordinate that is parallel to the x axis of the diagram in Figure 6, for proton transfer, or the y axis, for C-N cleavage, respectively. A concerted E2 elimination reaction in which both C-H and C-N cleavage are taking place in the transition state is expected to have some diagonal character of the reaction coordinate. If the curvatures of the surface are small, so that the transition state moves easily,^{7,18} a diagonal reaction coordinate is likely to give rise to characteristic changes in transition state structure with changing structure of the reactants that can be described by p_{xy} and other structure-reactivity interaction coefficients. For example, an increase in the basicity of the catalyzing base corresponds to an increase in the energy of the right side of the diagram. This is expected to cause movement of the transition state of a diagonal reaction coordinate to the right and upward, toward the position of higher energy on the right side, in the direction along (parallel to) the reaction coordinate, and to the left and upward, away from the position of higher energy, in the direction perpendicular to the reaction coordinate.^{7,18} The resultant of these two movements will be a new movement toward the top of the diagram, which corresponds to less C-N cleavage and a less negative β_{1g} . The horizontal components of the movement will cancel partially or completely. On the other hand, the horizontal reaction coordinate of an E1cB reaction mechanism that involves only proton transfer will tend to move uphill toward the position of higher energy on the right side under the same conditions, but should show little or no movement toward the top of the diagram, perpendicular to the reaction coordinate. This corresponds to $p_{xy} = \partial\beta_{1g}/\partial pK_{BH} = 0$.

A decrease in the basicity of the leaving group causes an increase in the energy of the top of the diagram. The resultant of movements parallel and perpendicular to the reaction coordinate will then tend to shift the transition state of the diagonal reaction coordinate toward the right, with less proton transfer and a smaller β , and will cause relatively little movement up or down on the diagram. For the same change in pK_a of the catalyst or leaving group these movements toward the top and toward the right, respectively, are identical, as required by eq 5. The horizontal reaction coordinate of an E1cB_{irr} mechanism will tend to move downhill perpendicular to the reaction coordinate under the same conditions, but should show little or no movement parallel to the reaction coordinate. This corresponds to $p_{xy} = \partial\beta/\partial pK_{1g} = 0$.

We have evaluated the p_{xy} coefficient for elimination reactions of *N*-(2-arylethyl)quinuclidinium ions by three methods.

First, Figure 7 shows that for the elimination reactions of *N*-(2-(*p*-nitrophenyl)ethyl)quinuclidinium ions the sensitivity of the reaction to the pK_a of the leaving quinuclidine (β_{1g}) is independent of the pK_a of the base catalyst over 12 pK units of catalyst strength. This describes a p_{xy} coefficient that is indistinguishable from zero and is consistent with the E1cB_{irr} mechanism (rate-determining proton transfer) for these compounds. In contrast to these results, Figure 7 also shows that the sensitivity to the pK_a of the leaving quinuclidine increases with decreasing pK_a of the

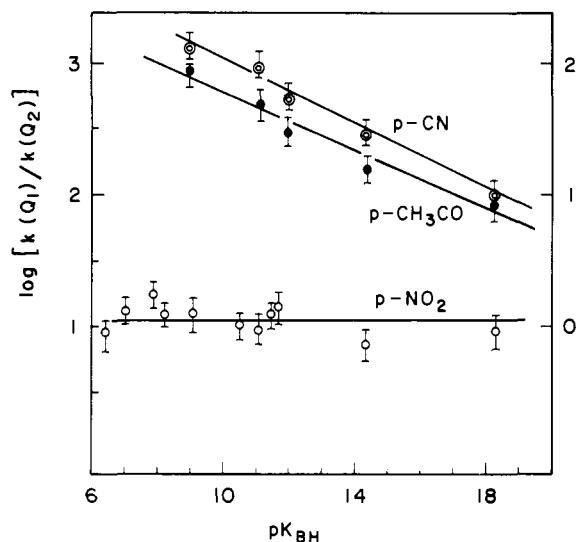


Figure 7. The change in the dependence of the rate on the pK_a of the leaving quinuclidine with changing pK_a of the base catalyst for the *p*-CH₃CO and *p*-CN substrates, for which $Q_1 = N$ -methyl-Dabco and $Q_2 =$ Dabco, and for the *p*-NO₂ substrate, for which $Q_1 = N$ -methyl-Dabco and $Q_2 =$ quinuclidine, in 60 vol % Me₂SO in water at 40 °C, $\mu = 0.30$ M (KCl). The left ordinate scale is for the *p*-NO₂ substrates and the right scale for the *p*-CH₃CO and *p*-CN substrates.

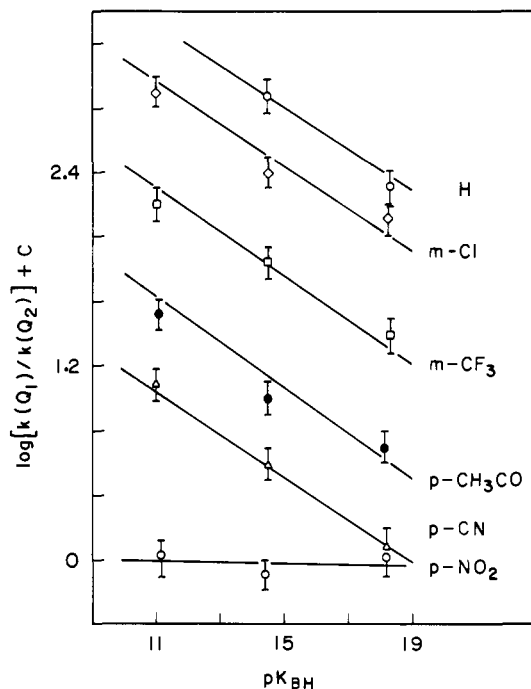


Figure 8. Dependence on the pK_a of the leaving quinuclidine as a function of the pK_a of the oxyanion catalyst in 60 vol % Me₂SO in water at 40 °C; $\mu = 0.30$ M (KCl). For the *p*-CN, *p*-CH₃CO, *m*-CF₃, and *m*-Cl substrates $Q_1 = N$ -methyl-Dabco and $Q_2 =$ Dabco, and for the *p*-NO₂ and unsubstituted substrate $Q_1 = N$ -methyl-Dabco and $Q_2 =$ quinuclidine. The ordinate scale is in arbitrary units and is set equal to 0 for the *p*-nitro substrate. Each substrate is shifted up the ordinate scale by a constant factor for clarity.

base catalyst for the elimination reactions of the *p*-acetyl and *p*-cyano substrates. This corresponds to downward movement on Figure 6 and to a positive interaction coefficient, with a value of $p_{xy} = \partial\beta_{1g}/\partial pK_{BH} = 0.018$, that supports a concerted E2 reaction mechanism for these compounds.

