

## Solvolytic Reactions in Fluorinated Alcohols. Role of Nucleophilic and Other Solvation Effects

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Rate constants and products for solvolyses of chlorodiphenylmethane (Ph<sub>2</sub>CHCl) and *p*-methoxybenzyl chloride in 2,2,2-trifluoroethanol (TFE)/water and TFE/ethanol are reported, along with additional kinetic data for solvolyses of *tert*-butyl and other alkyl halides (RX) in 97% w/w TFE/water and in 97% w/w hexafluoropropan-2-ol/water (HFIP). Results are discussed in terms of the solvent ionizing power (*Y*) and the solvent nucleophilicity (*N*), and contributions from other solvation effects are considered. Comparisons with other S<sub>N</sub>1 solvolyses show that solvolyses of Ph<sub>2</sub>CHCl in TFE mixtures are unexpectedly fast, but product ratios are unexceptional. An additional solvation effect influences solvolyses leading to delocalized cations, and a delocalized cationic transition state for concerted elimination may explain the recent results of Takeuchi et al., (*J. Org. Chem.* **1997**, *62*, 4904) without the need to postulate additional specific solvation effects for adamantyl systems, such as Bronsted-base solvation of  $\alpha$ - and  $\beta$ -hydrogen atoms; concerted elimination may occur because simple tertiary alkyl cations are too unstable to form in predominantly aqueous media. Iodide/bromide and bromide/chloride rate ratios are very similar for 1-adamantyl halides and corresponding solvolyses of *tert*-butyl halides; these ratios decrease in the order aq EtOH > TFE > HFIP, as expected for an electrophilic solvation effect (this effect can readily be incorporated into *Y* values). From kinetic data for a series of tertiary alkyl chlorides in 97% TFE/water, it is shown that the susceptibility of rates of solvolyses of RCl to *N* decreases with an increase in steric hindrance or with an increase in charge stabilization. Also, the small kinetic solvent isotope effects for typical solvolyses (e.g., methyl tosylate) indicate that nucleophilic attack lags behind heterolysis of the C–X bond.

Rates of reactions of short-lived carbocations (e.g., Ph<sub>2</sub>CH<sup>+</sup>) with solvents are several orders of magnitude less in fluorinated alcohols such as 2,2,2-trifluoroethanol (TFE) and hexafluoropropan-2-ol (HFIP) than in the more nucleophilic aqueous media.<sup>2</sup> Also, solvolytic reactions in fluorinated alcohols lead to less nucleophilically solvated cationic intermediates, showing products due to rearrangement, hydride shift, and elimination (i.e., greater carbocation character).<sup>3</sup> Solvent nucleophilicity (*N*) is one of the two main factors influencing the rates of solvolytic reactions, and the extended Grunwald–Winstein equation (1) accounts explicitly for the dependence of the

$$\log(k/k_0)_{\text{RX}} = lN + mY + c \quad (1)$$

logarithms of solvolysis rate constants (*k*) on *N* and on the solvent ionizing power (*Y*); *l* is the sensitivity of the substrate RX to changes in *N*, *m* is the sensitivity to *Y*, *c* is a residual intercept term (usually close to zero), and *k*<sub>0</sub> refers to solvolyses in 80% v/v ethanol/water.<sup>4</sup>

Adamantyl substrates are now considered to be more suitable as model substrates than *tert*-butyl chloride to define *Y* scales (by definition *m* = 1 and *l* = 0 for the model substrate); to try to minimize complications due to solvation of the leaving group (X), it is now usual to select *Y* values based on solvolyses of adamantyl-X

having the same leaving group (a wide range of suitable *Y*<sub>X</sub> values is now available).<sup>5</sup> In correlations of rate data for other solvolyses, a high dependence of solvolytic reactivity on *Y*<sub>X</sub> and a low dependence on *N* is taken as evidence for a solvolytically generated carbocation intermediate, so *l* (eq 1) is negligible, and there is a linear correlation with *Y*<sub>X</sub>.<sup>6</sup>

In fluorinated alcohols, substrates for which *l* > 0 usually react less rapidly than expected from an *mY* correlation (i.e., a downward deviation in a plot of log *k* vs *Y/N* as in eq 1), and a value of *l* can be obtained from eq 1. Additional solvation effects might be expected for substrates containing additional functional groups (e.g., hydrogen bonding to oxygen in substrates leading to carbocations having  $\alpha$ -carbonyl<sup>6c</sup> or  $\beta$ -carbonyl<sup>6d</sup> groups), but surprisingly, solvolyses in fluorinated alcohols of substrates leading to delocalized cationic intermediates have been found to occur more rapidly than expected from an *mY* correlation (i.e., an upward deviation).<sup>7</sup> We now report further investigations of this phenomenon, and we report additional kinetic data on solvolyses of *tert*-butyl

