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Deprotonation of the α-(*N*,*N*-dimethylcarbamoyl)-α-methyl-4-methoxybenzyl carbocation by alkanecarboxylate and halide ions†

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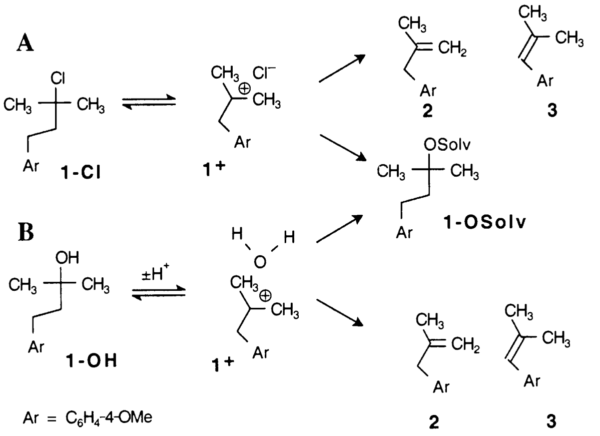
The product rate constant ratios $k_{elim}/k_{az}[N_3^-]$ for partitioning of the α-(*N*,*N*-dimethylcarbamoyl)-α-methyl-4-methoxybenzyl carbocation (**4⁺**) in aqueous methanol between deprotonation of the α-methyl carbon to form an alkene and nucleophilic addition of azide ion increase for reactions in the presence of carboxylate and halide ions. An analysis of these data gave second-order rate constants k_B for deprotonation of $\mathbf{4^+}$ by carboxylate ions which are correlated by a Brønsted coefficient of $\beta = 0.17$. The second-order rate constant for deprotonation of $\mathbf{4^+}$ by solvent water shows a 40-fold negative deviation from this correlation. Values of $k_{elim}/k_{az}[N_3^-]$ in 20% methanol in water increase by ≤30% as the halide ion concentration is increased from 0.0–0.80 mol dm^{-3} ($I = 0.80$, $NaClO_4$) due either to direct deprotonation of $\mathbf{4^+}$ by the halide ion or to a specific salt effect on the partitioning of $\mathbf{4^+}$. The value for k_B calculated with the assumption that this increase is due to deprotonation of $\mathbf{4^+}$ by chloride ion shows a small positive deviation from the Brønsted correlation of rate data for the reaction of carboxylate ions. However, all of these data show a satisfactory fit to a single Brønsted correlation with slope $\beta = 0.12$. These results are consistent with the conclusion that chloride ion shows a normal reactivity toward deprotonation of this α-methyl carbocation for a base of $pK_a \approx -8$ compared to substituted carboxylate anions, and an enhanced reactivity compared to solvent water.

Introduction

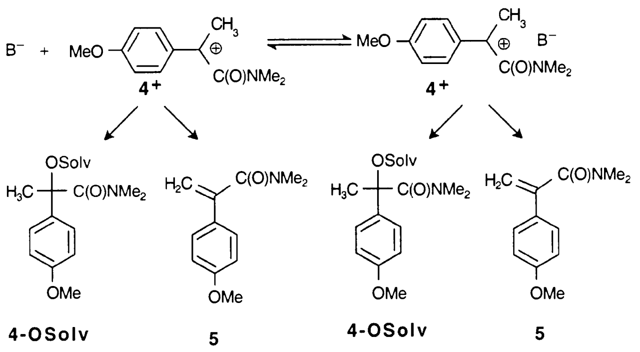
Alkene-forming elimination reactions of tertiary chlorides such as **1-Cl** are generally assumed to proceed through a tertiary carbocation–chloride anion pair intermediate that undergoes intramolecular proton transfer to form the alkene and hydrochloric acid (Scheme 1A).[1–4] However, there is no experimental evidence which clearly distinguishes alkene-forming elimination by this stepwise mechanism from a concerted reaction mechanism which avoids formation of the unstable reaction intermediate, and we have argued that the latter mechanism may be viable for reactions in aqueous solution.[5]



Scheme 1

The yields of alkenes **2** and **3** from acid-catalyzed solvolysis of the tertiary alcohol **1-OH** in a mostly aqueous solvent (Scheme 1B) are lower than for the reaction of the tertiary chloride **1-Cl**.[5] These data require either that chloride ions show a higher reactivity than water toward abstraction of β-protons from $\mathbf{1^+}$ or that additional **2** and **3** form by a concerted elimination reaction of **1-Cl**. Chloride ion is a weaker Brønsted base than water toward equilibrium proton transfer to form the corresponding conjugate acids, and therefore would not normally be expected to show a higher reactivity than solvent toward deprotonation of $\mathbf{1^+}$. On the other hand solvent water often shows an abnormally low chemical reactivity for its pK_a.[6–9]

There is scarce quantitative data for deprotonation of simple carbocations by weakly basic halide ions,[10,11] and it is not known whether this anion is sufficiently reactive as a Brønsted base to account for the observed yield of alkene from reaction of **1-Cl**. We report here the results of a study to determine the relative reactivity of added chloride ion, substituted carboxylate anions and solvent toward deprotonation of the simple carbocation $\mathbf{4^+}$ (Scheme 2). We find that the reaction of $\mathbf{4^+}$ in the presence of carboxylate anions results in large increases in the yield of **5**, so proton transfer from $\mathbf{4^+}$ to these anions is substantially faster than proton transfer to solvent. Increasing



Scheme 2

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† Electronic supplementary information (ESI) available: effect of sodium salts on $(k_{elim}/k_{az}[N_3^-])_{obsd}$ for partitioning of $\mathbf{4^+}$ and relative viscosities of sodium salt solutions. See http://www.rsc.org/suppdata/p2/b1/b100296l/

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concentrations of chloride anion result in only a small increase in the yield of **5** which may be due to deprotonation of $\mathbf{4^+}$ by this anion. This chloride ion effect is sufficiently large to provide support for the conclusion that this anion shows a normal reactivity for a base of $\mathrm{p}K_a \approx -8$ compared to substituted carboxylate anions, and an enhanced reactivity compared to solvent water.

Experimental

Inorganic salts and organic solvents were reagent grade from commercial sources and were used without further purification. Water was distilled and passed through a Milli-Q water purification system. α-(*N*,*N*-Dimethylcarbamoyl)-α-methyl-4-methoxybenzyl pentafluorobenzoate (**4-PFB**) was prepared by reaction of the alcohol **4-OH** with pentafluorobenzoyl chloride.[12] The ratio η/ρ of viscosities η and densities ρ of solutions of methanol–water were determined at 25 °C with a Cannon-Fenske type viscometer tube by a standard procedure.[13] Combining this ratio with the densities ρ obtained from the weights of known volumes of solvent gave the viscosity η.