Figure 8 shows that a positive p_{xy} coefficient is also observed for the reactions of the unsubstituted, *m*-chloro-, and *m*-(trifluoromethyl) compounds with a more limited series of base catalysts that cover a range of 7 pK_a units. This result supports the concerted E2 mechanism for these less activated substrates

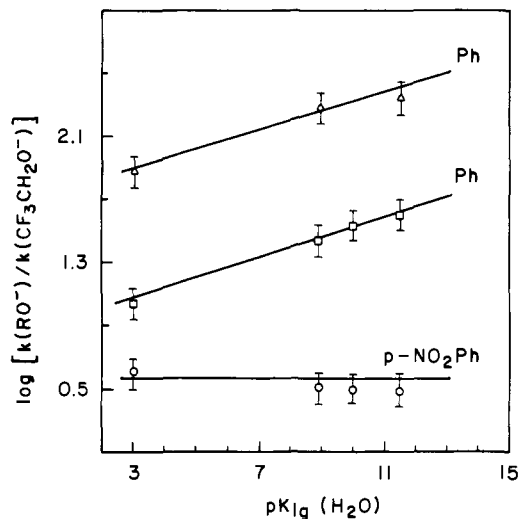


Figure 9. Dependence of the rate constant ratio for the hydroxide and trifluoroethoxide catalyzed reactions of *N*-(2-(*p*-nitrophenyl)ethyl)quinuclidinium ions (O) and *N*-(2-phenylethyl)quinuclidinium ions (□) and the rate constant ratios for the reactions of *N*-(2-phenylethyl)quinuclidinium ions with the anions of ethylene glycol and trifluoroethoxide (Δ) on $\text{p}K_{1g}(\text{H}_2\text{O})$ in 60 vol % Me_2SO in water at 40 °C; $\mu = 0.30$ M (KCl).

as well. There is no detectable difference in the size of the p_{xy} coefficient for the different substrates, except for the value of $p_{xy} = 0$ for the *p*-nitro compound. A concerted E2 mechanism has been demonstrated for the closely related *p*-MeO, unsubstituted, *p*-Cl and *p*-CF₃ substituted (2-arylethyl)trimethylammonium ions that is based on both primary hydrogen and nitrogen isotope effects⁶ and anti elimination for the unsubstituted compound.⁴⁰

Second, Figure 9 shows that for the elimination reactions of *N*-(2-(*p*-nitrophenyl)ethyl)quinuclidinium ions the sensitivity of the reaction to the base strength of the catalyst is independent of the $\text{p}K_a$ of the leaving quinuclidine over a range of 8 $\text{p}K_a$ units. This confirms an interaction coefficient of $p_{xy} = \partial\beta/\partial\text{p}K_{1g} = 0$ and an E1cB mechanism for these compounds. In contrast, the *N*-(2-phenylethyl)quinuclidinium ion shows an increase in sensitivity to the basicity of the catalyst as the basicity of the leaving group increases that corresponds to a positive value of $p_{xy} = 0.017$ and supports a concerted E2 reaction mechanism. Similar slopes are obtained by comparing the rate constants for either hydroxide or ethylene glycol anion with those for trifluoroethoxide anion (Figure 9) and from the data in Table III for the *m*-Cl, *m*-CF₃, *m*-NO₂, *p*-CH₃O, and *p*-CN compounds. These results correspond to the second expression of the p_{xy} coefficient in eq 5.

Third, Figure 10 shows that there is a decrease in the sensitivity of the elimination reactions of *N*-(2-phenylethyl)quinuclidinium ions to the $\text{p}K_a$ of the leaving quinuclidine as the basicity of the medium is increased⁴¹ by adding increasing amounts of Me_2SO to Me_2SO :water mixtures at a constant concentration of tetramethylammonium hydroxide. This corresponds to a positive interaction coefficient $p_{xy} = \partial\beta_{1g}/\partial\text{p}K_{\text{BH}}$. It also provides evidence that there is a steady increase in the basicity of the species of hydroxide ion that removes the proton from the substrate as the concentration of Me_2SO is increased; i.e., it does not support the hypothesis that proton removal is brought about by a particular species of (partially) desolvated hydroxide ion and that the only effect of Me_2SO is to increase the concentration of this active species in the solution. The same conclusions are supported by decreases in the sulfur and chlorine isotope effects that have been observed for the elimination reactions of (2-phenylethyl)dimethylsulfonium ion⁴² and (*p*-ClPh)₂CHCHCl₂⁴³ with increasing

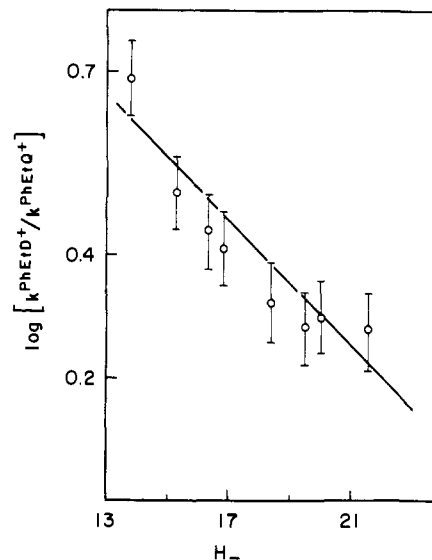


Figure 10. Log of the rate constant ratio for the reactions of PhEtD^+ and PhEtQ^+ against increasing concentrations of Me_2SO in Me_2SO :water mixtures containing 0.01 M tetramethylammonium hydroxide as measured by the H_- function⁴⁰ at 40 °C; $\mu = 0.01$ M.

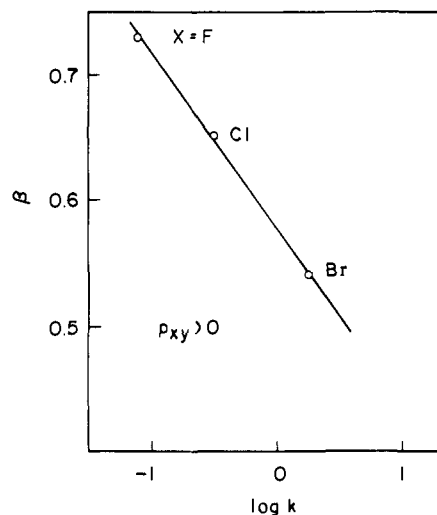


Figure 11. Brønsted β as a function of $\log k$ ($\text{M}^{-1} \text{s}^{-1}$) for the elimination reactions of 2-(*p*-nitrophenyl)ethyl halides catalyzed by hydroxide ion in 60 vol % Me_2SO in water at 40 °C; $\mu = 0.30$ M (KCl).