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**Table 1. Rate Constants ( $k/s^{-1}$ ) for Solvolyses of Chlorodiphenylmethane (1) at 25 °C<sup>a</sup>**

solvent composition	$k/s^{-1}$	
	trifluoroethanol/ethanol <sup>b</sup>	trifluoroethanol/water <sup>c</sup>
97		1.28 <sup>d</sup>
90	$(4.01 \pm 0.06) \times 10^{-1}$	1.33 <sup>e,f</sup>
80	$(1.28 \pm 0.06) \times 10^{-1}$	
70	$(4.14 \pm 0.07) \times 10^{-2}$	1.53 <sup>g</sup>
60	$(1.56 \pm 0.01) \times 10^{-2}$	
50	$(5.59 \pm 0.02) \times 10^{-3}$	
40	$(2.24 \pm 0.03) \times 10^{-3}$	
20	$(3.37 \pm 0.10) \times 10^{-4}$	
0	$5.34 \times 10^{-5}$ <sup>h</sup>	

<sup>a</sup> Determined conductometrically at least in duplicate; typically injected 10  $\mu$ L of 10% (v/v) substrate in dry acetonitrile into the kinetics apparatus, fitted with a turbostirrer, and containing 5 mL of solvent mixtures (see also ref 10a); errors shown are standard deviations. <sup>b</sup>Percent v/v trifluoroethanol/ethanol. <sup>c</sup>Percent w/w trifluoroethanol/water. <sup>d</sup>Lit.<sup>10b</sup> 1.05 (see also Table 4). <sup>e</sup>Injected 10  $\mu$ L of 3% (v/v) substrate in dry acetonitrile. <sup>f</sup>Calculated from data at lower temperatures;  $k = (4.03 \pm 0.40) \times 10^{-2}$  and  $(1.20 \pm 0.01) \times 10^{-1} \text{ s}^{-1}$  at  $-10.0$  and  $0.0$  °C;  $\Delta H^\ddagger = 15.1 \text{ kcal mol}^{-1}$ ,  $\Delta S^\ddagger = -7.5 \text{ cal mol}^{-1} \text{ K}^{-1}$ . <sup>g</sup>Data from ref 10b. <sup>h</sup>Data from ref 10c.

**Table 2. Rate Constants ( $k/s^{-1}$ ) for Solvolyses of *p*-Methoxybenzyl Chloride (2) in Trifluoroethanol Mixtures at 25 °C<sup>a</sup>**

solvent composition	$k/s^{-1}$	
	trifluoroethanol/ethanol <sup>b</sup>	trifluoroethanol/water <sup>c,d</sup>
97		$(1.94 \pm 0.04) \times 10^{-1}$ <sup>d</sup>
90	$(6.72 \pm 0.16) \times 10^{-2}$	$(2.07 \pm 0.01) \times 10^{-1}$ <sup>e,f</sup>
80	$(2.67 \pm 0.01) \times 10^{-2}$	$(2.73 \pm 0.04) \times 10^{-1}$ <sup>f,g</sup>
70	$(9.46 \pm 0.02) \times 10^{-3}$	$(3.32 \pm 0.09) \times 10^{-1}$ <sup>f</sup>
60	$(3.71 \pm 0.17) \times 10^{-3}$	$(4.53 \pm 0.03) \times 10^{-1}$ <sup>f</sup>
50	$(1.42 \pm 0.01) \times 10^{-3}$	$(6.29 \pm 0.25) \times 10^{-1}$ <sup>f</sup>
40	$(5.75 \pm 0.11) \times 10^{-4}$	$(9.01 \pm 0.13) \times 10^{-1}$ <sup>h</sup>
30		$(1.73 \pm 0.15)$ <sup>h</sup>
20	$(1.01 \pm 0.01) \times 10^{-4}$	
0	$1.67 \times 10^{-5}$ <sup>i</sup>	

<sup>a-c</sup> As for Table 1. <sup>d</sup>Data from ref 11a. <sup>e</sup> $k = (5.72 \pm 0.02) \times 10^{-3}$ ,  $(1.82 \pm 0.04) \times 10^{-2}$  and  $(2.07 \pm 0.01) \times 10^{-1} \text{ s}^{-1}$  at  $-10.0$ ,  $0.0$ , and  $25.0$  °C, respectively;  $\Delta H^\ddagger = 15.4 \text{ kcal mol}^{-1}$ ,  $\Delta S^\ddagger = -10.0 \text{ cal mol}^{-1} \text{ K}^{-1}$ . <sup>f</sup>Injected 10  $\mu$ L of 3% (v/v) substrate in dry acetonitrile into the kinetic apparatus. <sup>g</sup> $k = (2.22 \pm 0.02) \times 10^{-2}$  and  $(2.73 \pm 0.04) \times 10^{-1}$  at  $0$  and  $25$  °C;  $\Delta H^\ddagger = 15.7 \text{ kcal mol}^{-1}$  and  $\Delta S^\ddagger = -8.5 \text{ cal mol}^{-1} \text{ K}^{-1}$ . <sup>h</sup>Injected 10  $\mu$ L of 1% (v/v) substrate in dry acetonitrile. <sup>i</sup>Data from ref 11b.

