Application of the Ethanol–Trifluoroethanol Method to Solvolyses for Which Nucleophilic Involvement Is Questioned

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Abstract: The ethanol–trifluoroethanol (EtOH–TFE) method is applied to several solvolyses for which the extent of nucleophilic solvent assistance either has not been previously determined or is of sufficient importance and uncertainty as to warrant further investigation. The substrates examined and the mechanistic conclusions reached are as follows: benzyl chlorides (k_s except possibly for the highly activated *p*-methoxy derivative), *tert*-butyl chloride and bromide (rate-determining elimination in trifluoroethanol), cyclooctyl tosylate (a k_c substrate), 3-methyl-2-butyl tosylate (solvolysis by competitive k_s and k_Δ mechanisms), and 3,3-dimethyl-2-butyl tosylate (either a k_c or weak k_s substrate). In addition β-deuterium isotope effects are reported for 3-methyl-2-butyl tosylate solvolysis in 80% ethanol, 97% trifluoroethanol, and 97% 1,1,1,3,3,3-hexafluoro-2-propanol in order to examine the possibility that carbocation destruction may become rate determining in highly ionizing, weakly nucleophilic solvents; it is concluded that this possibility is not realized.

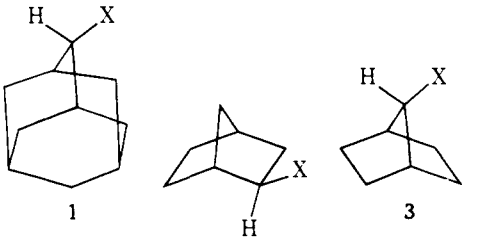
In the previous paper we have described the development of a method, designated the EtOH–TFE method, for the determination of involvement of solvent as a nucleophile or base in the rate-determining step of solvolysis reactions.[2] In the present paper we apply this method to the study of some reactions for which the extent of nucleophilic solvent assistance either has not been previously determined or is of sufficient importance and uncertainty as to warrant further investigation. The substrates we have chosen to examine are a series of substituted benzyl chlorides, *tert*-butyl chloride and bromide, cyclooctyl tosylate, 3-methyl-2-butyl tosylate, and 3,3-dimethyl-2-butyl tosylate.

Results

In Tables I and II are presented the requisite kinetic data for construction of EtOH–TFE plots for the substrates under consideration. In the preceding paper statistical methods were developed whereby the slopes, *y* intercepts, correlation coefficients, and standard deviations of the EtOH–TFE plots could be used to classify a substrate as being of k_s or limiting type. These criteria are presented in Table III, and the data for the substrates considered in the present study are presented in Table IV.

Discussion

Cyclooctyl Tosylate.[3] Recent work[4-7] has shown that nucleophilic solvent assistance is a facile process for most secondary derivatives. Thus, for example, even when neighboring group participation is possible, it must compete with nucleophilic solvent attack if it is to occur. There has been much debate concerning the frequency (or even possibility) of occurrence of reaction of secondary derivatives by a k_c mechanism.[8-22] Reaction by this mechanism has been proposed for the solvolysis of simple acyclic or monocyclic derivatives in solvents of very low nucleophilicity such as trifluoroacetic acid or 1,1,1,3,3,3-hexafluoro-2-propanol;[9-11] reaction by a k_s mechanism is apparently eliminated in these solvents by the low nucleophilicity of the solvent, and the k_Δ mechanism is shown not to operate by the observation that rearrangements of representative carbocations (e.g., 2-butyl or cyclopentyl) under stable-ion conditions involve equilibrating classical species.[12,13] There is also a group of secondary substrates for which the k_s mechanism is disfavored by steric hindrance to nucleophilic attack, **1–4**. However, for these reactions (in contrast to those of simple acyclic and monocyclic derivatives) carbon–carbon σ bond participation is possible and extremely difficult to prove or disprove, so these substrates may react either by a k_c or a k_Δ mechanism.[14-20]