Me_2SO concentration under similar conditions.

The Brønsted β values for general base catalysis of the elimination reactions of 2-(*p*-nitrophenyl)ethyl halides increase in the order bromide, chloride, and fluoride (Figure 11). The observation of general base catalysis shows that proton abstraction occurs in the rate-determining step, but the increase in β with increasing electronegativity of the halide is in the opposite direction from that expected from a Hammond effect on the proton abstraction step of an E1cB mechanism. The increase in β is observed as the leaving ability of the halide decreases. This represents a positive interaction between the base catalyst and the leaving group (positive p_{xy}) and is analogous to the increase in β with increasing $\text{p}K_a$ of the leaving quinuclidine in the *N*-(2-arylethyl)quinuclidinium ion series. We conclude that 2-(*p*-nitrophenyl)ethyl bromide and chloride undergo elimination by a concerted E2 mechanism (the mechanism for the fluoride compound is not established by this result).

This appears to be an example of a change in mechanism that is brought about by an increase in the nucleofugic ability of the

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leaving group, since the *N*-(2-(*p*-nitrophenyl)ethyl)quinuclidinium ions react by a stepwise E1cB mechanism. This is supported by the absolute rates of the reaction, which increase in the order $F < Cl < Br$ (Figure 11; there is a similar increase in aqueous solution^{38b}), and provide evidence that the leaving ability of the halide, not its electronegativity, is manifested in the observed rate constants.⁴⁴ The rate constants for the bromide and chloride represent increases of 40- and 7-fold, respectively, over the rate constants expected from a $\rho^* \sigma^*$ correlation based on the rate constants for the compounds with quinuclidine, fluoride, and *n*-propanethiolate as leaving groups (Table III).⁴⁵ For *p*-NO₂PhEtOTs the value of β is 0.68 and the rate constant for the reaction catalyzed by hydroxide ion shows a 6-fold positive deviation from the $\rho^* \sigma^*$ correlation, which is also consistent with an E2 mechanism. Similar rate increases have been taken as evidence for a concerted E2 mechanism in other systems.^{46,47} This conclusion has been questioned on the ground that no-bond resonance with the halogen may increase with increasing leaving group ability and stabilize the transition state for proton removal in an E1cB_{irr} mechanism.⁴⁸ However, there is no significant chlorine isotope effect for the E1cB elimination of (*p*-NO₂Ph)₂CHCHCl₂⁴⁹ and the positive p_{xy} coefficient described here provides evidence that the observed rate increases may be ascribed to an E2 reaction mechanism. The value of $p_{xy} = \partial\beta/\partial pK_{lg} = 0$ for *N*-(2-(*p*-nitrophenyl)ethyl)quinuclidinium ions shows that there is no detectable effect of a change in leaving ability of the leaving group on the amount of proton transfer in the transition state for this system.

An increase in the inverse solvent deuterium isotope effect for 2-(*p*-(trimethylammonium)phenyl)ethyl halides⁴ as the leaving halide is varied from Br to Cl to F provides evidence that the elimination reactions of these compounds also exhibit a positive p_{xy} coefficient and proceed by a concerted E2 mechanism.

The value of β_{lg} for the halides is not known but it is generally believed that these compounds react through a central transition state and the secondary α -deuterium isotope effect of $k_H/k_D = 1.09$ for the elimination reaction of 2-phenylethyl bromide⁵⁰ is larger than the value of $k_H/k_D = 1.03$ for (2-phenylethyl)trimethylammonium ion.⁵¹ The transition state for these reactions is positioned in Figure 6 near the center for the y coordinate and in accord with the measured β values (Table IV) for the x coordinate. However, the position of this transition state corresponds to a value of ρ close to zero, which is inconsistent with the observed values of ρ and indicates either that the transition state is less central than shown or that there is imbalance^{18,33} of the different structure-reactivity parameters in the transition state.

The Interaction between the Leaving Group and the β -Phenyl Substituent. The $p_{yy'}$ coefficient (eq 6) describes the change in sensitivity of the rate to the nature of the leaving group with changing substituents on the β -phenyl group, which is attached to the central part of the transition state, and the complementary change in sensitivity to substituents on the β -phenyl group as the nature of the leaving group is varied. Figure 12 shows that the

$$p_{yy'} = -\partial\beta_{lg}/\partial\sigma^- = -\partial\rho/\partial pK_{lg} \quad (6)$$

sensitivity to the pK_{lg} of the leaving group ($-\beta_{lg}$) decreases as the substituent constant σ^- increases for elimination reactions of *N*-(2-arylethyl)quinuclidinium ions catalyzed by hydroxide, tri-

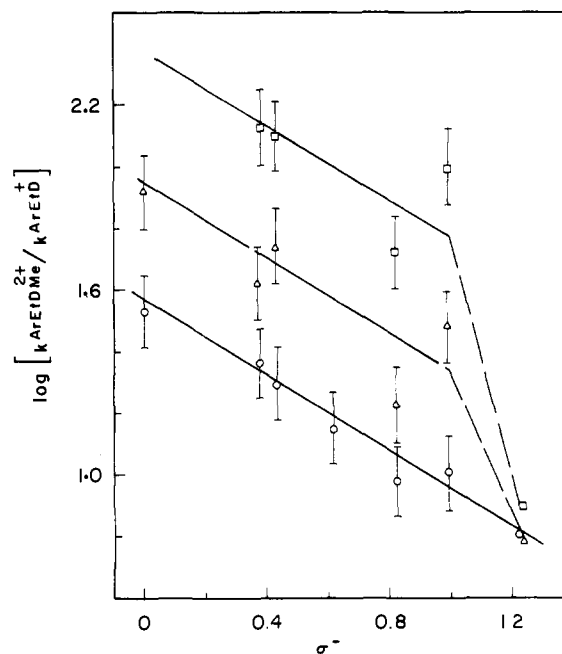


Figure 12. Interaction of the leaving group and substituents on the β -phenyl group in elimination reactions of *N*-(2-arylethyl)quinuclidinium ions. The rate constant ratio for *N*-methyl-Dabco and Dabco leaving groups is shown as a function of the σ^- value for a series of β -phenyl substituents for catalysis by HO⁻ (O), CF₃CH₂O⁻ (Δ), and (CF₃)₂CHO⁻ (□) in 60 vol % Me₂SO in water at 40 °C; $\mu = 0.30$ M (KCl).

fluoroethoxide, and hexafluoroisopropoxide anions. This means that there is less cleavage of the C-N bond to the leaving group as the β -phenyl substituent becomes more electron withdrawing. The results for all three catalysts are consistent with the same negative interaction coefficient of $p_{yy'} = -0.09$, excluding the data for the *p*-nitro compounds. The sign of this coefficient is opposite to that expected for a simple electrostatic interaction between polar substituents on the phenyl and quinuclidine groups.⁸

The same conclusion has been reached for elimination reactions of (2-arylethyl)trimethylammonium ions catalyzed by ethoxide ion, from the decrease in the nitrogen isotope effect with increasing values of the σ^- substituent constant.⁶ If there is a linear relationship between the nitrogen isotope effect and β_{lg} , and the maximum isotope effect is 4.2%,⁵² these data correspond to a $p_{yy'}$ coefficient of -0.18 .