halides and of other acyclic tertiary substrates, of relevance to recent reports from other research groups.<sup>8,9</sup>

## Results

Rate constants for solvolyses in TFE/ethanol and TFE/water of chlorodiphenylmethane (1) are given in Table 1 and of *p*-methoxybenzyl chloride (2) are given in Table 2. Solvolyses of substrate (RCl) gave a mixture of trifluoroethyl ether (ROCH<sub>2</sub>CF<sub>3</sub>) and either alcohol (ROH) or ethyl ether (ROEt), and molar concentrations of products in TFE/water are expressed as selectivities (*S*, eq 2) in Table 3 (an analogous equation was used for TFE/ethanol mixtures).

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**Table 3. Product Selectivities (*S*) for Solvolyses of Chlorodiphenylmethane (1) and *p*-Methoxybenzyl Chloride (2) in Trifluoroethanol Solvent Mixtures at 25 °C<sup>a</sup>**

solvent composition	[TFE]/[H <sub>2</sub> O]	selectivities <sup>b</sup>	
		1	2
97 TFE-H <sub>2</sub> O <sup>c</sup>	5.82	0.21 <sup>d</sup>	0.36 <sup>d</sup>
90	1.62	0.27	0.40 <sup>d</sup> (0.39) <sup>e</sup>
80	0.72	0.30	0.44
70	0.42	0.39	0.46
60	0.27	0.43 <sup>f</sup>	0.52
50	0.18	0.50 <sup>f</sup>	0.56 <sup>f</sup>
40	0.12	0.49 <sup>g</sup>	0.54 <sup>f</sup>
30	0.077	0.34 <sup>g</sup>	0.46 <sup>g</sup>
20	0.045		0.29 <sup>g</sup>
10	0.020		0.14 <sup>h</sup>
90 TFE-EtOH <sup>i</sup>	7.21 <sup>j</sup>	0.031 <sup>d</sup>	0.040 <sup>d</sup>
80	3.20 <sup>j</sup>	0.035	0.052
70	1.87 <sup>j</sup>	0.039	0.060
60	1.20 <sup>j</sup>	0.041	0.068
40	0.53 <sup>j</sup>	0.047	0.072
20	0.20 <sup>j</sup>		0.067

<sup>a</sup> Determined after 10 half-lives by response-calibrated HPLC at least in duplicate for each of two independent samples; typical error  $\pm 2\%$ ; 10  $\mu$ L of 10% (v/v) substrates in dry acetonitrile were injected into a sample tube containing 5 mL of trifluoroethanol mixtures. <sup>b</sup>Calculated from eq 2. <sup>c</sup>Weight percent. <sup>d</sup>Added 2,6-lutidine (2 $\times$  excess) into the stock solution. <sup>e</sup>Not containing 2,6-lutidine. <sup>f</sup>Injected 10  $\mu$ L of 3% (v/v) substrate. <sup>g</sup>Injected 10  $\mu$ L of 1% (v/v) substrate. <sup>h</sup>Injected 3 $\times$  10  $\mu$ L of 0.2% (v/v) substrate. <sup>i</sup>Volume percent. <sup>j</sup>Molar ratio of TFE/ethanol, and *S* defined by replacing [ROH] and [water] by [ROEt] and [EtOH] in eq 2.

$$S = [\text{ROCH}_2\text{CF}_3]/[\text{ROH}] \times [\text{water}]/[\text{TFE}] \quad (2)$$

Additional kinetic data in 97% w/w TFE/water are given in Table 4 and in HFIP/water are given in Table 5. Recent work on kinetic solvent isotope effects in MeOH(D) is supplemented with additional data for solvolyses of methyl tosylate in Table 6.

## Discussion

Although TFE/water mixtures and ethanol/water mixtures differ in nucleophilicity, the  $Y_{\text{Cl}}$  values of 2.83 for 97% TFE/water (97T) and of 2.75 for 40% v/v EtOH/water (40E) are so similar that the solvolysis rate ratio  $k_{40\text{E}}/k_{97\text{T}}$  gives a useful indication of the susceptibility of the rate of solvolysis of an alkyl halide (RCl) to solvent nucleophilicity (*N*).<sup>5</sup> It is recognized that ethanol/water mixtures are nonideal solvents,<sup>14</sup> but 80% ethanol/water is the chosen standard for *Y* plots, and comparisons of rate constants in 50% methanol/water ( $Y_{\text{Cl}} = 2.70$ ) with those for 97T would be expected to give similar rate ratios to  $k_{40\text{E}}/k_{97\text{T}}$ .

