4-Bromo-3-phenylisocoumarin (41). To a suspension of PBr_5 (0.864 g, 2.0 mmol) in 50 mL of chloroform was added dropwise 2-phenyl-1,3-indandione (1.12 g, 5.0 mmol) in 15 mL of chloroform. After refluxing for 6 h, the solution was cooled and filtered to remove residual PBr_5. Product isolation (ice water, cold 5% $NaHCO_3$ (2×)) afforded a yellow solid, 1-bromo-2-phenyl-inden-3-one (**40**). Owing to its instability no further purification was attempted: ^1H NMR δ 7.58–8.08 (m, 4 H), 7.10–7.38 (m, 5 H); IR 1820 cm^{-1} (C=O).

As described above for compound **38**, 2.84 g (10 mmol) of the solid, **40**, was dissolved in 50 mL of CH_2Cl_2 at 0 °C, and treated with 12.5 mmol of trifluoroperacetic acid in the presence of 2 g of Na_2HPO_4. After 3 h at 0 °C, the solution was filtered and salts were washed thoroughly with CH_2Cl_2. Product isolation (cold 5% $NaHCO_3$, water, satd NaCl, Florisil) gave 2.92 g of a solid. Recrystallization (hexane–chloroform) afforded **41** as white crystals, 2.46 g (82%): mp 100–101.5 °C; ^1H NMR δ 7.80–8.12 (m, 4 H), 7.60–7.77 (m, 2 H), 7.20–7.37 (m, 3 H); IR 1796 cm^{-1} (C=O).

Anal. Calcd for $C_{15}H_9BrO_2$: C, 59.83; H, 3.01; Br, 29.55. Found: C, 59.81; H, 2.94; Br, 29.50.

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The S_N2–S_N1 Spectrum. 3. Solvolyses of Secondary and Tertiary Alkyl Sulfonates in Fluorinated Alcohols. Further Evidence for the S_N2 (Intermediate) Mechanism[1,2]

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Abstract: Kinetic data are reported for solvolyses of secondary and tertiary alkyl tosylates in trifluoroethanol and hexafluoroisopropyl alcohol and also for 1-adamantylmethylcarbinyl (VI) and 1-bicyclo[2.2.2]octyl (VII) tosylates in a wide range of solvents. The relative solvolysis rates of 2-adamantyl (I), 1-adamantylmethylcarbinyl (VI), and 1-bicyclo[2.2.2]octyl (VII) tosylates are essentially independent of solvent (in ethanol, methanol, water, trifluoroethanol, hexafluoroisopropyl alcohol, acetic acid, formic acid, and trifluoroacetic acid). Thus these three substrates are good models for S_N1 (k_c or limiting) mechanistic behavior; they respond almost identically to changes in solvent ionizing power and are insensitive to changes in solvent nucleophilicity. In contrast relative solvolysis rates of 2-adamantyl and 2-propyl tosylates vary with solvent 10^5-fold from 134 in hexafluoroisopropyl alcohol to 0.0011 in ethanol. For straight-chain secondary alkyl tosylates, logarithms of solvolysis rate constants in hexafluoroisopropyl alcohol correlate with σ^* and give a large negative ρ^* value (−9.1). Other solvents give less negative ρ^* values (e.g., CF_3CO_2H, $\rho^* = -7.3$; CF_3CH_2OH, $\rho^* = -5.2$; H_2O, $\rho^* = -4.3$) and smaller 2-adamantyl/2-propyl (2-AdOTs/2-PrOTs) rate ratios. Increasing amounts of nucleophilic solvent assistance in the more nucleophilic solvents leads to decreased electron demand by the cationic center (i.e., less negative ρ^*), and solvolyses of 2-propyl become more rapid than 2-adamantyl. Solvent effects on the relative reactivity of secondary alkyl tosylates (ROTs) are correlated accurately by using the linear free energy relationship: $\log (k/k_0)_{ROTs} = Q' \log (k/k_0)_{2\text{-AdOTs}} (k/k_0)_{2\text{-AdOTs}} + (1 - Q') \log (k/k_0)_{2\text{-PrOTs}}$ where k refers to any solvent, k_0 refers to 80% ethanol/water (v/v), and Q' is an adjustable blending parameter. The high precision of correlations using this equation for 2-butyl, 2-pentyl, 3-pentyl, 4-heptyl, cyclopentyl, cyclohexyl, and cycloheptyl tosylates provides evidence for a gradual change of mechanism from S_N2 (one-stage) through S_N2 (intermediate) to S_N1 mechanisms. Solvolyses of 3-methyl-2-butyl tosylate show significant sensitivity to nucleophilic solvent assistance ($Q' = 0.42$). Solvolyses of pinacolyl (II), 2-*exo*-norbornyl (III), 2-*endo*-norbornyl (IV), menthyl (V), and cyclooctyl tosylates are either k_s or k_Δ (not k_c as proposed by others), since they respond less to changes in solvent ionizing power than the k_c mechanistic models (I, VI, VII).

S_N1 reactions proceed via transition states with high carbocation character to ion pair intermediates.[4] S_N2 reactions are accelerated relative to S_N1 reactions by rearside nucleophilic attack, and such nucleophilic assistance reduces the carbocation character in the transition state. S_N2 reactions occurring by a concerted mechanism will here be referred to as S_N2 (one-stage); they span a huge range of degrees of nucleophilic assistance, including classical S_N2 processes[4f] and some weakly assisted processes with relatively high carbocation character in the transition state.[2c,5] This variable character of the S_N2 process may be regarded as a "spectrum", implying a progressive series of changes or merging of character, and not a varying mixture of only two distinct processes (S_N2 and S_N1).[2a]

A further gradation of mechanism and reactivity between S_N1 and S_N2 (one-stage) processes can be achieved by using the S_N2 (intermediate) mechanism to account for relatively weakly nucleophilically assisted processes showing ion-pair characteristics.[2a] Thus, the S_N2 (intermediate) mechanism reconciles the evidence for both ion-pair intermediates and nucleophilic assistance.[4b] This

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(2) Previous papers in this series: (a) Bentley, T. W.; Schleyer, P. v. R. *J. Am. Chem. Soc.* **1976**, *98*, 7658. (b) Schadt, F. L.; Bentley, T. W.; Schleyer, P. v. R. *Ibid.* **1976**, *98*, 7667. (c) See also: Bentley, T. W.; Bowen, C. T. *J. Chem. Soc., Perkin Trans. 2*, **1978**, 557.

(3) (a) Swansea. (b) Erlangen.

(4) For the background to this work see: (a) Harris, J. M. *Prog. Phys. Org. Chem.* **1974**, *11*, 89. (b) Bentley, T. W.; Schleyer, P. v. R. *Adv. Phys. Org. Chem.* **1977**, *14*, 1. (c) Kirmse, W. *Top. Curr. Chem.* **1979**, *80*, 128–311. (d) Streitwieser, A., Jr. "Solvolytic Displacement Reactions"; McGraw Hill: New York, 1972; *Chem. Rev.* **1956**, *56*, 571. (e) Thornton, E. R. "Solvolysis Mechanisms", Ronald Press: New York, 1964. (f) Ingold, C. K. "Structure and Mechanism in Organic Chemistry", 2nd ed., Cornell University Press: Ithaca, NY, 1969, Chapter VII especially pp 430–431 and p 455.

(5) (a) Jencks, W. P. *Acc. Chem. Res.* **1980**, *13*, 161. (b) Knier, B. L.; Jencks, W. P. *J. Am. Chem. Soc.* **1980**, *102*, 6789.

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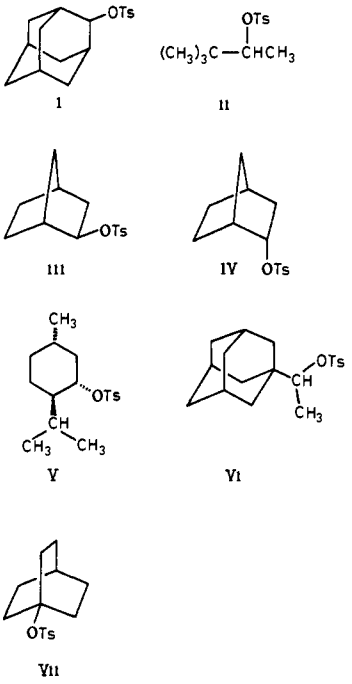
mechanism involves a pentacoordinate *intermediate* (a nucleophilically solvated ion pair[2] or "ion sandwich"[6]), similar to the *transition state* in the S_N2 (one-stage) reaction; nucleophilic assistance aids heterolysis of the bond between carbon and the leaving group as in the S_N2 (one-stage) mechanism. Alternatively, ion pairs could be formed by heterolysis before rate-limiting nucleophilic attack occurs,[7] and "internal return" to starting material would occur more rapidly than attack by nucleophile to give products.[8] Jencks[5] has proposed a "preassociation" mechanism with yet another timing—association of nucleophile (or solvent) with substrate occurs before the rate-limiting displacement. These different explanations raise fundamental questions about the factors influencing reactivity in solution: e.g., (i) the nature of the energy barrier to nucleophilic solvation of ions or of groups on which charge is developed when molecules undergo heterolysis and (ii) the factors influencing the reactivity of ion-pair intermediates.

We have investigated these mechanisms by examining solvolyses of a wide variety of secondary and tertiary sulfonates, e.g., 2-propyl, 2-adamantyl (I), pinacolyl (II), 3-methyl-2-butyl, cyclo-



heptyl, cyclooctyl, *exo*-2-norbornyl (III), *endo*-2-norbornyl (IV), menthyl (V), 1-adamantylmethylcarbinyl (VI), and 1-bicyclo-[2.2.2]octyl (VII) tosylates. These solvolyses span the range from S_N2 (one-stage) to S_N1 mechanisms and allow comprehensive analysis of the mechanistic changes.

Our approach is based on the S_N1 solvolyses of 2-adamantyl tosylate (I), which defines a limit and allows estimation of the magnitude of nucleophilic solvent assistance[10] in solvolyses of less sterically hindered secondary substrates.[2b,11a] These estimates can be used to "correct" solvolysis rates for nucleophilic solvent assistance, so the rates of corresponding hypothetical S_N1 reactions can be predicted. Such estimated S_N1 rate constants for ethanolyses of a wide range of alkyl chlorides correlate well with heats of ionization in SO_2ClF/SbF_5.[12] Thermochemical data in solution have also been related to gas-phase data, thus completing a link between ethanolyses of secondary and tertiary substrates and thermochemical data for carbocations in the gas phase.[12] On this basis, the magnitude of nucleophilic solvent assistance for solvolyses of methyl substrates has been estimated to be ca. 33 kcal/mol ($>10^{24}$ in rate at 25 °C).[12] No methyl cation nor ion pair is thus energetically possible in a solvolysis reaction, and methyl can be chosen as a model S_N2 (one-stage) substrate.

We use linear free energy relationships to analyze mechanistic, structural, and solvent effects on solvolytic reactivity.[2] The original two-parameter Grunwald–Winstein equation (1)[13] accounts for

$$\log (k/k_0) = mY_{t\text{-BuCl}} \quad (1)$$

changes in solvent ionizing power but does not correlate solvolysis data for substrates prone to nucleophilic solvent assistance when a wide range of solvents is employed.[2b] The four-parameter equation (2) also includes an *lN* nucleophilicity term and correlates

$$\log (k/k_0) = mY + lN \quad (2)$$

data for substrates varying as widely as methyl and 2-adamantyl tosylates.[2b] Equation 3 represents another approach.[2b] Methyl

$$\log (k/k_0)_{\text{ROTs}} = (1 - Q) \log (k/k_0)_{\text{CH}_3\text{OTs}} + Q \log (k/k_0)_{\text{2-AdOTs}} \quad (3)$$

and 2-adamantyl tosylates model mechanistic extremes (S_N2 and S_N1, respectively), within the range of compounds examined. The adjustable blending parameter Q reveals the extent to which any substrate approaches methyl ($Q = 0$) or 2-adamantyl ($Q = 1$) in behavior.