A negative $p_{yy'}$ coefficient is consistent with a transition state on a reaction coordinate that has an important horizontal component representing proton transfer.^{18,53} An electron-withdrawing substituent (larger σ^-) will lower the energy of the carbanion in the upper left corner of the diagram of Figure 6 so that the transition state will tend to slide downhill, perpendicular to the reaction coordinate, toward the top of the diagram. This corresponds to less C-N bond cleavage and a smaller value of $-\beta_{lg}$. There will also be movement parallel to the reaction coordinate that will tend to shift the transition state to the right if the reaction coordinate is predominantly horizontal. However, if the reaction coordinate has a predominant vertical component the shift parallel to the reaction coordinate will be toward the lower left corner of the diagram, which may lead to a larger value of $-\beta_{lg}$ and a positive $p_{yy'}$ coefficient.⁵⁴

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The small increase in ρ for the Dabco compared with the less basic *N*-methyl-Dabco leaving group (Table V) represents the complementary manifestation of a negative coefficient $p_{yy} = -\partial\rho/\partial pK_{1g}$ (eq 6).

The points for the elimination reactions of the *p*-nitro-substituted compounds in Figure 12 show significant negative deviations compared with the other *N*-(2-arylethyl)quinuclidinium ions for catalysis by the anions of trifluoroethanol and hexafluoro-2-propanol, but fit on the same line as the other compounds for catalysis by hydroxide ion. The negative deviations for the reactions with the more weakly basic catalysts reflect the change to a stepwise E1cB mechanism with a small value of β_{1g} for the *p*-nitro compounds. The different behavior for the different catalysts is a reflection of the positive p_{xy} interaction coefficient for the concerted E2 mechanism and the value of $p_{xy} \approx 0$ for the E1cB mechanism. The absence of a change in β_{1g} with changing basicity of the catalyst for the E1cB mechanism means that there is no significant change in the rate ratios for the *p*-nitro compounds in Figure 12 with changing pK_a of the catalyst, whereas the positive p_{xy} coefficient for the other compounds gives larger rate ratios with more weakly basic catalysts. The small values of β_{1g} in the range -0.12 to -0.15 for the *p*-nitro compounds (Table VI) are presumably limiting values for the effect of substituents in the leaving group on the proton abstraction step, so that a negative deviation below the point corresponding to this value in Figure 12 would not be possible.

An increase in the Hammett ρ values with decreasing leaving ability of the halide in the series I (2.07), Br (2.14), Cl (2.61), and F (3.12) corresponds to a negative p_{yy} coefficient for elimination reactions of 2-arylethyl halides catalyzed by ethoxide ion.^{56,57} A decrease in the observed Br:Cl:F rate constant ratio in ethanol from 4100:68:1 for 2-phenylethyl halides^{56,57} to 46:4:1 for 2-(*p*-nitrophenyl)ethyl halides (Table III) represents a decreased sensitivity to leaving group ability with an electron-withdrawing substituent on the β -phenyl group in this series. This is the complementary manifestation of a negative p_{yy} coefficient (eq 6).

A change in β_{1g} from -0.24 to -0.14 for the elimination of *N*-(2-phenylethyl)- and *N*-(2-(*p*-nitrophenyl)ethyl)quinuclidinium ions catalyzed by hydroxide ion in water has been observed previously.⁸ This corresponds formally to a negative p_{yy} coefficient, but it represents a change in reaction mechanism (E2 to E1cB) rather than a change in transition state structure for a single mechanism.

The Interaction between the Base Catalyst and the β -Phenyl Substituent. The p_{xy} coefficient (eq 7) describes a change in the amount of proton transfer as measured by the Brønsted β value, with changing substituents on the β -phenyl group, and the complementary change in sensitivity to substituents on the β -phenyl group with increasing basicity of the base catalyst.

$$p_{xy} = \partial\beta/\partial\sigma = \partial\rho/\partial pK_{BH} \quad (7)$$

A negative p_{xy} coefficient corresponds to a transition state on a reaction coordinate with a large horizontal component corresponding to proton transfer.⁵⁸ An electron-withdrawing substituent on the β -phenyl group will lower the energy of the carbanion intermediate in the upper left corner of Figure 6 and the predominant movement of the transition state along the x coordinate will be parallel to the reaction coordinate and toward the right. This corresponds to less proton transfer and a smaller β value. A positive p_{xy} coefficient corresponds to a transition state on a diagonal reaction coordinate that has a larger vertical com-

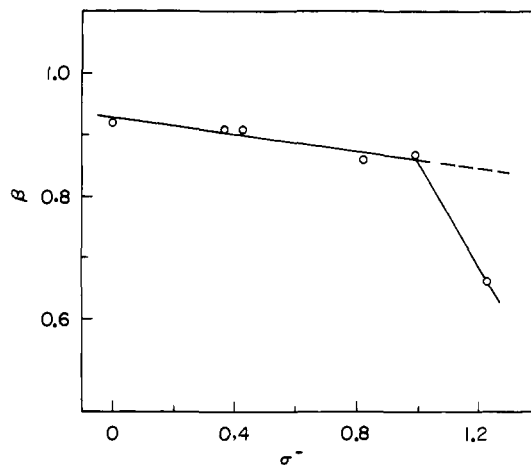


Figure 13. Brønsted β values as a function of σ^- constants for catalysis of the elimination reactions of ArEtDMe²⁺ ions in 60 vol % Me₂SO in water at 40 °C; $\mu = 0.30$ M (KCl).

ponent.⁵⁸ With a positive p_{xy} coefficient an electron-withdrawing β -phenyl substituent will give a net motion of the transition state to the left, corresponding to more proton transfer and a larger β . Conversely, an increase in base strength will raise the right side of the diagram and will give movement of the transition state toward the upper left corner. This movement corresponds to an increase in carbanionic character of the transition state and an increase in ρ .