The  $k_{40\text{E}}/k_{97\text{T}}$  ratio is 0.83 for 1-adamantyl chloride, so when the ratio is significantly lower (corresponding to a negative *I* value), a breakdown of the interpretation based

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**Table 4. Rate Constants ( $k/s^{-1}$ ) for Solvolyses of 1, 3–6, and *tert*-Butyl Halides in 97% w/w Trifluoroethanol/Water<sup>a</sup>**

RX	$T/^\circ\text{C}$	$k/s^{-1}$	$\Delta H^\ddagger/\text{kcal mol}^{-1}$	$\Delta S^\ddagger/\text{cal mol}^{-1} \text{K}^{-1}$
<i>t</i> -BuCl	25.0 <sup>b</sup>	$(1.42 \pm 0.02) \times 10^{-4}$	19.8	-10
	39.9 <sup>b</sup>	$(7.32 \pm 0.04) \times 10^{-4}$		
<i>t</i> -BuBr	25.0 <sup>c,d</sup>	$(2.66 \pm 0.01) \times 10^{-3}$		
<i>t</i> -BuI	25.0	$(3.23 \pm 0.03) \times 10^{-3}$		
<b>1</b>	25.0 <sup>e</sup>	$1.28 \pm 0.07$	14.2	-10.5
	10.0	$(3.45 \pm 0.04) \times 10^{-1}$		
	0.0	$(1.31 \pm 0.01) \times 10^{-1}$		
<b>3</b>	25.0 <sup>f</sup>	$6.73 \times 10^{-4}$		
<b>4</b>	25.0	$(4.90 \pm 0.05) \times 10^{-4}$		
<b>5</b>	25.0	$(1.05 \pm 0.01) \times 10^{-1}$		
<b>6</b>	25.0	$(4.71 \pm 0.01) \times 10^{-2}$		

<sup>a</sup> Determined conductometrically in duplicate except where stated otherwise; errors shown are average deviations. <sup>b</sup>Lit.<sup>12a</sup>  $k = 1.32 \times 10^{-4}$ ; also at 25.0 °C,  $k = (1.35 \pm 0.03) \times 10^{-4}$  and at 49.7 °C,  $k = (1.86 \pm 0.08) \times 10^{-3} \text{ s}^{-1}$ ;  $\Delta H^\ddagger = 19.7$ ,  $\Delta S^\ddagger = -10$  (determined by T.W.B. in earlier work at Princeton). <sup>c</sup>TriPLICATE measurement of rate constant. <sup>d</sup>For 97% v/v TFE/water,  $k = 2.88 \times 10^{-3} \text{ s}^{-1}$  (ref 12b). <sup>e</sup>Lit.<sup>10b</sup>  $k = 1.05 \text{ s}^{-1}$ . <sup>f</sup>From ref 12a.

**Table 5. Rate Constants ( $k/s^{-1}$ ) for Solvolyses of *tert*-Butyl Halides (*t*-BuX) and 1-Chloro-1-phenylethane (**3**) in 97% w/w Hexafluoropropan-2-ol/Water<sup>a</sup>**

RX	$T/^\circ\text{C}$	$k/s^{-1}$	$\Delta H^\ddagger/\text{kcal mol}^{-1}$	$\Delta S^\ddagger/\text{cal mol}^{-1} \text{K}^{-1}$
<i>t</i> -BuCl	25.0 <sup>b</sup>	$(2.55 \pm 0.02) \times 10^{-3}$	17	-14
	1.5	$(2.05 \pm 0.02) \times 10^{-4}$		
<i>t</i> -BuBr	25.0 <sup>c</sup>	$(1.77 \pm 0.10) \times 10^{-2}$	(16.2) <sup>d</sup>	(-11.7) <sup>d</sup>
<i>t</i> -BuI	25.0	$(1.08 \pm 0.02) \times 10^{-2}$	17	-10
	-0.1 <sup>e</sup>	$(7.0 \pm 0.3) \times 10^{-4}$		
	25.0 <sup>f</sup>	$(2.00 \pm 0.5) \times 10^{-1}$		
<b>3</b>	10.0 <sup>f</sup>	$(4.75 \pm 0.3) \times 10^{-2}$	14	-13
	0.02 <sup>f</sup>	$(2.00 \pm 0.5) \times 10^{-2}$		

<sup>a</sup> As for Table 1. <sup>b</sup>Other literature values in the range  $(2.45-2.69) \times 10^{-3} \text{ s}^{-1}$  (ref 13a). <sup>c</sup>TriPLICATE measurement of rate constant. <sup>d</sup>Activation parameters from ref 14a (also  $k = 2.2 \times 10^{-2} \text{ s}^{-1}$ ). <sup>e</sup>Five measurements of rate constant. <sup>f</sup>Initial rate constants determined by Carter (ref 13b).