Procedures for product studies

All reactions were carried out at 25 °C. The product yields were generally determined for reactions at a constant ionic strength which was maintained with sodium perchlorate. Solutions containing known salt concentrations and 1 mmol $\mathrm{dm^{-3}}$ sodium azide were prepared by mixing measured volumes of stock solutions of the salt and sodium perchlorate in methanol–water, each containing 1 mmol $\mathrm{dm^{-3}}$ sodium azide. The stock solutions of salts were prepared by mixing methanol (x $\mathrm{cm^3}$) with an aqueous solution of 1 mol $\mathrm{dm^{-3}}$ salt at pH ≈ 7 (y $\mathrm{cm^3}$), and then adding a small amount of water to give a final volume of $(x + y)$ $\mathrm{cm^3}$. The reactions were initiated by making a 100-fold dilution of a solution of substrate in acetonitrile to give a final concentration of *ca.* 2×10^{-4} mol $\mathrm{dm^{-3}}$ for the reactions in 50% methanol in water, and of *ca.* 1×10^{-4} mol $\mathrm{dm^{-3}}$ for the reactions in 20% methanol in water.

HPLC analyses

The products of the reaction of **4-PFB** with solvent and azide ion were separated as described in previous work[12] and detected by their absorbance at 275 nm, which is $\lambda_{\max}$ for **4-OH**. No peaks due to the products of addition of the basic anions used in these studies were observed. The ratios of the yields of reaction products were determined using eqn. (1), where A_1 and A_2

$$[\mathrm{P_1}]/[\mathrm{P_2}] = (A_1/A_2)(\varepsilon_2/\varepsilon_1) \qquad (1)$$

are the HPLC peak areas for the products $\mathrm{P_1}$ and $\mathrm{P_2}$ and $\varepsilon_2/\varepsilon_1$ is the ratio of the extinction coefficients for $\mathrm{P_2}$ and $\mathrm{P_1}$ at 275 nm. Ratios of $\varepsilon_{\mathrm{4\text{-}OH}}/\varepsilon_{\mathrm{4\text{-}X}} = 1.0$ for $\mathbf{4\text{-}N_3}$ and **4-OMe**, and $\varepsilon_5/\varepsilon_{\mathrm{4\text{-}N_3}} = 7.0$ were determined in previous work.[12]

These product ratios were determined after the first, second and tenth halftimes of reactions of **4-PFB** in 50% methanol in water; and after the second, fourth and tenth halftimes of reactions of **4-PFB** in 20% methanol in water and in all cases remained constant (±10%) with time.

Calculation of rate constant ratios

Rate constant ratios for partitioning of **4-PFB** between elimination and nucleophilic addition of azide ion $(k_{\mathrm{elim}}/k_{\mathrm{az}}[\mathrm{N_3^-}])_{\mathrm{obsd}}$, or between nucleophilic addition of solvent and azide ion $(k_{\mathrm{s}}/k_{\mathrm{az}}[\mathrm{N_3^-}])_{\mathrm{obsd}}$ were calculated from the ratio of product yields using eqn. (2), where k_{P} is either k_{elim} or k_{s} for formation of the alkene or solvent adduct, respectively. The rate constant ratios calculated directly from the ratios of product peak areas were reproducible to better than ±10%.

$$(k_{\mathrm{P}}/k_{\mathrm{az}}[\mathrm{N_3^-}])_{\mathrm{obsd}} = [\mathrm{P}]/[\mathbf{4\text{-}N_3}] \qquad (2)$$

Table 1 Observed first-order rate constants k_{solv} for reaction of **4-PFB** in methanol–water solvents in the presence of [NaX] and 1 mmol $\mathrm{dm^{-3}}$ sodium azide, 25 °C

	$10^4 \times k_{\mathrm{solv}}/\mathrm{s^{-1}}$ [a]	
NaX	50% methanol in water, $[\mathrm{NaX}] = 0.50$ mol $\mathrm{dm^{-3}}$	20% methanol in water, $[\mathrm{NaX}] = 0.80$ mol $\mathrm{dm^{-3}}$
No salt	2.1	9.2
$\mathrm{NaClO_4}$	1.8	6.3
NaCl	2.1	10
NaBr	2.2	9.9
$\mathrm{NaNO_3}$		8.8
$\mathrm{NaO_2CCH_3}$	2.1	9.3
$\mathrm{NaO_2CCH_2OCH_3}$	2.0	6.9
$\mathrm{NaO_2CCH_2Cl}$		7.3
$\mathrm{NaO_2CCHCl_2}$	1.8	6.0
$\mathrm{NaO_2CCF_3}$	1.8	5.9

[a] Determined as described in the text by monitoring the disappearance of **4-PFB** by UV spectroscopy or HPLC.

Kinetic methods

Kinetic studies were carried out at 25 °C in mixed methanol–water solvents at the same substrate concentrations used for product studies. The progress of the reaction was monitored either by following the change in the UV absorbance at 275 nm or the disappearance of the substrate by HPLC at 275 nm. In the latter case fluorene was added to the reaction mixture at zero time (1.5×10^{-5} mol $\mathrm{dm^{-3}}$ for reactions in 50% methanol in water and 4×10^{-6} mol $\mathrm{dm^{-3}}$ for reactions in 20% methanol in water) and was used as an internal standard to correct the observed areas of the substrate and product peaks from HPLC analyses for variations in the injection volume. In all cases good first-order kinetics were observed over at least three halftimes. First-order rate constants were determined from the slopes of linear semilogarithmic plots of reaction progress against time.

Results

The first-order rate constants k_{solv} ($\mathrm{s^{-1}}$) for solvolysis of **4-PFB** (Scheme 3) at 25 °C in 50% methanol in water ($I = 0.50$, $\mathrm{NaClO_4}$; units of I are given as mol $\mathrm{dm^{-3}}$ throughout) and in 20% methanol in water ($I = 0.80$, $\mathrm{NaClO_4}$), determined by following the disappearance of substrate by UV spectroscopy or HPLC, are reported in Table 1.

The yields of products of the reaction of **4-PFB** in the presence of sodium halide and sodium alkanecarboxylates at 25 °C in 50% methanol in water ($I = 0.50$, $\mathrm{NaClO_4}$) and in 20% methanol in water ($I = 0.80$, $\mathrm{NaClO_4}$) were determined by HPLC analysis. Fig. 1A shows the effect of increasing concentrations of chloride ion on the fractional product yields in 50% methanol in water ($I = 0.50$, $\mathrm{NaClO_4}$) and Fig. 1B shows the corresponding data for reactions in 20% methanol in water ($I = 0.80$, $\mathrm{NaClO_4}$). Similar changes in product yields with increasing concentrations of NaBr are observed for the reaction of **4-PFB** in the same solvents (data not shown).