The available data correspond to both positive and negative p_{xy} coefficients for elimination reactions of 2-arylethyl derivatives. Bourns and Smith observed a negative p_{xy} coefficient, based on an increase in the primary β -hydrogen isotope effect with electron-withdrawing substituents, for elimination reactions of (2-arylethyl)trimethylammonium ions catalyzed by ethoxide ion.⁶ However, the increase in ρ from 3.8 to 4.2 for base catalysis by *p*-nitrophenoxide and phenoxide ions, respectively, of the elimination reactions of (2-arylethyl)trimethylammonium ions in dimethylformamide⁵⁹ corresponds to a positive p_{xy} coefficient. Results that correspond to positive p_{xy} coefficients have also been reported for catalysis of elimination reactions of 2-arylethyl bromides by unbuffered substituted phenoxide ions in ethanol¹² and in dimethylformamide,⁶⁰ and for the reactions of 2-arylsulfonylethyl chlorides catalyzed by tertiary amines in acetonitrile.⁶¹ However, increases in primary β -hydrogen isotope effects with electron-withdrawing substituents on the β -phenyl group that correspond to negative p_{xy} coefficients have been observed for the elimination reactions of (2-arylethyl)dimethylsulfonium ions, 2-arylethyl bromides, and 1-phenyl-2-arylethyl chlorides.^{62,63} Some of these differences may reflect different transition state structures and mechanisms with different substrates and solvents. A primary goal of the experiments reported here was to obtain more extensive data, including direct measurements of Brønsted β values, in order to determine the sign and magnitude of the p_{xy} coefficients for reactions with the same activating group in the same solvent. The results would provide a test for the hypothesis that the reaction coordinate changes from a predominantly horizontal direction for amine leaving groups, with a large component of proton transfer, to a more diagonal direction with the better halide leaving groups.⁴

Figure 13 and Table IV show that the Brønsted β values decrease as the β -phenyl substituent becomes more electron withdrawing in the *N*-(2-arylethyl)quinuclidinium ion series. This

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(58) A negative p_{xy} coefficient corresponds to a reaction coordinate in a valley bounded by two level lines of constant energy that are rotated clockwise from the y axis, so that there is a positive curvature through the saddle point along the y coordinate. A positive p_{xy} coefficient always requires an important vertical component to the reaction coordinate unless the coefficient $p_y = \partial\rho/\partial\sigma$ is strongly negative. The absence of upward curvature in the Hammett plots for these reactions shows that p_y is not strongly negative.⁵⁵

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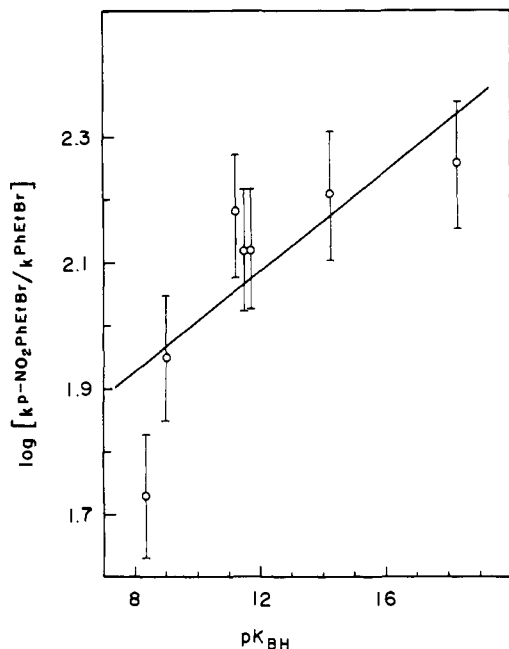


Figure 14. Dependence of the log of the p -NO₂PhEtBr:PhEtBr rate constant ratio on the basicity of the oxyanion catalyst in 60 vol % Me₂SO in water at 40 °C; $\mu = 0.30$ M (KCl).

decrease is made up of two parts. There is a small decrease that is only slightly outside the experimental error for the substrates that follow the E2 mechanism, which corresponds to an interaction coefficient of $p_{xy} = -0.07$, and a sharp decrease when the mechanism changes from E2 to E1cB as the β -phenyl substituent is changed from p -cyano to p -nitro with N -methyl-Dabco as the leaving group. A similar break occurs with Dabco as the leaving group (Table IV).

In contrast to the N -(2-arylethyl)quinuclidinium ion series, the E2 reactions of 2-arylethyl bromides exhibit an increase in β with electron-withdrawing substituents on the β -phenyl group and an increase in ρ with increasing base strength, which correspond to a positive p_{xy} coefficient. Figure 14 shows that the sensitivity to the β -phenyl substituent, as defined by the ratio of rate constants for the p -nitro and unsubstituted compounds, increases with increasing basicity of the catalyst. The value of β is larger for the p -nitro (0.55) than for the unsubstituted (0.48) compound. These data are consistent with an interaction coefficient of $p_{xy} = 0.06$. A positive p_{xy} coefficient can also result from a simple electrostatic interaction between polar substituents on the catalyst and the β -phenyl substituent,¹⁸ but the estimated value for this electrostatic interaction⁶⁴ of $p_{xy} \approx 0.013$ is small compared with 0.06.

The observed negative and positive p_{xy} coefficients for the alkylammonium and bromide leaving groups support previous conclusions regarding the nature of the transition states for these classes of 2-arylethyl derivatives.⁴

These structure–reactivity correlations and interactions can be a useful tool for distinguishing E1cB and E2 reaction mechanisms. In the N -(2-arylethyl)quinuclidinium ion series the change in mechanism is indicated by a sharp decrease in the Brønsted β value and by a smaller value of β_{1g} for catalysis by weak bases as the mechanism changes from E2 to E1cB. These changes cause breaks in plots of these structure–reactivity parameters against σ^- (Figures 12 and 13). However, a change in mechanism need not be accompanied by a changing structure–reactivity parameter, as in the case of β_{1g} for catalysis by hydroxide ion (Figure 12), or even by a deviation from a structure–reactivity parameter, as shown for the N -(2-(p -nitrophenyl)ethyl)quinuclidinium ions in several of the Hammett plots of Figure 5. A more general criterion of mechanism is provided by the structure–reactivity interaction coefficient itself, as illustrated by the change from $p_{xy} = 0$ for the E1cB mechanism to $p_{xy} = 0.02$ for the E2 mechanism in the N -(2-arylethyl)quinuclidinium ion series. It is noteworthy that this coefficient identifies the E2 mechanism even for compounds

that have a small amount of C–N bond cleavage in the transition state and values of β_{1g} that are indistinguishable from those for E1cB reactions.