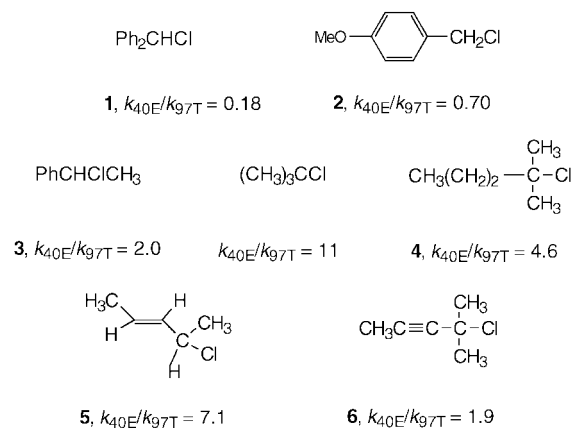
**Table 6. Kinetic Solvent Isotope Effect (KSIE) for Solvolyses of Methyl Tosylate in Methanol at 49.8 °C<sup>a</sup>**

rate constants/ $\text{s}^{-1}$		KSIE
MeOH	MeOD	
$(1.185 \pm 0.015) \times 10^{-5}$	$(1.065 \pm 0.015) \times 10^{-5}$	$1.11 \pm 0.03$

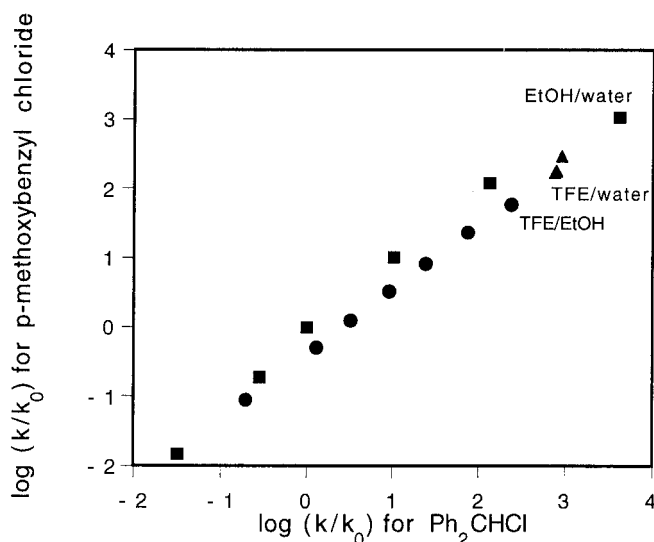
<sup>a</sup>Determined conductometrically in duplicate.

on eq 1 is apparent. Of the values of  $k_{40\text{E}}/k_{97\text{T}}$  in Scheme 1, only the value of 0.18 for Ph<sub>2</sub>CHCl is substantially less than 0.83 (so in this case the upward deviation is 4-fold); larger upward deviations in HFIP are probable, but solvolyses of Ph<sub>2</sub>CHCl in HFIP were too fast to measure.<sup>10b</sup> From our data for solvolyses of 1-chloro-1-phenylethane (**3**) in 97% HFIP (Table 5), we calculate an upward deviation of only 2-fold from the extended correlation line for aqueous ethanol vs  $Y_{\text{Cl}}$  (additional data from ref 15b); in contrast, TFE gives a downward deviation (Scheme 1).

Although the precision of many  $Y_{\text{X}}$  correlations is reduced when the positive charge generated during solvolyses can be delocalized onto aromatic rings or onto other  $\pi$ -electron systems adjacent to the reaction site, the effects are often small.<sup>7d,15c,16</sup> Solvolyses of Ph<sub>2</sub>CHCl show

**Scheme 1. Values of Solvolysis Rate Ratios in 40% Ethanol/Water Compared with 97% Trifluoroethanol/Water at 25 °C<sup>a</sup>**

<sup>a</sup> Data from Table 4 and refs 10b, 11, and 15.

**Figure 1.** Plot of logarithms of rate constants for solvolyses of chlorodiphenylmethane (**1**) vs rates for *p*-methoxybenzyl chloride (**2**); kinetic data from Tables 1 and 2 and refs 11a and 17.

some of the most marked effects, and a plot (Figure 1) of logarithms of rate constants for solvolyses of Ph<sub>2</sub>CHCl vs corresponding data for *p*-methoxybenzyl chloride shows a dispersion (ca. 3-fold in rate) into separate lines for ethanol/water and TFE/ethanol mixtures, and Ph<sub>2</sub>CHCl is relatively more reactive in TFE-rich media. Dispersion is apparent even when  $\log(k/k_0)$  is 0 (i.e., 40% TFE/ethanol), so deviations are not restricted to TFE-rich media.

Solvolysis rate data indicate that TFE does seem to be relatively more effective than ethanol at solvating delocalized cations<sup>7c</sup> (e.g., in solvolyses of benzylic substrates<sup>7a,b</sup> or of substrates undergoing rearrangement -  $k_{\Delta}$  solvolyses<sup>7c,d</sup>). Our results for **1** and **2** (Scheme 1) provide additional examples of benzylic substrates having  $k_{40\text{E}}/k_{97\text{T}}$  ratios < 0.8.