The yields of alkene **5** and azide ion adduct $\mathbf{4\text{-}N_3}$ were determined for the reactions of **4-PFB** in the presence of 1 mmol $\mathrm{dm^{-3}}$ azide ion in 50% methanol in water ($I = 0.50$, $\mathrm{NaClO_4}$) and in 20% methanol in water ($I = 0.80$, $\mathrm{NaClO_4}$). The product rate constant ratios $(k_{\mathrm{elim}}/k_{\mathrm{az}}[\mathrm{N_3^-}])_{\mathrm{obsd}}$ calculated from these product yields [eqn. (2)] for reactions in the presence of alkanecarboxylate anions, halide anions, or nitrate anion at constant ionic strength maintained with sodium perchlorate are reported in Table S1 of the supplementary information. Values of 0.59 and 0.31 were determined for the rate constant ratio

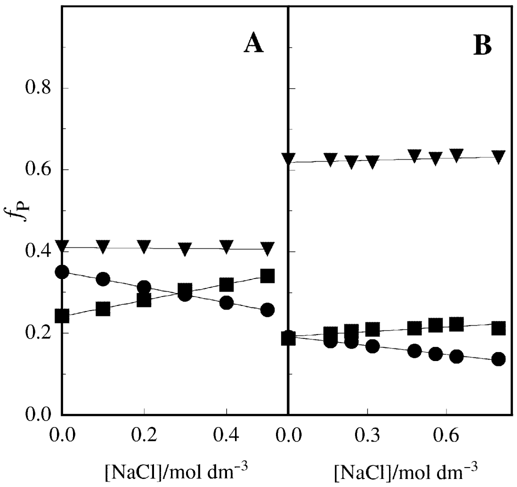


Fig. 1 Effect of increasing concentration of chloride ion on the fractional yields of the products of the reaction of **4-PFB**. **A** Reactions of **4-PFB** in 50% methanol in water ($I = 0.50$, $NaClO_4$). **B** Reactions of **4-PFB** in 20% methanol in water ($I = 0.80$, $NaClO_4$). Key: (●) solvent adducts, **4-OSolv**; (■) alkene, **5**; (▼) azide ion adduct, **4-N$_3$**.

$(k_{elim}/k_{az}[N_3^-])_{obsd}$ for reactions in 50% methanol in water ($I = 0.50$, $NaClO_4$) and 20% methanol in water ($I = 0.80$, $NaClO_4$), respectively.

The relative viscosities of solutions of mixed methanol–water solvents were determined as described in the Experimental section. Table S2 of the supplementary information reports: (1) values of (η_{NaX}^{max}) for the viscosity at 25 °C of solutions of 50% methanol in water that contain 0.50 mol dm^{-3} of sodium halide, sodium nitrate, or sodium alkanecarboxylate salts relative to the viscosity of 0.50 mol dm^{-3} sodium perchlorate ($\eta_{NaClO_4}^{max} = 1.0$) in the same solvent; (2) values of (η_{NaX}^{max}) (25 °C) of solutions of 20% methanol in water that contain 0.80 mol dm^{-3} of sodium halide, sodium nitrate, or sodium alkanecarboxylate salts relative to the viscosity of a 0.80 mol dm^{-3} sodium perchlorate ($\eta_{NaClO_4}^{max} = 1.0$) in the same solvent.

The values of (η_{NaX}^{max}) from Table S2 were used to calculate the maximum change in the relative solution viscosity, $\Delta\eta_{NaX}^{max}$, that occurs when $NaClO_4$ is substituted for by the same concentration of the second salt NaX [eqn. (3)]. The effect of partial replacement of $NaClO_4$ by a second salt NaX on the relative viscosity η_{NaX} was calculated using eqn. (4), where $\Delta\eta_{NaX}^{max}$ is the maximum change in viscosity for complete replacement of $NaClO_4$ by the second salt [eqn. (3)] and f_{NaX} is the fraction of sodium perchlorate replaced by the second salt. Eqn. (4) assumes that the change in η_{NaX} is directly proportional to f_{NaX}.

$$\Delta\eta_{NaX}^{max} = \eta_{NaX}^{max} - 1 \tag{3}$$

$$\eta_{NaX} = 1 + \Delta\eta_{NaX}^{max}(f_{NaX}) \tag{4}$$

There is good evidence that the reaction of **4-PFB** occurs through the liberated carbocation intermediate **4$^+$** which partitions between activation-limited reactions with solvent and addition of azide ion (Scheme 3)[12] with a diffusion-limited rate constant k_{az} (dm^3 mol^{-1} s^{-1}) that is expected to change in inverse proportion to the change in relative solvent viscosity (η_{NaX}).[14] We have used eqn. (5) and the values of η_{NaX} calculated

$$\frac{k_{elim}}{k_{az}[N_3^-]} = \eta_{NaX}\left(\frac{k_{elim}}{k_{az}[N_3^-]}\right)_{obsd} \tag{5}$$

from data in Table S2 [eqn. (4)] to correct the observed rate constant ratios $(k_{elim}/k_{az}[N_3^-])_{obsd}$ from Table S1 for the effect of changing solvent viscosity. Fig. 2A shows the effect of increasing [NaX] on these corrected rate constant ratios $(k_{elim}/k_{az}[N_3^-])$ for partitioning of **4$^+$** between alkene-forming elimination and addition of azide ion in 50% methanol in water ($I = 0.50$, $NaClO_4$); and, Fig. 2B shows the corresponding effect of increasing [NaX] on $(k_{elim}/k_{az}[N_3^-])$ for partitioning of **4$^+$** in 20% methanol in water ($I = 0.80$, $NaClO_4$). The viscosity correction causes no more than an 8% increase in the value of $(k_{elim}/k_{az}[N_3^-])$ determined for reactions in the presence of halide ion and no more than a 40% increase in the value of $(k_{elim}/k_{az}[N_3^-])$ for reactions in the presence of substituted acetate ions.