Equations like (3) provide a simple quantitative test for a mechanistic spectrum, and it is intended as a versatile approach. Various model compounds could be used. Some solvolyses (e.g., of acid chlorides)[14] are more sensitive to nucleophilic assistance than solvolyses of methyl tosylate. Other substrates may be more sensitive to solvent ionizing power than 2-adamantyl; in this paper two possible examples, 1-adamantylmethylcarbinyl (VI) and 1-bicyclo[2.2.2]octyl (VII) are shown to give very similar results to 2-adamantyl.

With use of 2 and 3, correlations including fluorinated alcohol/water mixtures were less precise than those for other solvents, but limited experimental data was available in 1976.[2b] To extend our data set and to remove ambiguities due to binary solvent mixtures, we now report kinetic data for solvolyses in pure trifluoroethanol, one of the solvents most prone to give internal return,[15] and in pure hexafluoroisopropyl alcohol (HFIP), which has attracted considerable interest as a new, very weakly nucleophilic solvolysis medium.[11c,15d,16-18] We also report correlations

(6) Bordwell, F. G.; Wiley, P. F.; Mecca, T. G. *Ibid.* **1975**, *97*, 132.
(7) (a) Shiner, V. J., Jr.; Nollen, D. A.; Humski, K. *J. Org. Chem.* **1979**, *44*, 2108 and references there cited. (b) Miller, L. S.; Zazzaron, D.; Dannenberg, J. J.; Metras, R.; Gillard, M. *Ibid.* **1980**, *45*, 641. (c) Blandamer, M. J.; Robertson, R. E.; Scott, J. M. W.; Vrielink, A. *J. Am. Chem. Soc.* **1980**, *102*, 2585. (d) Sneen, R. A. *Acc. Chem. Res.* **1973**, *6*, 46.
(8) There is evidence that internal return can occur, but the observed effects are usually small.[9]
(9) Raber, D. J.; Harris, J. M.; Schleyer, P. v. R. In "Ions and Ion Pairs in Organic Reactions"; Szwarc, M., Ed.; Wiley: New York, 1974; Vol. 2, pp 247–374.
(10) We define nucleophilic solvent assistance (or nucleophilic solvation) as the bonding of solvent as nucleophile or base (as distinct from general electrostatic solvation) to any atom of the substrate (e.g., α-carbon, β-hydrogen, etc), which contributes significantly to the kinetics of solvolysis.
(11) (a) Schleyer, P. v. R.; Fry, J. L.; Lam, L. K. M.; Lancelot C. J. *J. Am. Chem. Soc.* **1970**, *92*, 2542. (b) Bentley, T. W.; Liggero, S. H.; Imhoff, M. A.; Schleyer, P. v. R. *Ibid.* **1974**, *96*, 1970. (c) Schadt, F. L.; Schleyer, P. v. R.; Bentley, T. W. *Tetrahedron Lett.* **1974**, 2335.
(12) Arnett, E. M.; Petro, C.; Schleyer, P. v. R. *J. Am. Chem. Soc.* **1979**, *101*, 522.
(13) (a) Grunwald, E.; Winstein, S. *J. Am. Chem. Soc.* **1948**, *70*, 846. (b) Fainberg, A. H.; Winstein, S. *Ibid.* **1956**, *78*, 2770.
(14) (a) Swain, C. G.; Mosely, R. B.; Bown, D. E. *J. Am. Chem. Soc.* **1955**, *77*, 3731. (b) Peterson, P. E.; Vidrine, D. W.; Waller, F. J.; Henrichs, P. M.; Magaha, S.; Stevens, B. *Ibid.* **1977**, *99*, 7968.
(15) (a) Shiner, V. J.; Hartshorn, S. R.; Vogel, P. C. *J. Org. Chem.* **1973**, *38*, 3604. (b) Shiner, V. J., Jr.; Dowd, W.; Fisher, R. D.; Hartshorn, S. R.; Kessick, M. A.; Milakofsky, L.; Rapp, M. W. *J. Am. Chem. Soc.* **1969**, *91*, 4838. (c) Shiner, V. J., Jr.; Fisher, R. D.; Dowd, W. *Ibid.* **1969**, *91*, 7748. (d) Seib, R. C.; Shiner, V. J.; Sendijarević, V.; Humski, K. *Ibid.* **1978**, *100*, 8133.
(16) (a) Sunko, D. E.; Szele, I. *Tetrahedron Lett.* **1972**, 3617. (b) Lenoir, D.; Röll, W.; Weiss, E.; Wenke, G. *Ibid.* **1976**, 1991. (c) Gregoriou, G. A.; Paleos, C. M. *Chimica Chronica.* **1974**, *3*, 103. (d) Allard, B.; Casadevall, A.; Casadevall, E.; Largeau, C. *Nouv. J. Chim.* **1979**, *3*, 335. (e) Allard, B.; Casadevall, A.; Casadevall, E.; Largeau, C. *Ibid.* **1980**, *4*, 539. (f) Banks, R. M.; Maskill, H.; Natarajan, R.; Wilson, A. A. *J. Chem. Soc., Perkin Trans. 2*, **1980**, 427. (g) Ferber, P. H.; Gream, G. E.; Wagner, R. D. *Aust. J. Chem.* **1980**, *33*, 1569.

using eq 4 a modification of eq 3. Equation 4 is well suited to

$$\log (k/k_0)_{ROTs} = (1 - Q') \log (k/k_0)_{2\text{-PrOTs}} + Q' \log (k/k_0)_{2\text{-AdOTs}} \quad (4)$$

the range of compounds discussed here and enables us to monitor more precisely the mechanistic change from S_N2 (one-stage) to S_N1. The resulting correlations, with solvents having an extremely wide range of ionizing power and nucleophilicity, allow structural and solvent effects on the solvolytic reactivity of secondary and tertiary sulfonates to be interpreted mechanistically.

Results

As expected from previous work on *p*-bromobenzenesulfonic acid,[15b] conductance vs. concentration plots were nonlinear for *p*-toluenesulfonic acid in trifluoroethanol. With use of these plots as calibration curves to calculate the extent of reaction from observed conductances, low precision kinetic data were obtained.[19] Conductance vs. concentration plots are linear for up to 10^{-3} M *p*-toluenesulfonic acid in trifluoroethanol containing 2×10^{-3} M acetamide or benzamide (cf. previous use of urea[20a] or 2,6-lutidine[20b]). Table I shows kinetic data for solvolyses in trifluoroethanol containing acetamide or benzamide (conductometric studies) or sodium acetate (spectrophotometric studies). For solvolyses of tosylates in hexafluoroisopropyl alcohol (HFIP) containing various weak bases (e.g., benzamide, benzophenone, urea, dioxan), reliable results could not be obtained conductometrically. For solvolyses of tosylates in 97% w/w HFIP/water, in which the *p*-toluenesulfonic acid is completely dissociated, satisfactory rate constants could be obtained but conductance readings drifted upwards after the reaction was completed. This effect was not observed for solvolyses of chlorides[18b] and was not alleviated by removal of oxygen from the system. Satisfactory results were obtained spectrophotometrically in the presence of sodium acetate,[21] and agreement between conductometric and spectrophotometric data was established (Table II). Kinetic data for 1-bicyclo[2.2.2]octyl tosylate (VII) are given in Table III and for 1-adamantylmethylcarbinyl tosylate (VI) in Table IV. Compilations of additional kinetic data are given in Tables V and VI.

Table I. Rate Constants for Solvolyses of Secondary Alkyl Tosylates in Trifluoroethanol

tosylate	temp, °C	k, s^{-1}	$\Delta H^{\ddagger}$, kcal/mol	$\Delta S^{\ddagger}$, eu
2-propyl	75.21[a]	$(1.25 \pm 0.01) \times 10^{-4}$		
	49.91[a]	$(1.01 \pm 0.04) \times 10^{-5}$	21.6	−14.8
	50.14[b]	$(1.07 \pm 0.03) \times 10^{-5}$		
	25.0[c]	5.6×10^{-7}		
2-butyl	75.48[a]	$(3.82 \pm 0.04) \times 10^{-4}$		
	49.8[a]	$(3.03 \pm 0.06) \times 10^{-5}$	21.4	−13.1
	50.14[b]	$(3.09 \pm 0.02) \times 10^{-5}$		
	25.0[c]	1.74×10^{-6}		
2-pentyl	75.28[a]	$(4.19 \pm 0.08) \times 10^{-4}$		
	49.95[a]	$(3.10 \pm 0.10) \times 10^{-5}$	22.3	−10.2
	48.8[b]	$(2.97 \pm 0.05) \times 10^{-5}$		
	25.0[c]	1.55×10^{-6}		
3-pentyl	75.52[a]	$(1.25 \pm 0.02) \times 10^{-3}$		
	49.7[a]	$(1.02 \pm 0.01) \times 10^{-4}$	21.0	−11.8
	25.0[c]	6.24×10^{-6}		
4-heptyl	75.17[a]	$(1.36 \pm 0.06) \times 10^{-3}$		
	49.92[a]	$(1.26 \pm 0.03) \times 10^{-4}$	20.4	−13.4
	25.0[c]	8.2×10^{-6}		
cyclopentyl	53.0[a]	$(6.47 \pm 0.16) \times 10^{-4}$		
	25.0[a,d]	$(3.28 \pm 0.02) \times 10^{-5}$		
	25.0[b,e]	$(3.18 \pm 0.08) \times 10^{-5}$		
cyclohexyl	75.37[a]	$(4.75 \pm 0.04) \times 10^{-4}$		
	49.68[a]	$(2.91 \pm 0.03) \times 10^{-5}$	23.6	−6.3
	50.14[b]	$(3.20 \pm 0.11) \times 10^{-5}$		
	25.0[c]	1.27×10^{-6}		
pinacolyl (II)	75.1[f]	$(4.66 \pm 0.3) \times 10^{-3}$		
	49.78[a]	$(4.27 \pm 0.07) \times 10^{-4}$		
	50.14[b]	$(3.93 \pm 0.03) \times 10^{-4}$		
	48.83[b]	$(4.05 \pm 0.01) \times 10^{-4}$		
	25.0[a,d]	$(2.34 \pm 0.04) \times 10^{-5}$	21.8	−6.6
2-*exo*-norbornyl (III)	25.0[a,d]	$(4.34 \pm 0.05) \times 10^{-3}$		
2-*endo*-norbornyl (IV)	75.0[a]	ca. 9.2×10^{-4}		
	49.95[a]	$(8.85 \pm 0.09) \times 10^{-5}$		
	49.98[b]	$(9.21 \pm 0.05) \times 10^{-5}$		
	25.0[g]	5.0×10^{-6}		
2-adamantyl (I)	75.29[a]	$(6.18 \pm 0.10) \times 10^{-4}$		
	49.86[f]	$(3.59 \pm 0.20) \times 10^{-5}$	24.4	−3.6
	50.14[b]	$(4.23 \pm 0.13) \times 10^{-5}$		
	48.84[b]	$(3.35 \pm 0.22) \times 10^{-5}$		
	25.0[c]	1.40×10^{-6}		

[a] Determined conductometrically in duplicate; errors shown are average deviations; solvent contains <0.1% water (w/w), ca. 2×10^{-3} M acetamide or benzamide and initially ca. 10^{-3} M tosylate. [b] Determined spectrophotometrically in duplicate; errors shown are average deviations; solvent contains <0.1% water (w/w), ca. 2×10^{-3} M anhydrous sodium acetate and initially ca. 10^{-3} M tosylate. [c] Calculated from conductometric data at higher temperatures. [d] Calculated from a value of the rate constant at an accurately determined temperature close (±0.2 °C) to 25 °C. [e] Calculated by substracting 4-5% from a value of the rate constant at 25.4 ± 0.2 °C. [f] Determined conductometrically in triplicate. [g] Calculated from data at higher temperatures assuming $\Delta H^{\ddagger} = 21.5$ kcal/mol.