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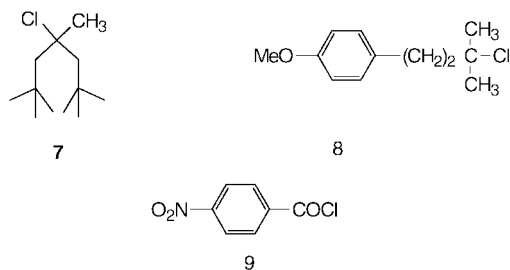
The environment at the reaction site can be probed from product selectivities (Table 3); the expected order of nucleophilic attack (EtOH > water > TFE<sup>18</sup>) is most prominent in TFE-rich solutions, consistent with greater selectivity for a longer-lived cation.<sup>9b</sup> Also, the less reactive<sup>2</sup> diphenylmethyl cation is slightly more selective than the *p*-methoxybenzyl cation, and continuing this trend, solvolyses of adamantyl substrates are virtually unselective.<sup>18</sup> As selectivities are lowest for solvolyses of Ph<sub>2</sub>CHCl in TFE-rich mixtures, preferential cation solvation by TFE (if any) does not appear to improve the prospects for nucleophilic attack by TFE. Overall, the *S* values (Table 3) are approximately constant, so there is no evidence from product studies for a greater concentration of TFE at the reaction site.

Ethanol/water selectivities (*S*) for solvolyses of **1** and **2** are typically 2–4,<sup>11a,18</sup> whereas the ratio of selectivities ( $S_{\text{TFE/water}}/S_{\text{TFE/ethanol}}$ ) is 6–10 (Table 3). Also, the  $S_{\text{TFE/water}}$  values of 0.2–0.5 (Table 3) are much larger than the rate ratios of 10<sup>-3</sup> obtained from direct measurements of the rates of nucleophilic attack on carbocations by TFE in TFE compared with attack by water in acetonitrile/water.<sup>2</sup> Hence, TFE appears to suppress nucleophilic attack by both water and ethanol, and the effect is larger for water, so both *S* values and  $k_{40E}/k_{97T}$  ratios may be affected by TFE in the second or third solvation shell; a further complication is that water and ethanol may act as general bases during nucleophilic attack on carbocations.<sup>17</sup> Consequently, deductions from *S* values in binary or ternary mixtures require due caution.

The highest value of  $k_{40E}/k_{97T}$  (Scheme 1) is 11 for *t*-BuCl. An increase in steric hindrance (e.g., **4**) reduces the  $k_{40E}/k_{97T}$  ratio, as reported recently,<sup>8b,8c</sup> presumably, a more hindered substrate is less able to benefit from nucleophilic solvent assistance, so the  $k_{40E}/k_{97T}$  ratio and hence the *l* values (eq 1) are reduced. Our results also show that an increase in charge stabilization by conjugation with a double bond (e.g., **5**) or a triple bond (e.g., **6**) also reduces the  $k_{40E}/k_{97T}$  ratio; these ratios may slightly underestimate nucleophilic solvent assistance because the cationic intermediates from solvolyses of **5** and **6** are delocalized, but trends are consistent with the expectation that formation of a more stable cation will require less nucleophilic assistance.

A  $k_{40E}/k_{97T}$  ratio of only 0.1 was reported recently for solvolyses of the more hindered tertiary chloride (**7**).<sup>8a</sup> In addition to a negative *l* value (eq 1), an *m* value of only 0.54 ± 0.06 was obtained and the product was almost exclusively elimination (>98% in TFE); the solvolysis rates can be correlated if the *N* term in eq 1 is replaced by the charge delocalization parameter (*J*),<sup>16c,19</sup> and it appears that the cationic transition state has a delocalized positive charge, consistent with the concerted unimolecular elimination recently proposed for solvolyses of **8** in largely aqueous solutions.<sup>9b,20</sup>

The nature of the intermediate (if any) in solvolyses of simple aliphatic tertiary substrates is of long-standing interest,<sup>9</sup> and older evidence<sup>22</sup> has been undermined by



recent work.<sup>2,9b</sup> Identification of initial products is complicated by the possibility of addition of HX to alkene; also, it is difficult to distinguish between the trapping of “free” carbocations by nucleophiles and the reactions of nucleophiles by preassociation mechanisms.<sup>9b</sup> Estimates, based on rate–equilibrium extrapolations, of the lifetime of the *tert*-butyl cation in water at 25 °C are ca. 10<sup>-10</sup> s.<sup>23</sup> However, a 1000-fold shorter lifetime in 50% v/v TFE/water for the cation derived from **8** has recently been estimated,<sup>9b</sup> and an even shorter lifetime would then be expected for the *tert*-butyl cation in water (*tert*-butyl is a less hindered substrate and the absence of TFE will further reduce lifetimes). The following rate–rate extrapolation indicates that the lifetime of the *tert*-butyl cation in water is less than the time required for a bond vibration (10<sup>-13</sup> s).