Semiquantitative Characterization of the Transition State. If it is assumed that all of the structure–reactivity interaction coefficients can be described by a single energy diagram, the values of the remaining coefficients $p_x = -\partial\beta/\partial pK_{BH}$, $p_y = \partial\beta_{1g}/-\partial pK_{1g}$, and $p_{xy} = \partial\rho_n/\partial\sigma$ may be calculated from eq 8–10 and normalized values of p_{xy} and p_{yy} .^{18,55} Hammett ρ values may be normalized

$$p_x = p_{xy} - p_{xy'} \quad (8)$$

$$p_y = p_{xy} + p_{yy'} \quad (9)$$

$$p_{y'} = p_{yy'} - p_{xy'} \quad (10)$$

to a scale of 0 to 1 by the equilibrium ρ value for formation of the carbanion intermediate. We have arbitrarily chosen a value of $\rho_{\text{equil}} = 5$ for 60% Me₂SO:water, but the conclusions do not depend strongly on this choice. For the series of N -(2-arylethyl)quinuclidinium ions the normalized values of $p_{xy} = 0.018 \pm 0.004$, $p_{yy'} = -0.018 \pm 0.008$, and $p_{xy'} = -0.015 \pm 0.010$ give values of $p_x = 0.03$, $p_y = 0$, and $p_{y'} = 0$. These approximate values are consistent with (but do not establish) a contribution of a Hammond effect to the proton transfer component of the reaction coordinate (positive p_x) and with the linear plots of $\log k$ against pK_{1g} ($p_y = 0$, plots not shown; see also ref 8). It is possible that the positive p_x coefficient contributes to the curvature of the Brønsted plot in Figure 3, but similar curvature has been observed in quite different reactions and attributed to a solvation effect.²⁷ The decrease in the nitrogen isotope effect with increasing pK_a of the leaving group for elimination reactions of (2-phenylethyl)dimethylanilinium ions catalyzed by ethoxide ion³⁴ corresponds to a negative coefficient of $p_y \sim -0.03$, assuming a maximum isotope effect of 4.2%.

The interaction parameters and movements of the transition state on the energy diagram of Figure 6 are determined by the orientation of the reaction coordinate and curvatures of the surface perpendicular and parallel to it. These are defined by the horizontal, vertical, and diagonal curvatures around the saddle point, a , b , and c , respectively. Conversely, the curvatures may be calculated from the observed structure–reactivity coefficients¹⁸ and are $a = 0$, $b = 51$, and $c = -55$. These curvatures correspond to “level lines” of constant energy through the saddle point at angles of 47° and 0° from the x axis. A reaction coordinate that bisects these level lines is rotated 24° counterclockwise from the x axis, as shown in Figure 6. A similar calculation based upon ρ values that were normalized using $\rho_{\text{equil}} = 7^{65}$ gives level lines at 14° and 45° and a reaction coordinate that is rotated 30° counterclockwise from the x axis. These calculations, although crude, provide a semiquantitative description of the reaction coordinate and transition state that is in agreement with the observed characteristics of the reaction.

Merging. The evidence described here and elsewhere,^{2,6,8,38} demonstrates that elimination reactions in the 2-phenylethyl series undergo a change from a stepwise E1cB mechanism for (2-(p -nitrophenyl)ethyl)ammonium ion to a concerted E2 mechanism for other derivatives that provide less stabilization to a carbanion intermediate. The change occurs with less electron-withdrawing substituents on the β -phenyl group, which destabilize the carbanion with respect to both leaving group expulsion and reprotonation, and with halides, which decrease the lifetime with respect to leaving group expulsion. This change means that there is a real borderline between mechanisms that can be described, following More O’Ferrall,^{5,66} by a shift from a pathway that proceeds through an intermediate carbanion in an energy well, with separate barriers for its formation and breakdown, to a concerted pathway

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that proceeds over a barrier with no intermediate. The rate-determining step of the E1cB mechanism (at low buffer concentrations) is formation of the carbanion intermediate with a reaction coordinate that is essentially horizontal on the energy diagram of Figure 6, whereas the concerted reaction proceeds with a reaction coordinate that has significant diagonal character and, presumably, with coupling of the proton transfer and C–N bond cleavage processes.

Given a change from a stepwise to a concerted reaction mechanism, the question remains of how and why does it occur? There are two ways such a change or "merging" of mechanisms can take place.^{5,66} (1) Two concurrent mechanisms can exhibit different transition state structures and structure–reactivity characteristics such that when the structure of the reactants or the experimental conditions are changed one mechanism becomes faster than the other and becomes the predominant observed mechanism. In this situation there will be a point at which both mechanisms coexist. (2) One mechanism can be *transformed* into the other as the structure of the energy surface for the reaction changes. Such a transformation of mechanism occurs when a reaction intermediate disappears because it becomes too unstable to exist, so that a stepwise mechanism is impossible and a concerted mechanism is enforced. The first situation holds for some general acid–base catalyzed reactions involving proton transfer between electronegative atoms, in which the transition state for the concerted mechanism is located on the reaction coordinate diagram at a position that is far away from the well for the intermediate of the stepwise mechanism.⁵³ A concerted mechanism is favored by coupling between two processes that lowers the energy of the transition state, so that the barrier for the concerted process is lower than the barriers for both steps of the stepwise reaction. This may be more likely for the small barriers in proton transfers between electronegative atoms than for the larger barriers that are often found for formation and cleavage of bonds to carbon. Concerted olefin-forming elimination reactions would then be more likely to represent enforced concerted reactions than coupled processes that coexist with stepwise mechanisms.

Changes in hydrogen and heavy atom isotope effects have frequently been interpreted as evidence for changes of transition state structure in concerted E2 reactions of (2-arylethyl)ammonium compounds.^{2,4,6,34} However, the demonstration of an E1cB mechanism for the (*p*-nitrophenyl)ethylammonium derivatives means that changing isotope effects for other (2-arylethyl)ammonium compounds could represent a varying mixture of the two transition states for the E1cB and E2 mechanisms, each of which could have a constant structure, rather than changes in the structure of a single E2 transition state. It is important, therefore, to distinguish whether the change in mechanism proceeds through a mixture of coexisting mechanisms or whether one mechanism is transformed into the other.

The data reported here are consistent with and support a sharp *transformation* of mechanism that arises from a disappearance of the well for the intermediate to give an enforced concerted mechanism of elimination.