Discussion

Definitions and Mechanistic Framework. According to the mechanistic framework of Winstein, *real* solvolyses are either nucleophilically solvent assisted (designated k_s and including both substitution and elimination processes) or anchimerically assisted (k_Δ), with k_c representing the *hypothetical* limit which is approached when nucleophilic solvent assistance and anchimeric assistance approach zero.[11a,26a] Solvolyses of 2-adamantyl tosylate are used as models for "limiting" behavior.[2,11a] When correlations of rates and products are observed, k_s and k_Δ are discrete processes.[27] One can therefore envisage a $k_s \rightarrow k_c$ spectrum of mechanisms in which the magnitude of nucleophilic solvent as-

(17) (a) Harris, J. M.; Mount, D. L.; Smith, M. R.; Neal, W. C., Jr.; Dukes, M. C.; Raber, D. J. *J. Am. Chem. Soc.* **1978**, *100*, 8147. (b) Raber, D. J.; Neal, W. C., Jr.; Dukes, M. D.; Harris, J. M.; Mount, D. L. *Ibid.* **1978**, *100*, 8137. (c) Harris, J. M.; Mount, D. L.; Raber, D. J. *Ibid.* **1978**, *100*, 3139.

(18) (a) Bentley, T. W.; Bowen, C. T.; Parker, W.; Watt, C. I. F. *J. Am. Chem. Soc.* **1979**, *101*, 2486. (b) Bentley, T. W.; Bowen, C. T.; Parker, W.; Watt, C. I. F. *J. Chem. Soc., Perkin Trans. 2*, 1980, 1244.

(19) During these preliminary stages trifluoroethanolyses of cyclopentyl tosylate were examined. The rate constants were found to be similar to but lower than those subsequently reported (Table I).

(20) (a) Roberts, D. D. *J. Org. Chem.* **1972**, *37*, 1510. (b) Gassman, P. G.; Saito, K.; Talley, J. J. *J. Am. Chem. Soc.* **1980**, *102*, 7613. (c) Roberts, D. D. *J. Org. Chem.* **1968**, *33*, 118. (d) Roberts, D. D.; Traynham, J. G. *Ibid.* **1967**, *32*, 3177.

(21) (a) Sinnott, M. L. *J. Org. Chem.* **1969**, *34*, 3638. (b) Bone, J. A.; Pritt, J. R.; Whiting, M. C. *J. Chem. Soc., Perkin Trans 2* **1975**, 1447. (c) Peterson, P. E.; Kelley, R. E., Jr.; Belloli, R.; Sipp, K. A. *J. Am. Chem. Soc.* **1965**, *87*, 5169.

(22) (a) Grob, C. A.; Kostka, K.; Kuhnen, F. *Helv. Chim. Acta* **1970**, *53*, 608. (b) Schleyer, P. v. R.; Woodworth, C. W. *J. Am. Chem. Soc.* **1968**, *90*, 6528. (c) Rhodes, Y. E.; DiFate, V. G. *Ibid.* **1972**, *94*, 7582.

(23) (a) Bentley, T. W.; Bowen, C. T.; Brown, H. C.; Chloupek, F. J. *J. Org. Chem.* **1981**, *46*, 38. (b) Brown, H. C.; Ravindranathan, M.; Chloupek, F. J.; Rothberg, I. *J. Am. Chem. Soc.* **1978**, *100*, 3143.

(24) (a) Hückel, W.; Tomopulos, K. *Justus Liebigs Ann. Chem.* **1957**, *610*, 78. (b) Hückel, W.; Riad, Y. *Ibid.* **1964**, *678*, 19. (c) Hückel, W.; Wächter, J. *Ibid.* **1964**, *672*, 62. (d) Hückel, W.; Vogt, O. *Ibid.* **1966**, *695*, 16. (e) Hückel, W.; Heinzel, M. *Ibid.* **1959**, *624*, 142. (f) Sera, A.; Yamagami, C.; Muruyama, K. *Bull. Chem. Soc. Jpn.* **1973**, *46*, 3864.

(25) (a) Huisgen, R.; Rauenbusch, E.; Seidl, G.; Wimmer, I. *Justus Liebigs Ann. Chem.* **1964**, *671*, 41. (b) Heck, R.; Prelog, V. *Helv. Chim. Acta* **1955**, *38*, 1541. (c) Brown, H. C.; Ham, G. *J. Am. Chem. Soc.* **1956**, *78*, 2735. (d) Allinger, N. L.; Szkrybalo, W. *Tetrahedron* **1968**, *24*, 4699. (e) Nordlander, J. E.; Gruetzmacher, R. R.; Kelly, W. J.; Jindal, S. P. *J. Am. Chem. Soc.* **1974**, *96*, 181. (f) Schleyer, P. v. R.; Donaldson, M. M.; Watts, W. E. *Ibid.* **1965**, *87*, 375. (g) Winstein, S.; Morse, B. K.; Grunwald, E.; Jones, H. W.; Corse, J.; Trifan, D.; Marshall, H. *Ibid.* **1952**, *74*, 1127. (h) Pross, A.; Koren, R. *Tetrahedron Lett.* **1974**, 1949. (i) Winstein, S.; Marshall, H. *J. Am. Chem. Soc.* **1952**, *74*, 1120.

(26) (a) Winstein, S.; Allred, E.; Heck, R.; Glick, R. *Tetrahedron* **1958**, *3*, 1. (b) Winstein, S.; Grunwald, E.; Jones, H. W. *J. Am. Chem. Soc.* **1951**, *73*, 2700.

(27) Schadt, F. L.; Lancelot, C. J.; Schleyer, P. v. R. *J. Am. Chem. Soc.* **1978**, *100*, 228.

Table II. Rate Constants for Solvolyses of Secondary Alkyl Tosylates in Hexafluoroisopropyl Alcohol (HFIP)

tosylate	temp, °C	10^5k, s^{-1} HFIP[a]	10^5k, s^{-1} 97% HFIP[b]
2-propyl	50.14	2.11 ± 0.06[d]	
	42.62	0.885 ± 0.02[d]	
	32.33	0.274 ± 0.016[d]	
	25.0	0.11[c,e]	0.155[f]
2-butyl	25.0	1.57 ± 0.06[d,g]	
2-pentyl	25.0	1.91 ± 0.2[g,h]	
3-pentyl	25.0	8.36 ± 0.14[d,g]	
4-heptyl	25.0	15.5 ± 0.5[d,g]	
cyclopentyl	25.0	41.5 ± 0.9[d,g]	
cyclohexyl	50.14	34.7 ± 0.7[d]	
	25.0	2.64 ± 0.05[g,i]	1.78 ± 0.07[d,g]
			1.75 ± 0.12[j]
			1.81[f]
pinacolyl (II)	25.0	105 ± 2[d,g]	62.3 ± 0.2[d,g]
		110 ± 3[j,k]	66.0 ± 0.9[j]
2-adamantyl (I)	50.13	139 ± 1[d]	
	42.63	76.3 ± 0.7[d]	
	25.0	14.7 ± 0.2[d,g,l]	8.68 ± 0.15[d]
		15.7 ± 0.9[j,k]	8.84[m]

[a] Solvent contains <0.06% water (w/w) and $<10^{-2}$ M anhydrous sodium acetate. [b] Solvent contains 3.0% water (w/w). [c] Calculated from data at other temperatures. [d] Determined spectrophotometrically in duplicate; errors shown are average deviations. [e] Using $\Delta H^{\ddagger} = 21.8$ kcal/mol and $\Delta S^{\ddagger} = -12.6$ eu; two direct measurements at 25 °C over about 1 half-life gave $k \approx 0.17 \times 10^{-5}$ s^{-1}, which was significantly reduced when an additional data point for >65% reaction was included. [f] Reference 2b. [g] Calculated by substracting 4–5% from a value of the rate constant at 25.4 ± 0.2 °C. [h] Determined spectrophotometrically in triplicate. [i] $\Delta H^{\ddagger} = 19.0$ kcal/mol and $\Delta S^{\ddagger} = -15.7$ eu. [j] Determined conductometrically in duplicate, errors shown are average deviations; values reported are calculated from rate constants at an accurately determined temperature close (±0.2 °C) to 25 °C. [k] Sodium acetate added. [l] $\Delta H^{\ddagger} = 16.6$ kcal/mol, $\Delta S^{\ddagger} = -20.5$ eu. [m] Reference 18b; other literature values; 9.75[2b] and 7.17.[16d]

sistance varies and a $k_\Delta \rightarrow k_c$ spectrum of mechanisms in which the magnitude of anchimeric assistance varies. The extent of nucleophilic solvent assistance (the k_s/k_c rate ratio) was greatly underestimated by previous workers,[4f,26b] with important consequences for the interpretation of reaction mechanisms and structure/reactivity relationships.[11a,27]

Choice of Models for Limiting Behavior. With use of 2-adamantyl tosylate (I) as a model system in a Grunwald–Winstein type equation, (5), a scale of solvent ionizing power for tosylates

$$\log (k/k_0)_{ROTs} = m \log (k/k_0)_{2\text{-}AdOTs} = mY_{OTs} \quad (5)$$

Y_{OTs} was defined, with $m = 1$ for rates of solvolyses in any solvent (k) relative to solvolyses in 80% v/v ethanol/water (k_0) at 25 °C.[2b] By restricting correlations to tosylates, effects due to differential solvation of leaving groups (e.g., by hydrogen bonding) are removed or substantially reduced.[2b] To demonstrate that 2-adamantyl tosylate solvolyses without rearside nucleophilic solvent assistance, we studied 1-bicyclo[2.2.2]octyl (VII) solvolyses; VII is a bridgehead system for which rearside nucleophilic attack and 1,2 elimination are prohibited by the carbon skeleton.[28] Equation 5 gave a high-precision fit of the data (Table III) having a slope of essentially unity (Table VII), showing that rearside nucleophilic solvent assistance is absent and that a Y_{OTs} scale based on (VII) would be almost identical to that for 2-adamantyl tosylate. Another possible model for limiting behavior is 1-adamantylmethylcarbinyl tosylate (VI), which is sterically hindered toward k_s reaction and has less driving force by rearrangement (k_Δ reaction) than the structurally similar pinacolyl system (II).[11b] Again