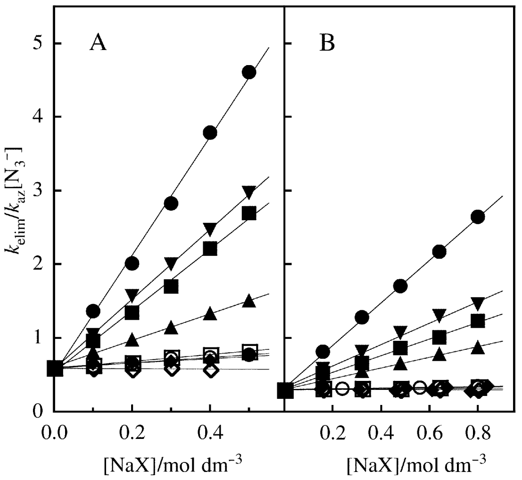
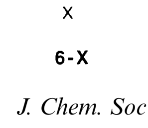


Fig. 2 The effect of increasing concentrations of NaX on the viscosity corrected (see text) product rate constant ratios $k_{elim}/k_{az}[N_3^-]$ for reaction of **4-PFB** in mixed methanol–water solvents. **A** Reactions of **4-PFB** in 50% methanol in water ($I = 0.50$, $NaClO_4$). **B** Reactions of **4-PFB** in 20% methanol in water ($I = 0.80$, $NaClO_4$). Key: (●) sodium acetate; (▼) sodium methoxyacetate; (■) sodium chloroacetate; (▲) sodium dichloroacetate; (◆) sodium trifluoroacetate; (○) sodium chloride; (□) sodium bromide; (◇) sodium nitrate.

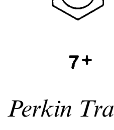
Discussion

The absence of a common chloride ion effect on the observed rate constants for solvolysis of **1-Cl** shows that there is no detectable trapping of the tertiary carbocation reaction intermediate **1$^+$** that regenerates **1-Cl**; and, the observation that the yields of the products of reaction of **1-Cl** in 50 : 50 (v/v) trifluoroethanol–water remain constant as the concentration of added hydroxide ion is increased from 0.0–0.50 mol dm^{-3} at $I = 0.50$, $NaClO_4$ shows that there is no detectable trapping of **1$^+$** by the conjugate base of solvent.[5] These results are consistent with the conclusion that **1$^+$** is trapped by reaction with molecules in the surrounding solvation shell at a rate that is substantially faster than diffusion, and they suggest that there should be no significant deprotonation of **1$^+$** by external halide ions.[5] A small increase in the yields of elimination relative to solvolysis products is observed for the reaction of **6-X** in 25% acetonitrile in water when 0.75 mol dm^{-3} $NaClO_4$ is replaced by 0.75 mol dm^{-3} NaCl.[11] This may reflect deprotonation of the tertiary carbocation **6$^+$** by added chloride ion. However, **6$^+$** may also be too unstable to undergo diffusional trapping by added anions, in which case the effect of chloride ion on product yield would be attributed to a specific salt effect.

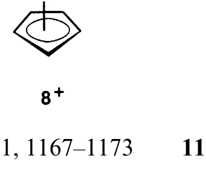
R^1 = Ph, Fc
R^2 = Ph, *tert*-Bu, Me, H



6-X



7+



8$^+$

By contrast with **1-Cl**, **4-PFB** reacts by a stepwise $D_N + A_N$ (S_N1)[15] mechanism through a carbocation reaction intermediate which partitions between α-methyl deprotonation (k_e, Scheme 3), nucleophilic addition of solvent (k_s) and addition of azide ion (k_{az}).[12] There is good evidence that $\mathbf{4}^+$ is trapped by azide ion at the diffusion-controlled limit with $k_{az} \approx 5 \times 10^9$ dm^3 mol^{-1} s^{-1},[16,17] and by substantially slower reactions with solvent to form the alkene (k_e) and nucleophile adduct (k_s). Combining the value for k_{az} with the product rate constant ratios k_e/k_{az} and k_s/k_{az} gave absolute values of k_e (s^{-1}) and k_s (s^{-1}) which are well below the diffusion-controlled limit,[12] so this carbocation is sufficiently stable to undergo deprotonation by basic anions such as chloride and acetate anion.

Product yields and product rate constant ratios for partitioning of $\mathbf{4}^+$ in the presence of carboxylate, halide and nitrate ions were first determined in 50% methanol in water. These experiments were then repeated in 20% methanol in water in order to minimize specific salt effects associated with working in a medium of high organic solvent content.[18] The smaller slope of the correlations obtained for reactions in the more aqueous solvent (Fig. 1 and 2) suggests that there are significant specific salt effects on product yields for reactions in 50% methanol in water. We were unable to examine these salt effects on product yields in a wholly aqueous solvent because of the low solubility of **4-PFB** in water.

Reactions of carboxylate ions

A sharp increase in the yield of alkene relative to solvent adduct is observed for the reaction of **4-PFB** in the presence of increasing concentrations of alkanecarboxylates due to deprotonation of $\mathbf{4}^+$ by RCO_2^-. General base catalysis by RCO_2^- has also been reported for deprotonation of the 1-(4-methylphenyl)-ethyl carbocation in 50 : 50 (v/v) trifluoroethanol–water to form 4-methylstyrene,[19] and for deprotonation of the α-methyl carbocation $\mathbf{7}^+$ by the acetate anion.[20]

The effect of added carboxylate anion on the observed rate constant for deprotonation of $\mathbf{4}^+$ (k_{elim}) was determined from the change in the product rate constant ratio $(k_{elim}/k_{az}[N_3^-])_{obsd}$ for partitioning of $\mathbf{4}^+$ between deprotonation and diffusion-controlled addition of azide ion for reactions in the presence of a constant concentration of 1 mmol dm^{-3} azide ion. The value of k_{az} (dm^3 mol^{-1} s^{-1}) for the diffusion-controlled reaction of azide should remain nearly constant with increasing $[RCO_2^-]$. However, small changes in k_{az} are expected due to the effect of these salts on the solvent viscosity (Table S1). The values of $(k_{elim}/k_{az}[N_3^-])_{obsd}$ were corrected for the effect of changes in relative solvent viscosity on k_{az} using eqn. (5) to give values of $k_{elim}/k_{az}[N_3^-]$.