(1) The transition states for the concerted and stepwise mechanisms are located near each other on the reaction surface defined by structure–reactivity parameters. In fact, the transition states for some of the concerted reactions fall almost on top of the position expected for the well of the carbanion intermediate of the stepwise reaction (Figure 6). It is difficult or impossible to construct a surface on such a diagram that allows the stepwise reaction pathway to proceed through the well and a coexisting concerted pathway to be separated from the well by a barrier, so that it avoids the well. This is in contrast to the coexisting stepwise and concerted reaction mechanisms for general acid–base catalysis of reactions involving proton transfer between electronegative atoms, which proceed through transition states that are widely separated on the reaction surface.⁵³

(2) The *change* from a stepwise to a concerted mechanism occurs with a sharp increase in β (Figure 13), but with virtually no change in the small value of β_{1g} in the range -0.15 to -0.17 for the reactions of the *p*-nitro- and *p*-cyano-substituted compounds

catalyzed by hydroxide ion (Table VI). This represents a movement of the transition state to the left, corresponding to more proton transfer, but almost no movement downward, for C–N cleavage, on the diagram of Figure 6. It means that the transition state for the concerted reaction is not only near that for the stepwise reaction, but occurs further along on the same pathway that the stepwise reaction must take in order to reach the carbanion intermediate. If these diagrams provide even a crude indication of what happens in these reactions it is difficult to understand how the reaction path for the concerted mechanism can suddenly bend downward and not fall into the well for the carbanion intermediate, if this well exists, while the stepwise reaction passes over the same path and falls into the well.

(3) The structure–reactivity interactions show that there is a sharp change in mechanism with no indication of a mixture of coexisting mechanisms in a transition region. This is shown most clearly by the interaction between the catalyzing base and the leaving group, which is undetectable with $p_{xy} \approx 0$ for the *N*-(2-(*p*-nitrophenyl)ethyl)quinuclidinium ions and has a constant value of $p_{xy} = 0.018$ for the E2 mechanism of the *p*-cyano and other *N*-(2-arylethyl)quinuclidinium ions (Figure 7 and 8). There are no intermediate values that would be expected for a mixture of mechanisms, in spite of the large range of base catalysts, leaving groups, and reaction rates that were examined and the small change in structure and reaction rates between the *p*-nitro (E1cB) and the *p*-cyano and *p*-acetyl (E2) compounds. The *p*-nitro-substituted compounds may have a special stabilization and barrier for reactions of the carbanion,³³ however, any such barrier does not cause an anomalously slow rate for the elimination reactions of these compounds (Figure 5). The change in mechanism also gives sharp breaks in the correlation curves for the Brønsted β values (Figure 13) and for β_{1g} with weak base catalysts (Figure 12), with no indication of the intermediate values that might be expected for a mixture of mechanisms over the range of reaction rates investigated.

These results provide the strongest evidence that changes in the isotope effects for elimination reactions of (2-arylethyl)ammonium compounds (excluding the *p*-nitro compound)^{2,4,6,31} represent changes in the structure of the transition state for a common E2 reaction mechanism, rather than a mixture of E2 and E1cB mechanisms.

(4) There is no indication of a concurrent E2 mechanism for *N*-(2-(*p*-nitrophenyl)ethyl)quinuclidinium ion. At high buffer concentrations the observed initial rates of elimination become independent of buffer concentration in aqueous solution and the reaction exhibits a large inverse solvent deuterium isotope effect, with values of k_{DOD}/k_{HOH} as large as 7.7, when the k_2 step becomes rate determining.³⁸ A concurrent E2 elimination reaction would be expected to give a significant increase in the observed rate constants with increasing buffer concentration and cause a decrease in the large inverse solvent isotope effect.

(5) The Hammett plots for the reactions of compounds with quinuclidine and Dabco leaving groups catalyzed by hydroxide ion predict that an E2 reaction should be observed for the *p*-nitro-substituted compounds (Figure 5) and that any additional E1cB reaction should appear as a positive deviation from this line. However, no such deviation is observed and the evidence suggests that the observed rate constants for the *p*-nitro compounds represent reaction entirely by the E1cB mechanism; i.e., there is no indication of the presence of the predicted E2 mechanism. Positive deviations from structure–reactivity correlations are often taken as evidence for a change in mechanism;⁴⁶ the present case represents the converse situation, in which the mechanism changes but the rate constants are correlated by a single line. The fit of the rate constants for the *p*-nitro-substituted compounds to the Hammett correlations is not caused by the choice of too large a value for the σ^- constant for this substituent, because the same value of σ^- provides a good fit of the rate constants for 2-(*p*-nitrophenyl)ethyl tosylates⁶⁷ and bromides⁶⁸ to a Hammett cor-

(67) $\rho = 2.4$ for the hydroxide-catalyzed reactions of 2-arylethyl tosylates (this work; Table III).

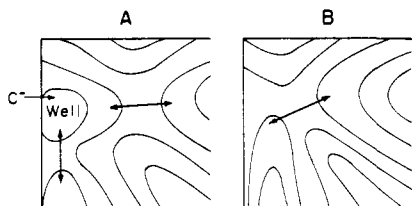


Figure 15. Speculative reaction coordinate contour diagrams to illustrate the transition from an E1cB_{irr} mechanism with a carbanion intermediate (A) to a concerted E2 mechanism when the carbanion no longer exists (B). These diagrams correspond to the upper left corner of Figure 6.

relation, although there is evidence that these compounds react through an E2 mechanism with less carbanion character in the transition state.

Positive deviations from the Hammett correlations are observed for the *p*-nitro compounds with weakly basic catalysts and poorer leaving groups (Figure 5). This is a necessary consequence of the different transition state structures, reaction coordinate directions, and interaction coefficients for the E2 and E1cB mechanisms. The change from a concerted to a stepwise mechanism involves a sharp decrease in β for general base catalysis (Figure 13). Therefore, as the pK_a of the catalyst is decreased the rate constants for the E1cB reaction of the *p*-nitrophenyl compound become relatively fast and show a positive deviation from Hammett plots for the concerted E2 reactions (Figure 5). Similarly, the dependence on the pK_a of the leaving group with weakly basic catalysts is smaller for the E1cB mechanism than for the E2 mechanism, so that the positive deviations from Hammett plots are larger for the E1cB mechanism with compounds that have poor leaving groups (Figure 12). This behavior is required by the positive coefficient $p_{xy} = \partial\beta_{1g}/\partial pK_{BH} = 0.02$, which gives rise to a more negative β_{1g} for the concerted, E2 reaction with weakly basic catalysts; the E1cB mechanism has a constant, small β_{1g} corresponding to $p_{xy} = 0$.