Table III. Rate Constants for Solvolyses of 1-Bicyclo[2.2.2]octyl Tosylate (VII)[a]

solvent[b]	temp, °C	k, s^{-1}	$\Delta H^{\ddagger}$, kcal/mol	$\Delta S^{\ddagger}$, eu
80% EtOH	75.0[c,d]	1.67×10^{-4}	24.7	−5.3
	75.0[e]	1.76×10^{-4}		
	25.0[c,d]	3.6×10^{-7}		
50% EtOH	50.0[f]	$(2.59 \pm 0.04) \times 10^{-4}$		
	25.0	$(1.08 \pm 0.03) \times 10^{-5}$	23.7	−1.7
90% EtOH	75.0	$(3.70 \pm 0.07) \times 10^{-5}$		
	56.7	$(4.74 \pm 0.10) \times 10^{-6}$	24.9	−7.6
	25.0[c]	7.6×10^{-8}		
EtOH	75.0[g]	$(4.4 \pm 0.6) \times 10^{-6}$		
	25.0[c,h]	5×10^{-9}		
HCO_2H	25.0[f]	$(4.75 \pm 0.07) \times 10^{-4}$		
CF_3CO_2H	−9.98[i]	$(2.32 \pm 0.15) \times 10^{-4}$		
	0.1[i]	$(9.8 \pm 0.1) \times 10^{-4}$	19.9	0.7
	0.05[j]	$(8.8 \pm 0.6) \times 10^{-4}$		
	25.0[c]	2.3×10^{-2}		
CH_3CO_2H	75.0[k]	$(4.6 \pm 0.5) \times 10^{-5}$		
	75.0[l]	3.8×10^{-5}		
	75.0[c,m]	4.26×10^{-5}		
	25.0[c,m]	7.96×10^{-8}	25.3	−6.3
	25.0[c,l]	5.6×10^{-8}	26.2	−1.7
97% CF_3CH_2OH	50.0	$(4.47 \pm 0.04) \times 10^{-4}$		
	25.0	$(2.74 \pm 0.07) \times 10^{-5}$	20.8	−9.8
70% CF_3CH_2OH	25.0	$(3.95 \pm 0.07) \times 10^{-5}$		
97% $(CF_3)_2CHOH$	25.0	$(1.52 \pm 0.02) \times 10^{-3}$		

[a] Determined conductometrically in duplicate except where otherwise noted; errors shown are average deviations. [b] % EtOH refers to % ethanol/water (v/v), % fluorinated alcohol refers to % fluorinated alcohol/water (w/w). [c] Calculated from data at other temperatures. [d] Reference 22a. [e] One measurement of rate constant. [f] Triplicate determination. [g] A linear relationship between conductance *p*-toluenesulfonic acid concentration was established at 25 and 50 °C for solutions up to 4×10^{-4} M. [h] Estimated assuming $\Delta H^{\ddagger} = 27$ kcal/mol. [i] Determined in unbuffered solution (ca. 5×10^{-3} M) from data over about 50% reaction. [j] Determined spectrophotometrically from quenched aliquots;[21c] the solution contained 0.05 M $NaOCOCF_3$ and 0.025 M water, and for trifluoroacetolysis of cyclohexyl tosylate we obtained $k = (2.67 \pm 0.17) \times 10^{-4}$ s^{-1} (lit.[2a] 2.7×10^{-4} s^{-1}). [k] Solvent contained 10^{-3} M $NaOCOCH_3$. [l] Reference 22b assuming a brosylate/tosylate rate ratio of 3.0. [m] Reference 22c.

Table IV. Rate Constants for Solvolyses of 1-Adamantylmethylcarbinyl Tosylate (VI) at 25 °C

solvent[a]	k, s^{-1}	$\Delta H^{\ddagger}$, kcal/mol	$\Delta S^{\ddagger}$, eu
80% EtOH[b,c]	7.9×10^{-7}	25.8	−0.1
70% EtOH[b,c]	2.3×10^{-6}	25.1	−0.2
60% EtOH[b,c]	6.7×10^{-6}	23.6	−3.0
50% EtOH[d]	1.8×10^{-5}		
HCO_2H[b]	7.5×10^{-4}		
CH_3CO_2H[b,c]	1.38×10^{-7}	27.8	3.5
97% CF_3CH_2OH[b]	9.7×10^{-5}	20.5	−8.2
97% $(CF_3)_2CHOH$[e,f]	5.4×10^{-3}		
20% $(CH_3)_2CO$[f,g]	1.02×10^{-3}		

[a] % EtOH refers to % ethanol/water (v/v); % fluorinated alcohol refers to % fluorinated alcohol/water (w/w); % $(CH_3)_2CO$ refers to % acetone/water (v/v). [b] Determined by Dr. S. H. Liggero, see also ref 11b. [c] Calculated from data at other temperatures. [d] Estimated from mY plot. [e] Determined spectrophotometrically. [f] Reference 32. [g] Determined conductometrically, using the mesylate and assuming a tosylate/mesylate rate ratio of 1.31–see ref 23a.

eq 5 and the data from Table IV lead to a high-precision fit having a slope close to unity. Correlations for the tertiary system CF_3CCH_3PhOTs also have close to unit slope, but the precision of the correlations is less satisfactory (Table VII). These results strongly support previous arguments that k_c processes should respond very similarly to variations in solvent ionizing power, even if they differ structurally (e.g., secondary and tertiary sys-

(28) (a) Doering, W. von E.; Levitz, M.; Sayigh, A.; Sprecher, M.; Whelan, W. P. *J. Am. Chem. Soc.* **1953**, *75*, 1008. (b) Schleyer, P. v. R.; Nicholas, R. D. *Ibid.* **1961**, *83*, 2700. (c) Raber, D. J.; Bingham, R. C.; Harris, J. M.; Fry, J. L.; Schleyer, P. v. R. *Ibid.* **1970**, *92*, 5977.

(29) (a) Koshy, K. M.; Tidwell, T. T. *J. Am. Chem. Soc.* **1980**, *102*, 1216. (b) Liu, K.-T.; Sheu, C-F. *Tetrahedron Lett.* **1980**, 4091.

Table V. Solvolysis Rate Constants of Tosylates at 25 °C

tosylate	10^5k, s^{-1} H_2O[a]	CH_3OH	CF_3CH_2OH[i]	$(CF_3)_2CHOH$[j]
2-propyl	41.1[b]	0.118[c,d]	0.056	0.11
2-butyl	105	0.146[e]	0.174	1.57
2-pentyl	127		0.155	1.91
3-pentyl	296	0.273[f]	0.624	8.36
4-heptyl	397		0.82	15.5
cyclopentyl	1150	0.985[c,g]	3.18	41.5
cyclohexyl	89.5	0.0159[c]	0.127	2.64
2-*endo*-norbornyl (IV)	26.9	0.0102[c]	0.50	(10.9)[k]
2-*exo*-norbornyl (III)	68500	3.48[c]	434	(17100)[k]
3-methyl-2-butyl	430	0.098[f]		
pinacolyl (II)	279		2.34	105
2-adamantyl (I)	31.5	0.00029[h]	0.14	14.7

[a] Calculated from rate data for the mesylate assuming a tosylate/mesylate rate ratio of 2.1.[2c] [b] Tosylate studied. [c] Reference 23b. [d] Other values 0.106[24a] and 0.127.[24f] [e] Average of 0.131[24b] and 0.161.[24f] [f] Reference 24f. [g] Other study 0.92.[24a] [h] Reference 2b. [i] Table I. [j] Table II. [k] Estimated from data for the mesylate in 97% $(CF_3)_2CHOH/H_2O$ (w/w) using a tosylate/mesylate rate ratio of 0.78[18b] and a factor of 1.6 (see Table II) to correct for change in solvent.

tems).[11a,28b] The similarity of m values suggests that anchimeric assistance is weak or negligible for solvolyses of 2-adamantyl substrates, in agreement with ^{13}C NMR shifts of stable 2-adamantyl cations.[30]

Additional mechanistic tests arise from studies of salt effects. Solvolyses of 1-adamantyl tosylate in ethanol[31] and cyclopentyl brosylate in 90% w/w HFIP/water[15d] show neither common-ion rate depressions nor special salt effects. In accord with these results, rates of solvolyses of 2-adamantyl tosylate (I) in 90% HFIP/water are increased only 10% by the addition of 0.03 M $NaClO_4$ showing the absence of a special salt effect; solvolysis rates of I in 97% HFIP are unaffected (±2%) by addition of 0.008 M NaOTs,[32] and solvolyses in pure HFIP are accelerated rather than depressed by *p*-toluenesulfonic acid.[16e] These results support earlier evidence that 2-adamantyl tosylate solvolyses by rate-determining formation of contact ion pairs without detectable nucleophilic solvent assistance or ion-pair return;[2a] nucleophilic solvation of the ion-pair intermediate might occur after the transition state.[2a]

^{18}O scrambling concurrent with solvolyses of 2-adamantyl benzenesulfonate[33a] does not provide unambiguous evidence for internal ion-pair return during solvolysis, because the same ion-pair intermediates may not be involved in both processes,[4b] or ^{18}O scrambling may occur by a concerted process.[5b] A key argument for absence of internal return during solvolysis is based on rate comparisons in acetic acid and ethanol/water mixtures having the same Y value, i.e., $[k_{EW}/k_{AcOH}]_Y$. We argued[2a] that ion-pair return would be less in ethanol/water than in acetic acid, but that internal return would not occur during pinacolyl solvolyses. Although both these proposals are supported by ^{18}O-scrambling studies,[33] $[k_{EW}/k_{AcOH}]_Y$ ratios are *lower* for 2-adamantyl than for pinacolyl, suggesting the absence of ion-pair return during solvolysis. The mechanism of ^{18}O-scrambling may be such that internal return is overestimated and, even so, the observed rate effects are relatively small. Alternatively if ^{18}O-scrambling is assumed to involve the same ion-pair intermediates as solvolysis, $[k_{EW}/k_{AcOH}]_Y$ ratios corrected for internal return would be significantly lower for 2-adamantyl than for pinacolyl and neophyl solvolyses (see Table IV[2a]); these "corrected" rate constants imply that we *underestimated* nucleophilic solvent assistance for acetolyses.[2b] Acceptance of this alternative assumption leads to a strong argument for the S_N2 (intermediate) mechanism, because many solvolyses of secondary substrates appear to involve both nucleophilic solvent assistance and ^{18}O scrambling.[2b,33]

Products of solvolyses of 2-adamantyl arenesulfonates in ethanol/water are markedly dependent on the leaving group,[34a] consistent with product formation from contact ion pairs. The preference for substitution with retention of configuration[34b] suggests that some products may be derived from solvent separated ion pairs.[34c]

Structural Effects. For 2-adamantyl (I), 1-bicyclo[2.2.2]octyl (VII), and 1-adamantylmethylcarbinyl (VI) tosylates, the relative rates, ca. 1:20:40, are almost independent of solvent (Table VII). In contrast relative rates of solvolyses of 2-adamantyl and 2-propyl tosylates vary 10^5-fold from 134 in HFIP to 0.0011 in ethanol (Table VIII). Satisfactory ρ^* correlations for the unbranched alkyl series (2-propyl–4-heptyl) are obtained (Table VIII).[2c,11b] An alternative parameter for inductive effects of alkyl groups (σ_1)[35b] gives correlations similar to σ^* for the limited series of compounds discussed here. Despite criticisms[35c] of the σ^* scale, there is little difference between correlations using σ^* and σ_1 for these alkyl groups—a slightly improved fit is obtained for correlations between σ_1 and solvolysis rates in HFIP. Sterically hindered substrates (e.g., pinacolyl (II)) deviate from the ρ^* correlations,[2c] except in the weakly nucleophilic solvents (HFIP and CF_3CO_2H).[11b,17a] Both the steric and the electronic effects of the alkyl groups should determine ρ^*, but for the series of unbranched alkyl tosylates steric effects may vary uniformly.