The lines through the solid symbols on Fig. 2A and 2B show the fit of these viscosity corrected data to eqn. (6)

$$\frac{k_{elim}}{k_{az}[N_3^-]} = \frac{(k_{elim})_o}{k_{az}[N_3^-]} + \frac{k_B[X^-]}{k_{az}[N_3^-]} \qquad (6)$$

derived for Scheme 3, where $(k_{elim})_o$ is the sum of the rate constants for deprotonation of $\mathbf{4}^+$ by solvent (k_e) and by 1 mmol dm^{-3} azide ion ($0.001k'_B$). For reactions in 50% methanol in water in the absence of carboxylate anions, 15% of alkene **5** forms by deprotonation of $\mathbf{4}^+$ by 1 mmol dm^{-3} azide ion and 85% forms by deprotonation by solvent.[12] An even smaller yield (13%‡) of **5**, which is not easily determined by our analytical methods (±5%), is formed by deprotonation of $\mathbf{4}^+$ by azide ion in 20% methanol in water. The data from Fig. 2A and 2B show a good fit to eqn. (6) with slopes $k_B/k_{az}[N_3^-]$. Combining these slopes with $[N_3^-]$ gives the values of k_B/k_{az} for partitioning of $\mathbf{4}^+$ between deprotonation by RCO_2^- and addition of azide ion reported in Table 2. Table 2 also reports a value of k'_B/k_{az} from earlier work for partitioning of $\mathbf{4}^+$ between deprotonation (k'_B, Scheme 3) and nucleophilic addition (k_{az}) of azide ion in 50% methanol in water, and a value for k'_B/k_{az} in 20% methanol in water calculated with the assumption that the relative reactivity of acetate and azide ion as Brønsted bases toward deprotonation of $\mathbf{4}^+$ is the same in 50 and 20% methanol in water.

Table 2 Ratios of second-order rate constants k_B/k_{az} for partitioning of $\mathbf{4}^+$ between deprotonation by alkanecarboxylate, halide and nitrate ions and addition of azide ion in 50% methanol in water ($I = 0.50$, $NaClO_4$) and 20% methanol in water ($I = 0.80$, $NaClO_4$), at 25 °C

Base	pK_a [a]	k_B/k_{az} [b] 50% methanol in water	k_B/k_{az} [b] 20% methanol in water
Cl^-	−8 [c]	3.7×10^{-4}	5×10^{-5}
Br^-	−10 [c]	4.7×10^{-4}	5×10^{-5}
NO_3^-		[d]	[d]
N_3^-	4.7 [c]	0.10 [e]	0.04 [f]
$CH_3CO_2^-$	4.8	8.0×10^{-3}	2.9×10^{-3}
$CH_3OCH_2CO_2^-$	3.5	4.7×10^{-3}	1.5×10^{-3}
$ClCH_2CO_2^-$	2.9	4.2×10^{-3}	1.1×10^{-3}
$Cl_2CHCO_2^-$	1.3	1.8×10^{-3}	7.3×10^{-4}
$CF_3CO_2^-$	0.23	2.9×10^{-4}	2×10^{-5}

[a] Values of the pK_a for the conjugate acids are from ref. 27 unless noted otherwise. [b] Determined by multiplying the value of the corresponding slope from Fig. 2 ($k_B/k_{az}[N_3^-]$) by the concentration of azide ion (1 mmol dm^{-3}). [c] From ref. 28. [d] The slope from Fig. 2 for reactions in the presence of nitrate ions is not significantly different from zero, so there is no detectable deprotonation of $\mathbf{4}^+$ by this anion. [e] From ref. 12. [f] Calculated assuming that the relative reactivity of azide and acetate ions as Brønsted bases toward deprotonation of $\mathbf{4}^+$ is the same in 50 and 20% methanol in water.

Reactions of halide and nitrate ions

The open symbols in Fig. 2A show the effect of increasing $[Cl^-]$, $[Br^-]$ and $[NO_3^-]$ on the corrected product rate constant ratios $k_{elim}/k_{az}[N_3^-]$ for partitioning of $\mathbf{4}^+$ in 50% methanol in water; and, the open symbols in Fig. 2B show similar data for reactions in 20% methanol in water. The addition of halide ions causes a much larger increase in the rate constant for deprotonation of a ferrocenyl-stabilized carbocation $\mathbf{8}^+$,[10] than observed here for deprotonation of $\mathbf{4}^+$ (Fig. 2B). We are unable to offer an interpretation for the significant difference between the halide ion effects on deprotonation of $\mathbf{8}^+$ and $\mathbf{4}^+$ other than to point out that this is somehow related to the significant difference in the structures of these carbocations.

The observed small increase in $k_{elim}/k_{az}[N_3^-]$ upon replacing ClO_4^- by these weakly basic inorganic ions (Fig. 2A and 2B) may be due to deprotonation of $\mathbf{4}^+$ (k_B, Scheme 3) or to a specific salt effect on $(k_{elim})_o$.[21] We are not able to thoroughly evaluate these specific salt effects; however, there is some evidence for the existence of small salt effects on k_e and k_s for the reaction of $\mathbf{4}^+$ with solvent.

(1) The substitution of NaCl or NaBr for $NaClO_4$ results in an *increase* in k_{solv} for solvolysis of **4-PFB** (Table 1). This is consistent with greater *stabilization* of the carbocation-like transition state for reaction with **4-PFB** by interaction with halide relative to perchlorate ion. A similar stabilization of the fully-formed carbocation $\mathbf{4}^+$ by interaction with halide ion would result in a *decrease* in the rate constant k_s for nucleophilic addition of solvent to the carbocation. Such stabilization of $\mathbf{4}^+$ by Cl^- compared with ClO_4^- contrasts with previously reported salt effects on the rate constants for solvolysis of ring-substituted 1-phenylethyl derivatives which proceed through transition states that are stabilized by ClO_4^- compared with Cl^- ions,[18] and on the rate constants for addition of water to the

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‡ Calculated as $k'_B[N_3^-]/(k_{elim})_o = \{k'_B[N_3^-]/k_{az}[N_3^-]\}/\{(k_{elim})_o/k_{az}[N_3^-]\}$ where $k'_B/k_{az} = 0.04$ (Table 2) and $(k_{elim})_o/k_{az}[N_3^-] = 0.31$ for reaction in the presence of 0.001 mol dm^{-3} azide ion (see Results section).