We speculate that the changes in mechanism and transition state structure occur as the reaction surface changes in the manner shown in Figure 15. The transition state for the E1cB (irreversible) mechanism involves passage over the ridge surrounding the well for the carbanion with an almost horizontal reaction coordinate, as shown in Figure 15A. As the substituents on the β -phenyl group are changed the carbanion becomes less stable and ceases to exist. A similar change occurs in the (*p*-nitrophenyl)ethyl series when the leaving group is changed from an amine to bromide ion. The well then becomes a broad ridge with a small curvature and the transition state involves passage over this ridge with a more diagonal reaction coordinate, corresponding to an E2 mechanism (Figure 15B). The value of β increases as the transition state shifts from the rim of the well to this broad ridge. The small curvature leads to easy sliding about of the transition state on the reaction surface with changing structure of the reactants so that the p_{xy} , p_{yy} , and p_{xy} coefficients are large enough to detect.

The 2-phenylethyl bromides react through a concerted E2 mechanism with a change from a negative to a positive p_{xy} coefficient that corresponds to a more vertical reaction coordinate with a larger contribution of carbon-leaving group bond cleavage (Figure 6, center). Movement of the transition state downward and to the right toward the center of the diagram is expected from the effects of a better leaving group on the motions of the transition state perpendicular and parallel to the reaction coordinate. The change in direction presumably reflects properties of the overall geometry of the energy surface that are not reflected in the simple equation for a saddle point. In particular, a reaction coordinate near the top of the diagram may be forced to have a predominantly horizontal direction because of an "edge effect" that arises from the steep increase of energy at the top of the diagram. The same

effect may be responsible for the similar, small values of $-\beta_{1g}$ for the E1cB and some E2 mechanisms in this region.

If the hypothesis is correct that the concerted E2 mechanism for these 2-arylethyl derivatives represents a transition from the E1cB mechanism that is enforced by the disappearance of a lifetime for the carbanion intermediate, it follows that nucleophilic vinylic substitution reactions with similar activating and leaving groups will also have no barrier for breakdown of the intermediate and will proceed through an enforced concerted mechanism. However, the absence of a correlation of leaving group ability with the observed rate constants for many such reactions indicates that there is little interaction between the entering and leaving groups in the transition state.⁶⁹ These reactions may then be described in terms of an uncoupled concerted mechanism, in which there is no reaction intermediate but coupling is weak or absent because of unfavorable bond angles and orbital overlap. The observation that the substitution of chlorine and bromine in β -*p*-nitrostyrene halides by benzenethiolate anion in methanol occurs with complete retention of configuration means that there is no carbanion intermediate in these reactions that has a long enough lifetime to undergo a large rotation before the halide ion leaves.⁷⁰ This is consistent with a concerted E2 reaction mechanism for the elimination reactions of 2-(*p*-nitrophenyl)ethyl bromide and chloride, as well as an uncoupled concerted mechanism for the styrene derivatives. However, the faster reactions of the *cis*- and *trans*- β -*p*-nitrostyrene fluorides give the same, thermodynamically stable product, so that the carbanion intermediate in methanol has a sufficient lifetime to rotate before fluoride ion is expelled.⁷⁰

Stronger evidence for the interpretations advanced here could be obtained from determinations of the lifetimes of the carbanion intermediates in a series of stepwise reactions. Extrapolation of the lifetimes of these intermediates as the structure of the activating group, the leaving group, or the catalyst is changed could identify the point at which the intermediate ceases to exist and the reaction becomes concerted.

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Registry No. 1 (R = *p*-NO₂; X = DMe) bromide, iodide, 73997-53-2; 1 (R = H; X = DMe) bromide, iodide, 73997-49-6; 1 (R = H; X = D) bromide, 73997-47-4; 1 (R = H; X = Q) bromide, 73997-44-1; 1 (R = H; X = HQ) bromide, 80632-02-6; 1 (R = *p*-NO₂; X = D) bromide, 73997-51-0; 1 (R = *p*-NO₂; X = HQ) bromide, 73997-52-1; 1 (R = *p*-NO₂; X = Q) bromide, 73997-48-5; 1 (R = *p*-Ac; X = DMe) tosylate, iodide, 80632-04-8; 1 (R = *p*-Ac; X = D) tosylate, 80632-06-0; 1 (R = *m*-CF₃; X = D) tosylate, 80632-08-2; 1 (R = *m*-CF₃; X = DMe) tosylate, iodide, 80632-10-6; 1 (R = *m*-Cl; X = D) tosylate, 80632-12-8; 1 (R = *m*-Cl; X = DMe) tosylate, iodide, 80632-14-0; 1 (R = *m*-NO₂; X = D) tosylate, 80641-92-5; 1 (R = *m*-NO₂; X = DMe) tosylate, iodide, 80632-16-2; 1 (R = *p*-CN; X = D) tosylate, 80632-18-4; 1 (R = *p*-CN; X = DMe) tosylate, iodide, 80632-20-8; 1 (R = H; X = Q), 73997-40-7; 1 (R = H; X = D), 73997-41-8; 1 (R = *p*-CN; X = Q), 80632-21-9; 1 (R = *p*-Ac; X = Q), 80632-22-0; 1 (R = *m*-NO₂; X = Q), 80632-23-1; 1 (R = *m*-CF₃; X = Q), 80632-24-2; 1 (R = *m*-Cl; X = Q), 80632-25-3; 2-phenylethyl bromide, 103-63-9; 2-(*p*-nitrophenyl)ethyl bromide, 5339-26-4; 2-(*p*-nitrophenyl)ethyl propyl sulfide, 80632-26-4; 2-phenylethyl tosylate, 4455-09-8; 2-(*m*-chlorophenyl)ethyl tosylate, 26416-24-0; 2-(*m*-(trifluoromethyl)phenyl)ethyl tosylate, 26416-25-1; 2-(*m*-nitrophenyl)ethyl tosylate, 69628-97-3; 2-(*p*-cyanophenyl)ethyl tosylate, 80632-27-5; 2-(*p*-nitrophenyl)ethyl chloride, 20264-95-3; 2-(*p*-nitrophenyl)ethyl fluoride, 56153-06-1; 2-(*p*-nitrophenyl)ethyl tosylate, 6948-72-7; pentafluorophenol, 771-61-9; acetic acid, 64-19-7; perfluoro-2-methyl-2-propanol, 2378-02-1; quinuclidinone H⁺, 80632-28-6; cacodylic acid, 75-60-5; hexafluoroacetone, 684-16-2; quinuclidine H⁺, 49623-78-1; acetohydroxamic acid, 546-88-3; hexafluoro-2-propanol, 920-66-1; tetrafluoroacetone, 360-52-1; hexafluoro-2-methyl-2-propanol, 1515-14-6; phenol, 108-95-2; trifluoroethanol, 75-89-8; ethylene glycol, 107-21-7; water, 7732-18-5; DabcoH⁺, 33937-19-8.

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