There is increasing electron demand by the cationic center in the series: trifluoroethanol ($\rho^* = -5.2$), trifluoroacetic acid ($\rho^* = -7.3$), HFIP ($\rho^* = -9.1$) (Table VIII). The ρ^* values for these solvents are substantially more negative than those for formolyses ($\rho^* = -3.5$) and acetolyses ($\rho^* = -2.1$), at one time regarded as closely approaching the S_N1 limit.[4f,26b] Even hydrolyses ($\rho^* = -4.3$) show larger substituent effects than formolyses.[2c] On the basis of much supporting evidence, 2-adamantyl tosylate (I) is assumed to react by a S_N1 (limiting) mechanism in all solvents examined.[2a,4b] Variations in the 2-adamantyl/2-propyl rate ratios (Table VIII) are attributed to nucleophilic solvent assistance in solvolyses of 2-propyl tosylate.[2b] Less negative ρ^* values are accompanied by decreasing 2-adamantyl/2-propyl rate ratios—a plot of the logarithms of these ratios vs. ρ^* gives a shallow curve. For solvolyses of the acyclic series, increased nucleophilic solvation of the cationic center decreases the electron demand, reflected in less negative ρ^* values, and accelerates solvolyses in the more nucleophilic solvent relative to solvolyses of 2-adamantyl tosylate. Nucleophilic solvation also accounts for major trends in the α-deuterium kinetic isotope (α-d) effects for solvolyses of 2-propyl sulfonates,[2b] but a more general account of both α- and β-deuterium kinetic isotope effects is needed;[11b,18b] e.g., it is not clear why trifluoroethanolysis of (VI) gives an α-d as low as 1.11,[11b] when limiting solvolyses of 2-adamantyl sulfonates have an α-d of 1.23.[36] (See also later discussion).

Previous *minimum* estimates of nucleophilic solvent assistance were based on the provisional assumption that trifluoroacetolyses of all secondary tosylates were S_N1 (k_c) processes.[2b,11a,37] Solvolyses in HFIP appear to be even closer to the k_c limit than trifluoroacetolyses (Table VIII). An upward revision of earlier estimates[2b] of nucleophilic solvent assistance is required, as well

(30) Farnum, D. G.: Clausen, T. P. *Tetradhedron Lett.* **1981**, 549.
(31) 1-Adamantyl tosylate has been studied in a range of solvents having $Y < 0$—see: (b) Kevill, D. N.; Kolwyck, K. C.; Weitl, F. L. *J. Am. Chem. Soc.* **1970**, *92*, 7300.
(32) We thank Dr. I. Roberts (Swansea) for these results.
(33) (a) Paradisi, C.; Bunnett, J. F. *J. Am. Chem. Soc.* **1981**, *103*, 946. (b) Diaz, A. F.; Lazdins, I.; Winstein S. *Ibid.* **1968**, *90*, 1904.
(34) (a) Harris, J. M.; Becker, A.; Fagan, J. F.; Walden, F. A. *J. Am. Chem. Soc.* **1974**, *96*, 4484. (b) Bone, J. A.; Pritt, J. R.; Whiting, M. C. *J. Chem. Soc. Perkin Trans 2* **1975**, 1447. (c) Raber, D. J.; Harris, J. M.; Hall, R. E. Schleyer, P. v. R. *J. Am. Chem. Soc.* **1971**, *93*, 4821.
(35) (a) Taft, R. W., Jr.; In "Steric Effects in Organic Chemistry"; Newman, M. S., Ed.; Wiley: New York, 1956; Chapter 13, p 591. (b) Taft, R. W.; Levitt, L. S. *J. Org. Chem.* **1977**, *42*, 916. (c) For discussion and leading references see ref 2c, 35b, and 35d. (d) Burden, A. G.; Chapman, N. B.; Shorter, J. S.; Toyne, K. J.; Wilson, L. M. *J. Chem. Soc., Perkin Trans. 2* 1980, 1212. DeTar, D. F. *J. Am. Chem. Soc.* **1980**, *102*, 7988.
(36) (a) Harris, J. M.; Hall, R. E.; Schleyer, P. v. R. *J. Am. Chem. Soc.* **1971**, *93*, 2551. (b) Shiner, V. J., Jr.; Fisher, R. D. *Ibid.* **1971**, *93*, 2553.
(37) Pritt, J. R.; Whiting, M. C. *J. Chem. Soc., Perkin Trans 2* **1975**, 1458.

Table VI. Solvolysis Rate Constants of Tosylates at 25 °C

	10^5k, s^{-1}								
tosylate	CF_3CO_2H	HCO_2H	AcOH	50% EtOH	80% EtOH	EtOH	MeOH	97% T[a]	70% T[a]
cycloheptyl		162[b]	0.255[c]	14.9[d,e]	4.24[d,e]	0.361[f,g]	1.07[f,g,h]	10.5[e,i]	23.3[e,i]
cyclooctyl		4000[j,b]	2.82[k,l]	171[m]	11.7[n]	0.332[f,j]		516[m]	580[m]
2-*exo*-norbornyl	46800[o]	5100[p]	2.33[q]	424[r,s]	23.1[s]	0.446[t,u]	3.48[v]	475[s]	1050[s]
2-*endo*-norbornyl	41.7[o]	3.01[p]	0.0083[f,q]	0.368[d,s]	0.032[s,w]	0.0015[f,t]	0.0102[v]	0.46[i,s]	0.62[i,s]
menthyl			0.0024[f,x]	0.137[e,y]	0.017[e]	0.0017[f,x,z]	0.0067[f,z]	0.44[e]	0.476[e]
3-methyl-2-butyl	175[aa]	27[bb]	0.048[i,bb]	5.0[aa]	0.71[aa]		0.098[v]	1.62[i,cc]	3.55[i,cc]
pinacolyl	409[dd]	31.8[dd]	0.019[dd]	2.02[d,dd]	0.127[d,dd]			2.66[i,cc]	3.55[i,cc]

[a] T refers to trifluoroethanol/water (w/w). [b] Reference 25a. [c] Reference 25b. [d] Calculated from data for the brosylate, assuming a brosylate/tosylate rate ratio of 5.0. [e] Reference 17b. [f] Extrapolated from data at higher temperatures. [g] Reference 24c. [h] Assuming $\Delta H^{\ddagger}$ = 20 kcal/mol. [i] Calculated from data for the brosylate, assuming a brosylate/tosylate rate ratio of 3.0. [j] Reference 20d. [k] Reference 25c. [l] See also ref 20d, 25b, and 25d. [m] Reference 17a. [n] Average of data from ref 17a and 20d. [o] Reference 25e. [p] Reference 23b. [q] Reference 25f. [r] Estimated from mY plot using data for 80%, 70%, and 60% ethanol/water. [s] Reference 17c. [t] Reference 24d. [u] See also ref 23b. [v] Table V. [w] Estimated from mY plot of ethanol/water data. [x] Reference 25g. [y] Average of estimates from an mY plot and from a value of k at 75.7 °C using $\Delta H^{\ddagger}$ = 26.5 kcal/mol. [z] Reference 24e. [aa] Reference 25h. [bb] Reference 25i. [cc] Reference 15c. [dd] Reference 2a, Table III.

Table VII. Results of Correlations (25 °C)[a,b]

	Q' eq 4				mY_{OTs} eq 5			
tosylate	Q'	intercept	std dev in log k	correlatn coeff	m	intercept	std dev in log k	correlatn coeff
2-propyl	0.0 (defined)				0.33 ± 0.12	−0.45 ± 0.30	0.79	0.692
2-butyl[c,d]	0.20 ± 0.03	−0.05 ± 0.06	0.12	0.995	0.47 ± 0.11	−0.42 ± 0.29	0.64	0.838
2-pentyl[c,e,f]	0.27 ± 0.03	−0.11 ± 0.08	0.12	0.996	0.56 ± 0.14	−0.58 ± 0.39	0.70	0.859
3-pentyl[f]	0.30 ± 0.03	0.01 ± 0.07	0.16	0.994	0.53 ± 0.08	−0.28 ± 0.22	0.56	0.915
4-heptyl[c,e,f]	0.47 ± 0.04	−0.16 ± 0.09	0.15	0.995	0.67 ± 0.10	−0.49 ± 0.28	0.51	0.941
cyclopentyl[g,h]	0.30 ± 0.03	0.00 ± 0.06	0.14	0.995	0.51 ± 0.07	−0.28 ± 0.18	0.48	0.926
cyclohexyl[i]	0.44 ± 0.02	−0.01 ± 0.04	0.10	0.998	0.63 ± 0.07	−0.27 ± 0.18	0.47	0.951
cycloheptyl[j]	0.36 ± 0.05	−0.01 ± 0.07	0.17	0.991	0.55 ± 0.08	−0.27 ± 0.13	0.33	0.947
cyclooctyl[j]	0.84 ± 0.04	0.03 ± 0.07	0.13	0.997	0.87 ± 0.02	−0.02 ± 0.03	0.07	0.999
2-*exo*-norbornyl[j,k]	0.74 ± 0.03	−0.01 ± 0.07	0.16	0.996	0.82 ± 0.04	−0.15 ± 0.09	0.23	0.992
2-*endo*-norbornyl[j,k]	0.60 ± 0.05	0.07 ± 0.11	0.26	0.990	0.69 ± 0.02	−0.03 ± 0.05	0.13	0.997
menthyl[j]	0.64 ± 0.09	0.18 ± 0.11	0.26	0.977	0.69 ± 0.07	0.03 ± 0.10	0.25	0.976
3-methyl-2-butyl[j,l]	0.42 ± 0.03	−0.12 ± 0.05	0.11	0.998	0.66 ± 0.07	−0.38 ± 0.17	0.38	0.965
pinacolyl[j,k]	0.76 ± 0.04	−0.04 ± 0.10	0.16	0.996	0.82 ± 0.03	−0.12 ± 0.08	0.15	0.995
2-adamantyl	1.0 (defined)				1.0 (defined)			
1-bicyclo[2.2.2]octyl[m]	1.03 ± 0.03	−0.01 ± 0.05	0.10	0.999	1.04 ± 0.02	−0.01 ± 0.04	0.08	0.999
1-adamantylmethylcarbinyl[n]	1.07 ± 0.04	−0.06 ± 0.08	0.13	0.998	1.05 ± 0.04	−0.03 ± 0.08	0.14	0.997
CF_3CCH_3Ph[o]	1.04 ± 0.01	−0.29 ± 0.20	0.31	0.990	1.06 ± 0.01	−0.32 ± 0.17	0.30	0.991

[a] For the following 11 solvents (unless stated otherwise) 80% ethanol/water (v/v); 50% ethanol/water (v/v); ethanol; acetic acid; formic acid; trifluoroacetic acid; methanol; water; trifluoroethanol *or* 97% trifluoroethanol/water (w/w); 70% trifluoroethanol/water; hexafluoroisopropyl alcohol *or* 97% hexafluoroisopropyl alcohol/water (w/w). [b] Data from Table III of ref 2a (for the first six solvents listed above), from Table II of ref 2b (for 70% trifluoroethanol/water), and from Tables V and VI of this work (unless stated otherwise). [c] Excluding ethanol. [d] Using $k = 8.87 \times 10^{-6}$ s^{-1} for 70% trifluoroethanol/water from ref 15c, assuming a brosylate/tosylate rate ratio of 3.0. [e] Excluding methanol. [f] Excluding 70% trifluoroethanol/water. [g] Using $k = 2.0 \times 10^{-4}$ s^{-1} for 50% ethanol/water from mY plot.[20c] [h] Using $k = 1.09 \times 10^{-4}$ s^{-1} for 70% trifluoroethanol/water from ref 15d, assuming a brosylate/tosylate rate ratio of 3.0. [i] Using $k = 5.07 \times 10^{-6}$ s^{-1} for 70% trifluoroethanol/water from ref 17b. [j] Using the data given in Table VI. [k] Also using additional data for water and hexafluoroisopropyl alcohol from Table V. [l] Also using additional data for water from Table V. [m] Using the data given in Table III except for 90% EtOH. [n] Using the data given in Table IV except for 70 and 60% EtOH. [o] Using data for seven solvents given in ref 29–50% ethanol/water from mY plot.