Table 3 Rate constant ratios for partitioning of **4**$^+$ between deprotonation and nucleophilic addition of azide ion, and absolute rate constants for deprotonation of **4**$^+$ in 20% methanol in water ($I = 0.80$, $NaClO_4$), 25 °C

Base	k_B/k_{az}	k_B/dm^3 mol^{-1} s^{-1}
HOH	5.5×10^{-6} [a]	2.8×10^{4} [b]
Cl$^-$	5×10^{-5} [c]	2.5×10^{5} [b]
	$\leq 1.9 \times 10^{-4}$ [d]	$\leq 9.5 \times 10^{5}$ [b]

[a] Determined from the values of the *y* intercept from Fig. 2B ($(k_{elim})_o/k_{az}[N_3^-]$) as described in text. [b] Determined from the corresponding partition rate constant ratio using a value of $k_{az} = 5 \times 10^9$ dm^3 mol^{-1} s^{-1}. [c] Determined by multiplying the value of the corresponding slope from Fig. 2B ($k_B/k_{az}[N_3^-]$) by the concentration of azide ion (1 mmol dm^{-3}). [d] Upper limit calculated as described in text.

trianisylmethyl carbocation which were observed to *increase* when $NaClO_4$ was replaced by sodium halide.[22]

(2) The yield of **4-N$_3$** remains essentially constant for reactions of **4-PFB** as Cl$^-$ is substituted for ClO_4^- (Fig. 1). This reflects the compensating increasing yield of **5** and decreasing yield of **4-OSolv** (Fig. 1). The decrease in the yield of **4-OSolv** relative to **4-N$_3$** provides evidence that the substitution of ClO_4^- by Cl$^-$ causes a decrease in k_s for the capture of **4**$^+$ by solvent relative to the invariant rate constant for addition of azide ion to **4**$^+$. This is consistent with the stabilization of **4**$^+$ by a specific chloride ion salt effect. No increase in the yield of **4-OSolv** from chloride ion catalysis of solvent addition is expected, because there is little or no catalysis of addition of water to **7**$^+$,[20] the 1-(4-methoxyphenyl)ethyl carbocation or the 1-(4-dimethylaminophenyl)ethyl carbocation by acetate ion,[23a,24] which is a considerably stronger base than chloride ion.

(3) The increase in the yield of **5** with increasing [Cl$^-$] is consistent with deprotonation of **4**$^+$ by chloride ion. There may be a compensating decrease in k_e for deprotonation of **4**$^+$ due to the same type of specific salt effect proposed to result in a decrease in k_s. It is also possible that there are different specific salt effects on k_s and k_e since the reactions of solvent to give **4-OSolv** and **5** occur at different positions on the carbon skeleton of **4**$^+$ and result in formation of different adducts [**4–O(H)Solv**$^+$ and $SolvOH_2^+$] to the solvent oxygen.

Fig. 2 shows that there is a good fit of experimental data for the partitioning of **4**$^+$ in the presence of Cl$^-$, Br$^-$ and NO_3^- to eqn. (6), derived for Scheme 3. Combining the slopes of the correlations from Fig. 2, $k_B/k_{az}[N_3^-]$, with $[N_3^-] = 0.001$ mol dm^{-3} gives the values of k_B/k_{az} for partitioning of **4**$^+$ between deprotonation by these weakly basic anions and addition of azide ion reported in Table 2. The absolute rate constants (k_B) from Table 3 were calculated from these rate constant ratios and a value of $k_{az} = 5 \times 10^9$ dm^3 mol^{-1} s^{-1} for the diffusion-limited trapping of **4**$^+$ by azide ion.[16,17]

This treatment assumes that the change in the rate constant for deprotonation of **4**$^+$ (k_{elim}) is due primarily to general-base catalysis on the deprotonation of **4**$^+$ with a second-order rate constant k_B, and that the specific salt effects on the rate constant for deprotonation of **4**$^+$ by solvent, k_e are small. The uncertainty in k_B/k_{az} for reactions in 20% methanol in water that arise from the uncertainty in the specific salt effect on k_e was evaluated by determining the slope of a two-point correlation using: (1) the observed value of $k_{elim}/k_{az} = 3.5 \times 10^{-4}$ mol dm^{-3} for reactions in the presence of 0.80 mol dm^{-3} sodium chloride (Fig. 2B); and (2) the value of $k_{elim}/k_{az} = 2.0 \times 10^{-4}$ mol dm^{-3} calculated for reaction at 0 mol dm^{-3} sodium chloride with the assumption that the specific chloride ion salt effect causes the same 35% decrease in k_e as was observed for k_s (Fig. 1B). This slope gives an upper limit of $k_B/k_{az} \leq 1.9 \times 10^{-4}$ for deprotonation of **4**$^+$ by chloride ion in 20% methanol in water reported in Table 3. A similar procedure was used to determine an upper limit of k_B/k_{az} for the reaction of bromide ion.

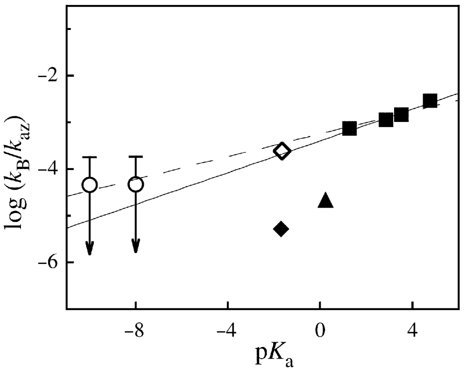
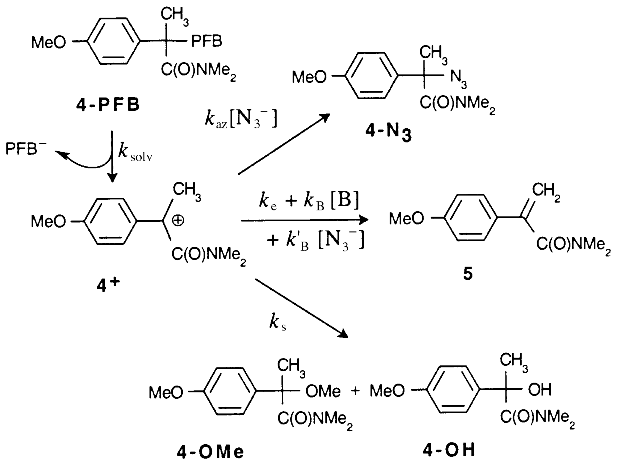


Fig. 3 Brønsted correlation of rate constant ratios k_B/k_{az} for partitioning of **4**$^+$ in 20% methanol in water ($I = 0.80$, $NaClO_4$) between deprotonation by Brønsted bases (k_B, Scheme 3) and diffusion-controlled addition of azide ion (k_{az}). Key: (■) alkanecarboxylate anions; (▲) trifluoroacetate ion; (○) halide ions; (◆) water. The ratio k_e/k_{az} (mol dm^{-3}) for partitioning of **4**$^+$ between deprotonation by solvent (k_e, Scheme 3) and diffusion-controlled addition of azide ion is shown for comparison (◇). The upper and lower limits for the rate constants for reaction of halide ions were estimated as described in the text.