Direct measurements<sup>2</sup> of the rates of reactions of Ph<sub>2</sub>CH<sup>+</sup> with solvent are as follows: aqueous acetonitrile (1.3 × 10<sup>9</sup> s<sup>-1</sup>), TFE (3.2 × 10<sup>6</sup> s<sup>-1</sup>), and HFIP (ca. 1.1 × 10<sup>1</sup> s<sup>-1</sup>).<sup>2</sup> A typical rate ratio for  $k_{\text{water}}/k_{\text{TFE}}$  is 10<sup>3</sup> (seven values<sup>2</sup>), and for  $k_{\text{TFE}}/k_{\text{HFIP}}$  is >10<sup>4</sup> (three values<sup>2</sup>); so a  $k_{\text{water}}/k_{\text{HFIP}}$  ratio of >10<sup>7</sup> is expected; the cumyl cation (PhC(CH<sub>3</sub>)<sub>2</sub><sup>+</sup>) reacts with HFIP with a rate constant of 9 × 10<sup>3</sup> s<sup>-1</sup>,<sup>2</sup> which can be extrapolated to >9 × 10<sup>10</sup> s<sup>-1</sup> in water. Hence, even this phenyl-stabilized cation may have a lifetime of only ca. 10<sup>-11</sup> s in water. A 10<sup>4</sup> correction factor for replacement of Ph by Me can be obtained directly from experimental data for rates of attack by HFIP on PhCHCH<sub>3</sub><sup>+</sup>, which reacts >10<sup>4</sup> times faster than attack on Ph<sub>2</sub>CH<sup>+</sup>; hence, a “lifetime” of ca. 10<sup>-15</sup> s is estimated for the *tert*-butyl cation in water. Even allowing an uncertainty of 10<sup>2</sup> in the above calculation, it appears that the *tert*-butyl cation may be too unstable to exist as an intermediate in highly aqueous (TFE-free) media, so both elimination and substitution may be enforced concerted reactions.<sup>24</sup>

The importance of hydrogen bonding to the departing leaving group during solvolyses (electrophilic assistance) is well established.<sup>9a,25</sup> An alkyl iodide would be expected to hydrogen bond less strongly than an alkyl chloride to a hydrogen bond donor solvent such as a fluorinated alcohol. Rate ratios for solvolyses of 1-adamantyl (1-Ad) and *tert*-butyl halides (e.g., iodides/bromides and bromides/chlorides, see Table 7) follow the order 80% ethanol/water > TFE > HFIP, in line with the order of increasing  $\alpha$  values of the solvents.<sup>27</sup> Allowance is made for this relatively small effect (ca. 5-fold) in the *Y<sub>x</sub>* values for the

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**Table 7. Iodide/Bromide (I/Br) and Bromide/Chloride (Br/Cl) Rate Ratios for Solvolyses of 1-Adamantyl and *tert*-Butyl Halides at 25 °C**

solvent	I/Br		Br/Cl	
	1-Ad <sup>a</sup>	<i>t</i> -Bu	1-Ad <sup>b</sup>	<i>t</i> -Bu <sup>b</sup>
80% ethanol	2.1	2.6 <sup>c</sup>	35	39
97% TFE	1.0	1.2 <sup>d</sup>	18	22
97% HFIP	0.4	0.6 <sup>e</sup>	9	9

<sup>a</sup> Data from ref 26a. <sup>b</sup>Data from ref 26b. <sup>c</sup>Kinetic data for *t*-BuI from ref 26c and for *t*-BuBr from ref 26d. <sup>d</sup>Data from Table 4. <sup>e</sup>Data from Table 5.

various leaving groups.<sup>5</sup> As the rate ratio 1-AdI/1-AdBr varies from 3.7 in ethanol to 1.3 in water,<sup>26</sup> there is probably a small dependence of I/Br rate ratios on solvent polarity even in the absence of a specific electrophilic effect due to fluorinated alcohols.

Although most of the I/Br and Br/Cl rate ratios are slightly greater for solvolyses of *tert*-butyl halides than 1-adamantyl halides (Table 7), the differences are very small; these results provide important evidence that solvolysis rates are not significantly affected by differences in the susceptibility of *tert*-butyl and 1-adamantyl substrates to electrophilic assistance<sup>28</sup> (i.e., rates of reactions of substrates having saturated alkyl groups can be correlated adequately using eq 1). An almost directly contrary viewpoint was developed from solvatochromic measures of solvent effects by a "double difference" method, in which solvolysis rates in methanol, ethanol, TFE, and HFIP led to estimates of the sensitivity (*a*) of substrates to electrophilic solvent assistance (separated from the sensitivity to solvent dipolarity,  $\pi^*$ ).<sup>29</sup> Surprisingly, it was found that *a* was significantly higher for solvolyses of 1-AdCl (*a* = 6.5) than for BuCl (*a* = 4.1). As solvolyses of 1-AdI had an *a* value of 5.4 (for 1-AdBr, *a* = 6.0),<sup>29</sup> this treatment leads to the very surprising conclusion that changes in the leaving group lead to smaller changes in *a* than changes in the alkyl group.