Table VIII. Structural Effects on Solvolytic Reactivity of Secondary Alkyl Tosylates in Various Solvents

solvent	$k_{2\text{-adamantyl}}/k_{2\text{-propyl}}$	ρ^*[a]
hexafluoroisopropyl alcohol[b]	134	−9.14 ± 0.52
trifluoroacetic acid[c]	36.1	−7.30 ± 0.13
trifluoroethanol[d]	2.50	−5.24 ± 0.32
formic acid[c]	1.11	−3.49 ± 0.27
water[e]	0.75	−4.28 ± 0.05
acetic acid	0.077	−2.10 ± 0.30
80% ethanol/water[c]	0.0082	−1.17 ± 0.41
ethanol	0.0011	

[a] For the series 2-propyl, 2-butyl, 2-pentyl, 3-pentyl, and 4-heptyl; σ^* data from ref 35a. [b] Kinetic data from Table II. [c] Kinetic data from ref 2a. [d] Kinetic data from Table I. [e] Kinetic data from ref 2c.

as a search for solvents with even lower nucleophilicity than HFIP.

Solvent Effects. The solvent effects on the solvolytic reactivities of a secondary tosylate (ROTs) can be correlated by using the three-parameter equation (4). This is a modification of eq 3, designed to accommodate the S_N2–S_N1 ($k_s \rightarrow k_c$) spectrum of secondary and tertiary solvolyses. In eq 4, k refers to the solvolytic rate constant in any solvent, k_0 refers to the rate constant in 80% ethanol/water (v/v), 2-PrOTs refers to 2-propyl tosylate, 2-AdOTs refers to 2-adamantyl tosylate (I), and Q' is an adjustable blending parameter. *Experimental* values of log $(k/k_0)_{2\text{-PrOTs}}$ and log $(k/k_0)_{2\text{-AdOTs}}$ are used in the correlations, and values of Q' for other tosylates (ROTs) are found by least-squares calculation using *experimental* values of log $(k/k_0)_{ROTs}$. Equation 4 thus contains only one adjustable parameter (Q')—the slope of the correlation line is set at unity. In practice we also vary the intercept; i.e., we do not assume that the data (k_0) for the standard solvent (80% ethanol/water (v/v)) fits the correlation better or is more reliable experimentally than the data for the other solvents.

Correlations for a wide variety of simple secondary substrates are shown in Table VII, including comparisons with the simpler equation (5), in which the effects of solvent nucleophilicity (or 2-propyl character) are not allowed for explicitly. Although equations like (5) are usually regarded as having two parameters where only m is adjustable, the intercept is also varied and can be of substantial magnitude (Table VII). In contrast, the intercept

Table IX. Correlations for Cyclohexyl Tosylate[a]

solvent	obsd log $(k/k_0)_{ROTs}$	calcd log $(k/k_0)_{ROTs}$ Q' eq (4)	calcd log $(k/k_0)_{ROTs}$ mY_{OTs} eq (5)
80% EtOH/H_2O	0.00	−0.01	−0.27
50% EtOH/H_2O	1.06	0.95	0.55
EtOH	−1.21	−1.28	−1.37
acetic acid	−1.19	−1.16	−0.65
formic acid	1.72	1.84	1.65
trifluoroacetic acid	2.56	2.53	2.62
methanol	−0.67	−0.64	−0.85
70% trifluoroethanol	0.83	0.94	1.00
water	3.08	3.01	2.33
HFIP	1.55	1.42	2.12
trifluoroethanol	0.23	0.37	0.84

[a] Using parameters given in Table VII.

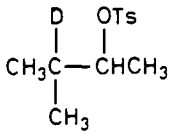
for correlations using eq 4 is generally closer to zero (Table VII). Thus it could be argued that, in practice, eq 4 requires only one adjustable parameter whereas eq 5 requires two adjustable parameters.

One of the least precise correlations using eq 3 was for 2-propyl ($Q \approx 0.5$), a substrate approximately half-way on this logarithmic scale between methyl and 2-adamantyl in its response to a range of solvents.[2b] In contrast data for cyclohexyl tosylate ($Q' \approx 0.5$) are correlated very well by eq 4. Observed and calculated values of log (k/k_0) for cyclohexyl tosylate are in remarkably good agreement, the *maximum* "error" in log k being 0.14 for trifluoroethanol (Table IX). This corresponds to less than a 40% factor in the rate constant and may partly be due to experimental errors in comparisons of data from various sources at different temperatures. Correlations of the same data using eq 5 give far less satisfactory results (Table IX), the most deviant points being those for water, HFIP, and trifluoroethanol. This emphasises the wider range of solvent nucleophilicity and ionizing power in the solvents examined in this study, compared with those employed previously.[2b,13,14] Some of the more common solvents used earlier tended to have a compensating decrease in nucleophilicity with an increase in ionizing power.[38] Only acetic acid with an ionizing power (Y_{OTs}) less than 80% ethanol/water but with a nucleophilicity similar to that of formic acid[2b] was an exception. Our set of solvents now includes water, HFIP, and formic acid, which have similar ionizing powers but widely differing nucleophilicites.[2b]

The mY equation was first proposed over 30 years ago,[13a] and in the meantime there has been a deepening appreciation of the complexity of solvolytic processes. Multicomponent product mixtures have been analyzed,[39a] various ion-pair intermediates have been suggested,[9] salt effects[9] and solvent effects have been examined,[4] differential solvation of initial states of the substrates have been shown to be significant,[39b] activation parameteres ($\Delta H^{\ddagger}$, $\Delta S^{\ddagger}$, $\Delta C_p^{\ddagger}$) and various kinetic isotope effects have been evaluated,[39c] and the position of transition states on the reaction coordinate have been discussed.[40] Therefore, it is all the more remarkable that one or both of the simple equations (4) or (5) correlate solvolytic kinetic data so well (Table VII). While acknowledging the potential complexity of the details of solvolytic processes, it is possible to unify the major features of the correlations using the $k_s \rightarrow k_c$ and $k_\Delta \rightarrow k_c$ mechanistic framework.

Mechanistic Considerations. Equation 4 differs from eq 5 in having a blend of S_N2 character modeled by the log $(k/k_0)_{2\text{-PrOTs}}$ term. The adjustable parameter $(1 - Q')$ indicates the susceptibility of a k_s substrate to nucleophilic solvent participation. When $Q' = 1$ (e.g., 2-adamantyl tosylate), the substrate is not susceptible to nucleophilic attack and, as Q' decreases, susceptibility to nucleophilic attack increases. Comparison of eq 4 with the published equation for calculating minimum estimates of nucleophilic solvent assistance (k_s/k_c ratio)[2b] shows that $(1 - Q')$ is proportional to the logarithm of k_s/k_c ratio. Evaluation of eq 5 provides additional evidence. Equation 5 should fit k_s solvolyses less well than eq 4, and the plots of eq 5 should be characterized by negative intercepts for the following reason. The intercept is the difference between observed and calculated values for 80% ethanol/water, which is more nucleophilic than most of the other solvents.[2b] Consequently a correlation for all solvents will underestimate nucleophilic solvent assistance in 80% ethanol/water leading to a negative intercept for correlations using eq 5. This intercept can be used as a mechanistic criterion in a manner similar to the well established comparisons of rate data in acetic acid and in ethanol/water mixtures having the same Y value, i.e., $[k_{EtOH/H_2O}/k_{AcOH}]_Y$.[2a] Summarizing, eq 4 and eq 5 should fit the $k_s \rightarrow k_c$ and $k_\Delta \rightarrow k_c$ spectrum of mechanisms, respectively. Lower values of Q' (eq 4) or m (eq 5) reflect a lower sensitivity to solvent ionizing power, probably because of greater delocalization of charge in nucleophilically solvent-assisted or anchimerically assisted solvolyses. For the first eight entries (including cycloheptyl) in Table VII, $Q' < 0.5$ and the intercept for correlations using eq 5 is negative (significantly less than zero). Equation 4 correlates the data much better than does eq 5. These eight substrates are susceptible to nucleophilic solvent assistance, confirming previous conclusions based on kinetic[2,17a] and stereochemical evidence.[41] Values of Q' vary significantly suggesting a mechanistic spectrum.[2,26b]

Because of its large β-deuterium isotope effect ($k_H/k_D \approx 2$), 3-methyl-2-butyl tosylate (VIII) is thought to solvolyze by a k_Δ



VIII

process involving a hydride shift, although the lack of substantial rate acceleration is recognised.[17a,42] Surprisingly the k_s–k_c equation (4) fits the solvolytic data for 3-methyl-2-butyl well. In contrast, the k_Δ–k_c equation (5) fits the data for 3-methyl-2-butyl only about the same as for cyclohexyl and cycloheptyl. Our results support previous suggestions that these solvolyses are influenced by solvent nucleophilicity.[17a,25h]

None of the remaining substrates in Table VII gives a correlation for eq 4 significantly better than that for eq 5. All these substrates have $Q' > 0.6$ and, as Q' increases, the significance of the $(1 - Q')$ term becomes more difficult to assess. Therefore, at present we cannot use comparisons between these correlations to distinguish between weakly nucleophilically assisted processes (k_s) and anchimerically assisted processes (k_Δ), and these processes may occur concurrently. The slopes of the correlations for cycloctyl[17a,43] ($m = 0.87$), 2-*exo*-norbornyl[44] ($m = 0.82$), pinacolyl[15c,45] ($m = 0.82$), menthyl[17a,46] ($m = 0.69$), and 2-*endo*-norbornyl[17c,23b,44] ($m = 0.69$) tosylates are significantly lower than the slopes of unity obtained (Table VII) for the models for limiting solvolyses (2-adamantyl, 1-bicyclo[2.2.2]octyl, and 1-adamantylmethylcarbinyl tosylates). We propose that the lower slopes reflect delocalization of charge in the transition state either by nucleophilic solvation of the cationic center or by neighboring group effects. Therefore, solvolyses of substrates with $m < 0.9$ are not good models for k_c processes—they are either k_s, k_Δ, or a combination of the two.

(38) Kaspi, J.; Rappoport, Z. *Tetrahedron Lett.* **1977**, 2035.
(39) (a) Campbell, N. C. G.; Muir, D. M.; Hill, R. R.; Parish, J. H.; Southam, R. M.; Whiting, M. C. *J. Chem. Soc. B* **1968**, 355. (b) Abraham, M. H. *Prog. Phys. Org. Chem.* **1974**, *11*, 1–87. (c) Laughton, P. M.; Robertson, R. E. In "Solute-Solvent Interactions"; Coetzee, J. F., Ritchie, C. D., Eds.; Dekker, New York, 1969; Vol 1, Chapter 7. Kurz, J. L.; Lee, J. *J. Am. Chem. Soc.* **1980**, *102*, 5427.
(40) (a) This aspect of reaction mechanisms has recently been criticized vigourously—see sceptical epilogue of ref 40b. (b) Arnett, E. M.; Reich, R. *J. Am. Chem. Soc.* **1980**, *102*, 5892.
(41) See ref 11–13 of ref 2a.
(42) (a) Winstein, S.; Takahashi, J. *Tetrahedron* **1958**, *2*, 316. (b) Inomoto, Y.; Robertson, R. E.; Sarkis, G. *Can. J. Chem.* **1969**, *47*, 4599.
(43) Parker, W.; Watt, C. I. F. *J. Chem. Soc., Perkin Trans 2* **1975**, 1647.
(44) Winstein, S.; Trifan, D. *J. Am. Chem. Soc.* **1952**, *74*, 1147, 1154.
(45) Ando, T.; Morisaki, H.; *Tetrahedron Lett.* **1979**, *121*.
(46) Hiršl-Starčević, S.; Majerski, Z.; Sunko, D. E. *J. Org. Chem.* **1980**, *45*, 3388.