Scheme 3

Table 3 summarizes the rate constant ratios determined for partitioning of **4**$^+$ between nucleophilic addition of azide ion and deprotonation by solvent and chloride ion in 20% methanol in water. This table reports both the value of k_B/k_{az} determined from the slope of Fig. 2B, and the range of values that are consistent with the experimental data assuming a modest salt effect on k_B/k_{az} (see above).

Brønsted correlations

Fig. 3 (■) shows the good linear Brønsted correlation of values of k_B/k_{az} for partitioning of **4**$^+$ between deprotonation by different substituted carboxylate anions and deprotonation by azide ion determined for reactions in 20% methanol, where the values of the pK_as are for ionization of the corresponding carboxylic acids in water. The rate constant ratio k_B/k_{az} for deprotonation of **4**$^+$ by trifluoroacetate ion (▲) exhibits a 20-fold negative deviation from the correlation line for the reaction of other carboxylate ions. It has been excluded from this correlation, because this deviation is not understood. This deviation may be due to an abnormally low chemical reactivity for trifluoroacetate anion; however, this anion shows a normal reactivity for its pK_a toward deprotonation of the 1-(4-methylphenyl)ethyl carbocation.[19] It is also possible that the slope of Fig. 2 underestimates the value of k_B/k_{az} because of an increase in the value of $(k_{elim})_o$ due to a specific trifluoroacetate salt effect. A small salt effect on $(k_{elim})_o$ will not affect the value of k_B/k_{az} determined from the slopes of Fig. 2 when there is strong catalysis of deprotonation of **4**$^+$, but it may have a significant effect on the slope when catalysis is weak as may be the case for trifluoroacetate ion.

The slope of the Brønsted correlation from Fig. 3, $\beta = 0.17$, is slightly larger than $\beta = 0.14$ determined for the deprotonation of 1-(4-methylphenyl) carbocation by a similar series of alkanecarboxylate ions in 50 : 50 (v/v) trifluoroethanol–water.[19] This similarity in Brønsted parameters reflects the relatively small difference in the absolute rate constants for deprotonation of **4**$^+$ and the 1-(4-methylphenyl) carbocation.[19]

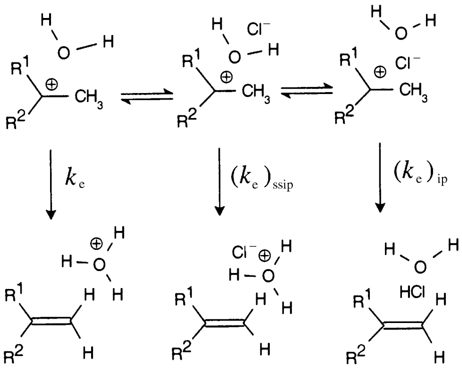
Fig. 3 also includes data for the reaction of halide ions (○) using the values of k_B/k_{az} determined as the slopes of the correlations from Fig. 2. The upper limit for these rate constants shown on Fig. 3 was determined as described above by assuming that the decrease in k_e from specific halide ion salt effects is the same as observed for k_s. The lower limit for k_B/k_{az} is 0, because of the possibility that the observed changes in $k_{elim}/k_{az}[N_3^-]$ are due to a specific halide ion salt effect. The data for the reactions of halide ions (○) show a positive deviation from the Brønsted correlation defined by data for the reaction of alkanecarboxylate ions (solid line, Fig. 3). However, all of these data also show a reasonably good correlation ($r = 0.992$) to a single Brønsted coefficient of $\beta = 0.12$ (dashed line, Fig. 3). This is consistent with the conclusion that chloride ion shows a normal reactivity for an anionic base of $pK_a \approx -8$.

The values of the second-order rate constant k_B for deprotonation of **4**$^+$ by chloride ion and first-order rate constant k_e for deprotonation by solvent are similar. However, the observation of even a small yield of **5** from deprotonation of **4**$^+$ by chloride ion requires that chloride anion show a larger molar reactivity than solvent (mostly water), which is present at very high concentration. A value of $k_{HOH}/k_{az} = 5.5 \times 10^{-6}$ for partitioning of **4**$^+$ between deprotonation by solvent water and addition of azide ion in 20% methanol in water (Table 3) was determined from $k_e/k_{az} = 2.7 \times 10^{-4}$ mol dm^{-3} and 0.90 for the mole fraction of water (f_{HOH}) in this solvent using eqn. (7).[§]

$$\frac{k_{HOH}}{k_{az}} = \left(\frac{k_e}{k_{az}}\right)\frac{f_{HOH}}{[HOH]} \qquad (7)$$

The value of $k_{HOH}/k_{az} = 5.5 \times 10^{-6}$ (Fig. 3, ◆) for deprotonation of **4**$^+$ in 20% methanol in water exhibits a 40-fold negative deviation from the correlation line for carboxylate ions. There may be at least two causes for this abnormally low reactivity of solvent as a Brønsted base: (a) the transition state for deprotonation of **4**$^+$ by chloride ion is stabilized relative to the transition state for reaction of water by electrostatic interactions between the base, which bears a partial negative charge, and the acid which bears a partial positive charge.[23] (b) There may be an unfavorable requirement for breaking the stabilizing network of solvent hydrogen bonds to the reacting water molecule on moving to the transition state for deprotonation of **4**$^+$ by water.

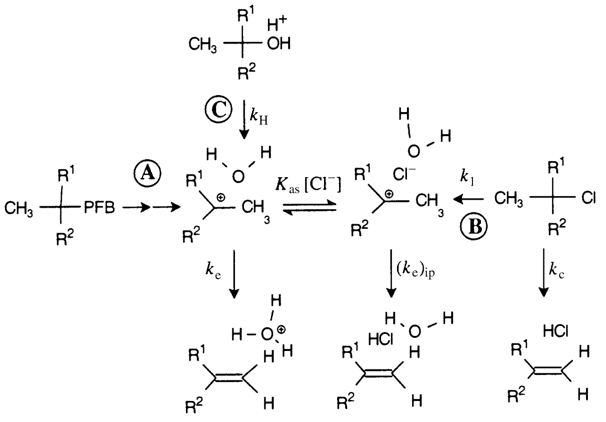
In conclusion, a simple explanation for our experimental data is that chloride ion provides a modest stabilization of the transition state for deprotonation of **4**$^+$ to form the alkene **5**. It is not clear whether there is any transition state stabilization due to direct deprotonation of the carbocation by chloride ion within the intimate ion pair [$(k_e)_{ip}$, Scheme 4] or to chloride ion stabilization of positive charge at a nascent hydronium ion by hydrogen bonding within the solvent separated ion pair [$(k_e)_{ssip}$, Scheme 4]. In addition, we are unable to rigorously exclude the possibility that the effect of chloride ion on the ratio of the yields of **5** and **4-N**$_3$ is due to a specific salt effect by chloride ion on the reactivity of the medium toward deprotonation of **4**$^+$.