A major advantage of eq 1 over solvatochromic methods (based on  $\pi^*$ ,  $\alpha$ , and  $\beta^{29}$ ) is that fewer adjustable parameters are required. Applications of eq 1 to correlate solvolysis rates require a suitable *Y* scale, and the *Y<sub>X</sub>* scales based on 1-adamantyl solvolyses are employed widely.<sup>5</sup> No additional parameters are needed for many S<sub>N</sub>1 solvolyses, but considerable attention is currently being given to improve the precision of correlations for solvolyses occurring via delocalized cationic transition states;<sup>15c,16,30</sup> either a wider range of *Y* scales or an extra adjustable parameter will be required.

The range of *l* values (eq 1) was originally expected to lie between 0 and 1.<sup>4b</sup> Although compounds such as *p*-nitrobenzoyl chloride (**9**) have long been known to have

a higher sensitivity to nucleophilicity,<sup>31</sup> it was not expected that the mechanism of solvolysis was comparable. Recent work on solvolyses of **9** and related compounds<sup>32</sup> indicates the possibility of a concerted substitution mechanism, with a kinetic solvent isotope effect (MeOH/MeOD) of 2.3.<sup>33</sup> We have confirmed (Table 6) that S<sub>N</sub>2 solvolyses of methyl tosylate give a small MeOH/MeOD rate ratio (1.1), as expected from earlier work on H<sub>2</sub>O/D<sub>2</sub>O;<sup>34,35</sup> S<sub>N</sub>1 solvolyses of Ph<sub>2</sub>CHCl also show a small MeOH/MeOD rate ratio of 1.1.<sup>36</sup> The kinetic solvent isotope effect has been noted as a disappointing criterium of the mechanism,<sup>37</sup> but in a recent study of an S<sub>N</sub>2(P) solvolysis of (PhO)<sub>2</sub>POCl, we found an *l* value (eq 1) of ca. 1.8 and a (MeOH/MeOD) rate ratio as high as 3.1.<sup>38</sup> Perhaps the small solvent isotope effects in typical S<sub>N</sub>2 solvolyses indicate an early transition state, with nucleophilic assistance lagging behind departure of the leaving group, as recently re-emphasized in the case of neighboring group participation.<sup>39</sup>

## Conclusions

The rates of S<sub>N</sub>1 solvolytic reactions of a substrate (RX) depend on the solvent ionizing power (*Y* or *Y<sub>X</sub>*<sup>5</sup>), which includes contributions from electrostatic and electrophilic solvation of the developing anion (X<sup>-</sup>). Relative rates of solvolyses of 1-adamantyl or *tert*-butyl substrates having different halide leaving groups are influenced by solvent electrophilicity, but solvolyses of substrates having saturated alkyl groups (e.g., 1-adamantyl and *tert*-butyl) respond very similarly to changes in solvent electrophilicity (Table 7). Solvolyses leading to delocalized cations, which may be formed by neighboring group participation or by charge delocalization onto adjacent  $\pi$ -electrons, show unusual effects in that rates of solvolyses in fluorinated alcohols may be faster than expected from an *mY* plot for aqueous ethanols, and this effect is in the opposite direction from that due to solvent nucleophilicity. A delocalized cationic transition state for concerted elimination may explain the recent results for **7**, without the need to postulate additional specific solvation effects for adamantyl systems, such as Bronsted-base solvation of  $\alpha$ - and  $\beta$ -hydrogen atoms.<sup>8a</sup> As would be expected, increases in steric hindrance or in cation-stabilization lead to decreases in susceptibility to solvent nucleophilicity (Scheme 1).

## Experimental Section

**Chemicals.** Chlorides **4–6** were available from previous work;<sup>15c</sup> chlorodiphenylmethane (**1**),<sup>17</sup> *p*-methoxybenzyl chloride (**2**),<sup>11a</sup> and *tert*-butyl bromide<sup>13a</sup> were obtained as reported earlier; 1-chloro-1-phenylethane (**3**) was prepared and purified by standard methods;<sup>13b</sup> *tert*-butyl iodide was first washed with aqueous sodium metabisulfite and was freshly

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distilled to remove traces of iodine, which may catalyze solvolyses;<sup>40</sup> methyl tosylate was a commercial sample (BDH).

**Kinetics.** MeOD was Aldrich (>99.5+ %D), and other solvents were prepared as described previously.<sup>26a,b</sup> Kinetic data were obtained by our standard procedures.<sup>41</sup>

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**Product Studies.** Product ratios were obtained using the same techniques and equipment as described previously.<sup>17</sup>

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