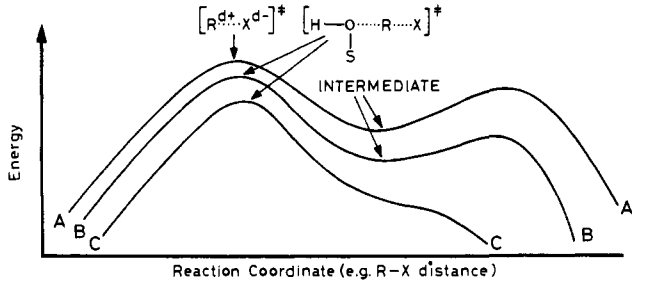


Figure 1. Schematic representation of the upper portion of potential energy surfaces for merging of substitution mechanisms. Nucleophilic assistance decreases from S_N2 (one-stage) mechanism (C) to S_N2 (intermediate) mechanism (B) to S_N1 mechanism (A). Substrate is RX and solvent is SOH. Electrophilic solvation has been excluded. The species shown represent transition states, with and without nucleophilic solvation.

Some of the above conclusions conflict with recent interpretations. Solvolysis of 2-*endo*-norbornyl tosylate (IV) has recently been discussed in detail, and it was argued that the solvolyses were either weak k_s[17c,47] or essentially k_c (limiting).[23b] Our results (Table VII) show a good correlation using eq 4 with an intercept close to zero. The Q' value 0.60 is intermediate between 2-propyl and 2-adamantyl. The precision of the fit for eq 5 is also good, but the m value, 0.69, is considerably less than the value of unity expected from limiting behavior. Such evidence confirms that *endo*-norbornyl tosylate does not solvolyze by an essentially k_c process and is consistent with a weakly assisted k_s mechanism.[44] A modest degree of nucleophilic solvent assistance is also shown by the $[k_{EtOH/H_2O}/k_{RCO_2H}]_Y$ rate ratios; solvolyses of IV in ethanol/water mixtures are about twice as fast as in carboxylic acid solvents having comparable Y_{OTs} values.[17c] As acetic acid is now known to be a relatively nucleophilic solvent,[2b,14b] this criterion of mechanism appears to be less sensitive to nucleophilic solvent assistance than was thought previously. Solvolyses of menthyl and of cyclooctyl tosylates were recently proposed to be k_c processes.[17] However for menthyl tosylate, $[k_{EtOH/H_2O}/k_{CH_3CO_2H}]_Y$ is about three times greater than for 2-adamantyl tosylate and Q' is 0.65, consistent with k_s behavior. Solvolysis of cyclooctyl tosylate appears from deuterium isotope effects to be a k_Δ process with hydride as the migrating species;[43] this conclusion is supported by our correlations (Table VII), which also show a marked contrast between the behavior of cyclooctyl and cycloheptyl sulfonates.

General Implications: The S_N2 (Intermediate) Mechanism. Support for the S_N2 (intermediate) mechanism comes from specific examples in which there is evidence for nucleophilic solvent assistance *and* evidence for ion-pair intermediates.[4b] In addition there is a general argument for this mechanism based on the gradation of reactivity of secondary solvolyses (Table VII), caused by variation in the extent of nucleophilic solvent assistance to heterolysis of the carbon to leaving-group bond.[2a] This leads to a simple merged mechanism (Figure 1), including three mechanistic possibilities: (A) S_N1, transition state leading to intermediate ion pair is not nucleophilically solvated—the intermediate ion pair *may* be nucleophilically solvated; (B) S_N2 (intermediate) via a nucleophilically solvated transition state leading to a nucleophilically solvated ion-pair intermediate; (C) S_N2 (one-stage), nucleophilically assisted, no intermediate formed. Increasing nucleophilic assistance reduces the activation energy for heterolysis (mechanisms B and C, Figure 1) and decreases the relative stability of the intermediate; strongly assisted processes become one stage (mechanism C). Subsequent rapid reactions of the intermediates from mechanisms A and B explains the variety of products,[48] and the variation in kinetic isotope effects for formation of each product.[49] An alternative explanation[49] of these dissected isotope effects requires different rate-limiting steps for formation of each product but, under these circumstances, an equation as simple as eq 4 would not be expected to correlate the rate data satisfactorily. A similar argument can be made against the mechanism of Shiner and co-workers,[7a] who propose *four* different rate-limiting steps to account for the solvolytic reactivity of secondary sulfonates in the range of solvents well correlated by eq 4.

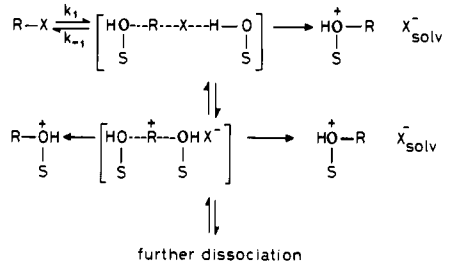


Figure 2. Ion-pair scheme for solvolytic reactions of substrate (RX) including both nucleophilic and electrophilic assistance by solvent (SOH).

In S_N1 reactions nucleophilic attack may be "late" (i.e., it may occur close to or after the first transition state), so nucleophilic assistance is zero but the intermediate is a nucleophilically solvated ion pair.[2a] Product-forming steps from nucleophilically solvated ion-pair intermediates in S_N2 (intermediate) processes should be the same or similar to those from intermediates in S_N1 processes, because they involve very similar cationic intermediates. Such ion pairs may react further by displacement of the leaving group, giving a protonated ether with overall inversion of configuration as in the classical S_N2 process; alternatively they may undergo internal return to starting material or further dissociation to a solvent-separated ion pair leading to substitution with retention or inversion of configuration (Figure 2).[33b,50] The same or very similar nucleophilically solvated ion pairs may react by elimination because the precision of the correlations appears to be independent of the products—e.g., 2-adamantyl sulfonates (I) give mainly substitution;[34] pinacolyl sulfonates (II) give mainly rearrangement;[15c,51] cyclohexyl sulfonates give mainly elimination.[48b] As discussed above, special salt effects or common-ion effects are not observed, so there is no evidence for long-lived intermediates; the lifetimes of ion-pair intermediates may even be insufficient for them to be solvent equilibrated.[5a] This would explain why ion pairs formed by addition to double bonds appear to react differently from those formed by solvolysis.[11b,52] (See also above discussion of ^{18}O scrambling.[33])

Although we propose a spectrum of mechanisms, the relative rates are strongly influenced by the extent of nucleophilic solvent assistance, which appears to be modeled very well by eq 4. Fluorinated alcohols previously appeared to give slightly anomalous results,[2b] but are now correlated well (Table VII). Thus, there is now no indication of significant mechanistic changes (e.g., major shifts in magnitudes of internal ion-pair return) even in these weakly nucleophilic media.

The Possibility of Internal Ion-Pair Return. Shiner et al. showed that trifluoroacetolysis of pinacolyl tosylate (II) did not involve internal return but suggested that 2-propyl sulfonates were retarded several hundred fold by internal return, because the reaction was much slower than trifluoroacetolysis of pinacolyl sulfonates (II).[15c] With use of revised rate constants[2a,11b] and Shiner's original estimate of a rate factor of 10 for differences in inductive/hyperconjugative effects between pinacolyl and 2-propyl solvolyses, a retardation only 16–19-fold due to internal return is predicted for trifluoroacetolysis of 2-propyl sulfonates. Following a detailed analysis of cyclopentyl solvolyses, Shiner accepted that his kinetic schemes could be fitted using an internal return factor of 10.[7a] The linear correlation for trifluoroacetolyses of sulfonates, including 2-propyl, 2-butyl, 3-pentyl, and pinacolyl, suggests that inductive/hyperconjugative effects are much higher than those

(47) Brown, H. C. with comments by Schleyer, P. v. R. "The Non Classical Ion Problem"; Plenum Press: New York, 1977; p 217.
(48) (a) Laureillard, J.; Casadevall, A.; Casadevall, E. *Tetrahedron Lett.*, **1980**, 1731. (b) Lambert, J. B.; Putz, G. J. *J. Am. Chem. Soc.* **1973**, *95*, 6313.
(49) Gregoriou, G. A.; Varveri, F. S. *Tetrahedron Lett.*, **1978**, 287.
(50) (a) Doering, W. von E.; Zeiss, H. H. *J. Am. Chem. Soc.* **1953**, *75*, 4733. (b) Sinnott, M. L.; Jencks, W. P. *Ibid.* **1980**, *102*, 2026.
(51) Bunnett, J. F.; Eck, D. L. *J. Am. Chem. Soc.* **1973**, *95*, 1900.
(52) (a) Chwang, W. K.; Nowlan, V. J.; Tidwell, T. T. *J. Am. Chem. Soc.* **1977**, *99*, 7233. (b) Brown, H. C.; Kawakami, J. H. *Ibid.* **1975**, *97*, 5521.

assumed by Shiner (see also Table VIII).[11b] This would further reduce the rate retardation attributable to internal return.

The correlations using eq 4 and 5 show no unusual deviations for pinacolyl solvolyses, nor for 2-adamantyl solvolyses (Table VII). Therefore, both the major structural and solvent effects on reactivity in secondary solvolyses can be explained quantitatively without postulating appreciable internal return, although small amounts may be present.[2b,11b] Despite the increased precision of our correlations, it is difficult to put a lower limit on the magnitude of internal return (i.e., $k_{-1}/(k_{-1} + k_2)$, Figure 2), because it may be partially accommodated in our correlations by an apparent sensitivity to solvent nucleophilicity: e.g., for solvolyses of *exo*-norbornyl sulfonates (III) known to undergo internal return,[9] polarimetric/titrimetric (k_α/k_t) rate ratios are greater in acetic acid than in the more nucleophilic ethanol/water mixtures—presumably, the k_t rate constants used for our correlations fit eq 4 satisfactorily because both internal return and nucleophilic solvent assistance lead to increased rates in ethanol/water mixtures relative to acetic acid. As before,[2b] we propose that internal return of substantial magnitude (>5-fold effect on k_t) is absent.

Shiner's current interpretation relies heavily on the interpretation of α- and β-deuterium kinetic isotope effects,[7a] particularly the apparently constant α-deuterium effect (α-*d*) of 1.15 for pinacolyl sulfonates (II). We proposed[11b] that α-*d* effects might be more dependent on the structure of the substrate than assumed by Shiner; also trends in α-*d* effects in a range of solvents can be explained by varying amounts of nucleophilic solvent assistance.[2b,36a] Strong support for the latter proposal has recently been obtained. Second-order reactions of (methoxymethoxy)-2,4-dinitrobenzene with nucleophiles in water give α-*d* effects (per deuterium) between 1.05 and 1.16, and water (α-*d* = 1.11) does not appear to react by a different mechanism.[53] These and similar results with α-*d* effects between 0.99 and 1.18 (for different atoms as the nucleophile) were explained by concerted reactions having a "loose" S_N2 transition state with high cationic character.[5b,53] An α-*d* as low as 1.11 has been observed for trifluoroethanolysis of VI,[11b] a good model for k_c reactions (Table VII); these and other results[4b] cast considerable doubt on the utility of α-*d* effects for distinguishing between nucleophilically assisted and nucleophilically unassisted processes.