Scheme 4

Reactivity of carbocation–chloride ion pairs

The data reported in this work, show that there are small increases in the yield of an elimination reaction product for reaction of the tertiary benzoate ester **4-PFB** [R^1 = –C(O)NMe$_2$, R^2 = –C$_6$H$_4$-4-OMe, Scheme 5] as the concentration of chloride anion is increased from 0.0 to 0.8 mol dm−3and that these increases may be due to deprotonation of **4**$^+$ by chloride ion. Pathway A for Scheme 5 shows a more detailed mechanism for this reaction, through an intermediate carbocation–chloride ion encounter complex which forms with an association constant K_{as} and collapses to **5** and HCl with a rate constant $(k_e)_{ip}$.



Scheme 5

Eqn. (8) shows the relationship between the observed rate

$$k_{elim} = k_e + (k_e)_{ip}K_{as}[Cl^-] \qquad (8)$$

constant for deprotonation of **4**$^+$ and the rate and equilibrium constants from Scheme 5 when $K_{as}[Cl^-] << 1$. A comparison of eqns. (6) and (8) shows that the observed second-order rate constant for the chloride ion-catalyzed reaction (k_B) is equal to $K_{as}(k_e)_{ip}$ for Scheme 5A, so $(k_e)_{ip} = k_B/K_{as}$. The value of K_{as} for formation of a weak encounter complex between the carbocation and anion has not been determined but is expected to lie between 0.1 and 1.0 mol dm^{-3}.[25] Combining this range of values for K_{as} with $k_B \approx 2.5 \times 10^5$ dm^3 mol^{-1} s^{-1} for reaction in 20% methanol in water (Table 3) gives $(k_e)_{ip} = 2.5 \times 10^5$ s^{-1} to 2.5×10^6 s^{-1}. By comparison, $k_e = 1.4 \times 10^6$ s^{-1} has been estimated for direct deprotonation of **4**$^+$ by 20% methanol in water.[¶]

[§] The value of $k_e/k_{az} = 2.7 \times 10^{-4}$ mol dm^{-3} for partitioning of **4**$^+$ in 20% methanol in water was calculated using the value of $(k_{elim})_o/k_{az}[N_3^-] = 0.31$ determined for reaction in the presence of 1 mmol dm^{-3} azide (see the Results section), the relationship $(k_{elim})_o/k_{az} = (k_e + k'_B[N_3])/k_{az}$ (Scheme 3) and the value of $k'_B/k_{az} = 0.04$ from Table 2. It is assumed in deriving eqn. (7) that the reactivities of water and methanol toward deprotonation of **4**$^+$ are the same.

[¶] Calculated from the values of $k_e/k_{az} = 2.7 \times 10^{-4}$ mol dm^{-3} (see footnote 3) and $k_{az} = 5 \times 10^9$ dm^3 mol^{-1} s^{-1}.[16,17]

Scheme 5B shows the hypothetical alkene-forming elimination reaction of the chloride **4-Cl** through an ion pair reaction intermediate $\mathbf{4^+{\cdot}Cl^-}$ (k_1, $(k_e)_{ip}$) and Scheme 5C shows the formation of alkene from the hypothetical acid-catalyzed reaction of the alcohol **4-OH** through an ion-dipole intermediate $\mathbf{4^+{\cdot}HOH}$ (k_H, $k_e \approx 1.4 \times 10^6$ s^{-1}). Our data show that the yield of alkene **5** from reaction of the carbocation–chloride ion pair that forms by ionization of **4-Cl** may be small or up to twice as large as the yield from reaction of the ion dipole pair that forms by ionization of **4-OH** ($k_e \approx 1.4 \times 10^6$ s^{-1}) depending upon whether the true value of $(k_e)_{ip}$ lies close to the approximate lower limit of 2.5×10^5 s^{-1} or the upper limit of 2.5×10^6 s^{-1} established by our data. Again these data allow for no firm conclusions about the importance of deprotonation of $\mathbf{4^+}$ by chloride ion relative to deprotonation by solvent. An even larger *range* of values for $(k_e)_{ip}$ can be calculated using the range of values of k_B from Table 3, so the yield from reaction of a carbocation–chloride ion pair may be even greater than two fold larger than the yield from reaction of the corresponding free carbocation (k_e, Scheme 5).

It has been shown in earlier work that the yield of the alkenes **2** and **3** from acid-catalyzed dehydration of the alcohol **1-OH** by pathway C for Scheme 5 ($R^1 = CH_3$, $R^2 = CH_2CH_2C_6H_4$-4-OMe) through the ion–dipole pair $\mathbf{1^+{\cdot}HOH}$ in 20 : 80 TFE–water is 2–4 times smaller than the yield of alkenes from the elimination reaction of the corresponding alkyl chloride **1-Cl** in the same solvent.[5] It was suggested that this result provided evidence for a concerted elimination reaction of **1-Cl** (k_c, Scheme 5), because the low basicity of chloride ion relative to solvent would favor the observation of a low yield of alkenes from reaction of the $\mathbf{1^+{\cdot}Cl^-}$ ion pair intermediate. These arguments must be revised, because a comparison of the values of $(k_e)_{ip}$ and k_e estimated in this work for deprotonation of the related carbocation $\mathbf{4^+}$ in 20% methanol in water (see above) shows that yield of alkene from the deprotonation of the carbocation–chloride ion pair intermediate [$(k_e)_{ip}$] may be twice as large as from deprotonation of the free carbocation (k_e). Therefore, fully stepwise elimination is a viable mechanism to account for the 2–4 times larger yield of alkene from reaction of the $\mathbf{1^+{\cdot}Cl^-}$ ion pair compared to $\mathbf{1^+{\cdot}HOH}$ ion–dipole pair. On the other hand, our data are also consistent with a much smaller relative yield from the reaction of $\mathbf{1^+{\cdot}Cl^-}$.

We have summarized in earlier work arguments to support the existence of a concerted elimination reaction in largely aqueous solvent for the reaction of **1-Cl**[5] (k_c, Scheme 5) and for the reaction of cumyl derivatives that contain electron-withdrawing ring substituents.[26] The discussion from ref. 5 must be revised to account for the *possibility* of a relatively large yield of alkenes **2** and **3** from partitioning of $\mathbf{1^+{\cdot}Cl^-}$. On the other hand this concerted reaction mechanism remains viable, and additional work is needed to clearly distinguish the stepwise and concerted pathways.

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