Other evidence[7c,d] for substitution by nucleophilic attack on preformed ion pairs (not nucleophilically solvated) is also open to criticism. Rates of solvolyses of secondary sulfonates in aqueous dioxan appear to be influenced by micellar effects;[54] the arguments against the earlier interpretation[7d] are now overwhelming.[2a,4b,54] Heat capacity effects[7c] and solvent isotope effects[39c] have proved difficult to fit into a consistent mechanistic framework; e.g., addition of small amounts of ethanol or acetonitrile to water makes only a small change in rates of solvolyses of 1-adamantyl substrates but dramatically reduces $\Delta C_p^{\ddagger}$.[55a] These effects may be greatly influenced by structural properties of solvents and by solvent reorganization.[40b,55]

In Winstein's extended ion-pair scheme (Figure 2), the contact ion pair is often abbreviated as R^+X^-. It appears that this interpretation has sometimes been taken too literally. There is considerable evidence for electrophilic solvent assistance (e.g., by hydrogen bonding),[4b] which is often ignored because it is not usually included in mechanistic classifications. Although Winstein accepted that intimate ion pairs could be formed with nucleophilic solvent assistance,[33b] which is crucial in terms of a S_N2 or S_N1 classification, even nucleophilic solvation was not often included explicitly in mechanistic formulations. *However, he did publish a clear example including such solvation.*[33b] The common practice to omit both nucleophilic and electrophilic solvation from Winstein's ion-pair scheme appears to have led to considerable confusion; both nucleophilic and electrophilic solvent molecules should be considered explicitly (Figure 2).

Both S_N2 (one-stage) and S_N2 (intermediate) mechanisms could be elaborated further by inclusion of a preassociation step,[5] but this may be unnecessary for solvolysis. Substrates should be solvated at the rear (e.g., by dipolar interactions) before reaction begins, and a small barrier (if any) to solvent reorganization resulting in nucleophilic solvent assistance should easily be overcome. A mechanistic alternative involving increasing nucleophilic solvation at the rear, taking place while the carbon-leaving group bond is being broken, may avoid the need to postulate the extraordinarily short-lived cationic intermediates discussed recently by Jencks.[5]

Conclusions

Solvolyses of secondary alkyl sulfonates fit the mechanistic framework outlined previously,[2b,27] i.e., these processes generally are either nucleophilically solvent assisted or anchimerically assisted. The former are part of a S_N2–S_N1 (k_s–k_c) spectrum modeled by eq 4, and the latter are part of a k_Δ–k_c spectrum modeled by eq 5. Exceptional substrates (e.g., 2-adamantyl (I), 1-adamantylmethylcarbinyl (VI), and 1-bicyclo[2.2.2]octyl(VII)) solvolyze by S_N1 mechanisms closely approaching the k_c limit (not assisted nucleophilically or anchimerically). Solvolyses of 2-propyl, 2-butyl, 2-pentyl, 3-pentyl, 4-heptyl, 3-methyl-2-butyl, cyclopentyl, cyclohexyl, and cycloheptyl tosylates are k_s processes (i.e., these substrates are susceptible to nucleophilic solvent assistance[10] and react by S_N2 (one-stage) or S_N2 (intermediate) mechanisms. Other mechanistic assignments, although less clearcut because assistance is weak, are as follows: cyclooctyl (k_Δ), 2-*exo*-norbornyl (III, k_Δ), 2-*endo*-norbornyl (IV, k_s), menthyl (V, k_s), and pinacolyl (II, possibly k_s)—see Table VII.

The extent of nucleophilic solvent assistance for the k_s solvolyses depends on the solvent and increases in the order: hexafluoroisopropyl alcohol, trifluoroacetic acid, trifluoroethanol, formic acid, water, acetic acid, methanol, ethanol. Structural effects on reactivity decrease in the same order, due to decreasing electron demand by the cationic center—see Table VIII. Such *major* structural and solvent effects on the rates of secondary solvolyses demonstrate the variable extents of nucleophilic solvent assistance inherent in the S_N2 (one-stage), S_N2 (intermediate), and S_N1 spectrum of mechanisms (Figure 1), all without appreciable internal ion-pair return (i.e. $k_2/k_{-1} + k_2) \geq 0.2$ or 0.5 in Figure 2). Therefore it does not seem appropriate to explain much smaller kinetic effects (e.g. α- and β-deuterium and solvent kinetic isotope effects, heat capacities of activation, salt effects) using mechanisms in which the role of nucleophilic solvent assistance is ignored.

Nucleophilic solvent assistance is a major determinant of the reactivity and solvation of carbocations, but its importance has frequently been underestimated. Such assistance usually occurs in the same activation step as heterolysis of the carbon–leaving group bond, but the timing may be such that heterolysis is initiated before nucleophilic assistance becomes significant. There may be a small free energy barrier, but probably not a separate barrier, to nucleophilic solvent assistance. It is not necessary, nor reasonable on energetic grounds, to postulate formation of ion-pair intermediates from aliphatic substrates before rate-determining nucleophilic attack occurs.[7]

Experimental Section

Purification of Chemicals. Tosylates and mesylates were prepared and purified as described previously.[2] Trifluoroethanol (Aldrich) was dried by distillation from 3-Å molecular sieves through a triple-pass column (3 × 30 cm), under nitrogen. The fraction distilling between 73 and 74 °C was collected and stored under nitrogen over 3-Å molecular sieves; portions were removed by syringe when required. The water content, determined by means of Karl Fischer titration to be <0.05% w/w, was considered to be acceptable for use in kinetic studies. The solvent is hygroscopic and solvents with greater water content did not give steady conductance readings in the presence of acetamide. Hexafluoroisopropyl alcohol (Fluorochem or Du Pont) was purified as described previously (method B).[18b]

Kinetic Methods. Conductance measurements were made as described previously,[2a] except that the capacity of the cells was about 8 mL. Spectrophotometric measurements were made by continuous monitoring

(53) Craze, G.-A.; Kirby, A. J.; Osborne, R. *J. Chem. Soc., Perkin Trans 2* **1978**, 357.
(54) Mergelsberg, I.; Langhals, H.; Rüchardt, Ch. *Chem. Ber.* **1980**, *113*, 2424.
(55) (a) Mohanty, R. K.; Robertson, R. E. *Can. J. Chem.* **1977**, *55*, 1319. (b) Albery, W. J.; Kreevoy, M. M. *Adv. Phys. Org. Chem.* **1978**, *16*, 87.

at 273 nm using a Pye-Unicam SP1800 UV-visible spectrophotometer with SP874 cell compartment thermostated by water circulated from a Colora NB-DS ultrathermostat. Cells of 1-cm path length fitted with PTFE stoppers were used, and the temperature change between the cell and the water bath was measured by using a calibrated thermistor. The precision of measurements at 25 °C was reduced by changes in room temperature, which were more marked for the longer kinetic runs when overnight operation was required. Typical absorbance changes were from about 0.7-0.2.

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Mechanism of Formation of Grignard Reagents. Rate of Reaction of Cyclopentyl Bromide with a Rotating Disk of Magnesium[1]

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Abstract: Careful studies of the dependence of the rate of reaction (k) of cyclopentyl bromide in diethyl ether with the surface of a rotating magnesium disk as a function of the angular velocity (ω) of the disk confirm the relation $k \propto \omega^{1/2}$ expected for a mass-transfer limited reaction. More limited studies also indicate that the variations in this rate with other parameters are compatible with those expected for a mass-transfer limited reaction: $k \propto (\eta)^{-5/6}(\rho)^{1/6}$ (η is the shear viscosity of the solution and ρ is its density); $k \propto D^{2/3}$ (D is the diffusion coefficient of the alkyl halide).

Introduction

We have suggested that the rate of reaction of cyclopentyl bromide with magnesium in diethyl ether is mass-transfer limited under conditions representative of those used in preparing Grignard reagents.[3-9] The experiments on which this suggestion was based were carried out using a geometry for the magnesium sufficiently complicated that exact analysis of the rate of mass transfer to the magnesium surface as a function of agitation and solution viscosity was impossible.[3,4] Here we describe a parallel but more easily analyzed study of the reaction of cyclopentyl bromide in ethereal solutions at a rotating magnesium disk. The mass transfer characteristics of this system are, in principle, well defined.[10-13] The rate of reaction of a mass-transfer limited process is inversely proportional to the thickness X_D of a diffusional boundary layer whose dependence on disk angular velocity ω (s^{-1}), medium kinematic viscosity η/ρ ($cm^2\ s^{-1}$), and reactant diffusion coefficient D ($cm^2\ s^{-1}$) is described by eq 1.[10,12] For a diffusion-controlled

$$X_D = 1.61 D^{1/3}\omega^{-1/2}(\eta/\rho)^{1/6} \quad (1)$$

process the rate is equal to the flux $\mathbf{j}$ (mol $cm^{-2}\ s^{-1}$) of the reacting material at the disk surface, as described by Fick's first law of diffusion (eq 2). The heterogeneous rate constant k_s is, therefore,

$$\mathbf{j} = -DX_D^{-1}[RBr]_t \quad (2)$$

given by eq 3. Experimentally, the reaction of alkyl halides with

$$k_s = DX_D^{-1} = 0.62 D^{2/3}\omega^{1/2}(\eta/\rho)^{-1/6} \quad (3)$$

magnesium in ethereal solutions is pseudo first order in alkyl halide and pseudo zero order in magnesium (eq 4). Inspection of eq

$$-d[RBr]/dt = k^{obsd}[RBr]_t \quad (4)$$

2-4 reveals that k_s can be calculated from k^{obsd} according to eq 5, where V is the solution volume and A is the apparent area of the magnesium disk.

$$k_s = k^{obsd}VA^{-1} \quad (5)$$

Results

Apparatus-Procedure-Products. Experiments were carried out using the apparatus illustrated in Figure 1. The magnesium disks used for most experiments had radii of 0.79 cm. Only the bottom surface of each disk was exposed; the top and sides were covered with phenolic enamel. The steel brush (C in the diagram) was used to scratch the surface to initiate reaction:[14] the disk was raised

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(3) Rogers, H. R.; Hill, C. L.; Fujiwara, Y.; Rogers, R. J.; Mitchell, H. L.; Whitesides, G. M. *J. Am. Chem. Soc.* **1980**, *102*, 217-226.
(4) Rogers, H. R.; Deutch, J.; Whitesides, G. M. *J. Am. Chem. Soc.* **1980**, *102*, 226-231.
(5) Rogers, H. R.; Rogers, R. J.; Mitchell, H. L.; Whitesides, G. M. *J. Am. Chem. Soc.* **1980**, *102*, 231-238.
(6) Hill, C. L.; Vander Sande, J. B.; Whitesides, G. M. *J. Org. Chem.* **1980**, *45*, 1020-1028.
(7) Lawrence, L. M.; Whitesides, G. M. *J. Am. Chem. Soc.* **1980**, *102*, 2493-2494.
(8) Walborsky, H. M.; Aronoff, M. S. *J. Organomet. Chem.* **1973**, 31-53.
(9) Bodewitz, H. W. H. J.; Schaart, B. J.; Van der Niet, J. D.; Blomberg, C.; Bickelhaupt, F.; den Hollander, J. A. *Tetrahedron* **1978**, *34*, 2523-2527.
(10) Levich, V. G. "Physicochemical Hydrodynamics"; Prentice-Hall: Englewood Cliffs, N.J., 1962; Chapters 2 and 3.
(11) Albery, W. J. "Electrode Kinetics"; Clarendon: Oxford, 1975; Chapter 3.
(12) Adams, R. N. "Electrochemistry at Solid Electrodes"; Marcel Dekker: New York, 1969; Chapter 4.
(13) Riddiford, A. C. *Adv. Electrochem. Electrochem. Eng.* **1966**, *4*, 47-116.

(14) Scratching the magnesium surface in the assembled apparatus provided an effective method of initiating reaction across the entire surface of the disk; the metallurgical factors underlying this initiation are discussed elsewhere.[6] Traces of transition metals have no influence on the rate of formation of Grignard reagents,[3] although they may, in principle, catalyze reaction of preformed Grignard reagent with unreacted alkyl halide (Kochi, J. K. *ACS Symp. Ser.* **1977**, *55*, 167-185, and references cited). We have found no evidence for this type of reaction in the present work.

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