Cyclooctyl tosylate solvolysis is of interest in this context since there are indications that it may be quite unlike the other monocyclic secondary derivatives in that it reacts by a k_c, not a k_s, mechanism in nucleophilic solvents such as acetic acid.[23-25] There is a large amount of transannular hydride shift in the solvolysis of cyclooctyl derivatives (approximately 50% for acetolysis of the brosylate)[24b,26] just as there is in many reactions of medium-ring compounds.[27] In principle, the concerted or nonconcerted nature of this hydride shift should be discernible by study of kinetic deuterium isotope effects. The following effects[8] have been measured for acetolysis: 1.08 for 5,5,6,6-tetradeuteriocyclodecyl tosylate;[23] 1.21 for 3,3,4,4,5,5,6,6,7,7-decadeuteriocyclooctyl tosylate;[24a] and 1.12 for *trans*-5-deuterio-, 1.04 for *cis*-5-deuterio-, and 1.18 for 1-deuteriocyclooctyl brosylate.[24b] The maximum secondary β-deuterium isotope effect has been established by Shiner[28] as being less than 1.5, and values greater than this are probably primary isotope effects. The limiting magnitude of secondary effects for more remote deuteria is not well defined, however. Such effects would, of course, be expected to be small, and several workers have measured negative γ-*d*'s for secondary processes.[30] There also are no well-defined examples of remote primary deuterium isotope effects, but one might expect that

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Table I. Solvolysis Rate Constants of Secondary Alkyl Chlorides and Tosylates

compd	solvent	temp, °C	rate constant, s^{-1}	$\Delta H^{\ddagger}$, kcal/mol	$\Delta S^{\ddagger}$, eu
p-methylbenzyl chloride	80% EtOH	95.3	$4.95 \pm 0.16 \times 10^{-4}$		
		75.7	$1.13 + 0.03 \times 10^{-4}$		
		25.0[a]	1.02×10^{-6}	18.6	−23.7
	70% EtOH	95.3	$1.05 + 0.00 \times 10^{-3}$		
		75.7	$2.37 \pm 0.07 \times 10^{-4}$		
		25.0[a]	2.05×10^{-6}	18.7	−21.8
	60% EtOH	95.3	$2.13 \pm 0.00 \times 10^{-3}$		
		75.7	$5.09 \pm 0.07 \times 10^{-4}$		
		25.0[a]	5.30×10^{-6}	17.8	−22.4
	97% TFE	75.7	$7.95 \pm 0.05 \times 10^{-4}$		
		49.0	$8.81 \pm 0.27 \times 10^{-5}$		
		25.0[a]	8.79×10^{-6}	17.7	−22.2
	85% TFE	75.7	$1.30 \pm 0.01 \times 10^{-3}$		
		49.0	$1.36 \pm 0.01 \times 10^{-4}$		
		25.0[a]	1.28×10^{-5}	18.2	−19.9
	70% TFE	75.7	$2.60 \pm 0.02 \times 10^{-3}$		
		49.0	$2.65 \pm 0.00 \times 10^{-4}$		
		25.0[a]	2.60×10^{-5}	18.4	−17.7
	60% TFE	75.7	$3.55 \pm .0.42 \times 10^{-3}$		
		49.0	$3.78 \pm 0.04 \times 10^{-4}$		
		25.0[a]	3.61×10^{-5}	18.7	−18.3
p-methoxybenzyl chloride	90% EtOH	25.1	$2.33 \pm 0.02 \times 10^{-4}$		
		9.7	$3.71 + 0.04 \times 10^{-5}$		
		−8.6[a]	3.66×10^{-6}	19.4	−10.0
	80% EtOH	25.1	$1.24 \pm 0.01 \times 10^{-3}$		
		9.7	$1.89 \pm 0.01 \times 10^{-4}$		
		−8.6[a]	1.71×10^{-5}	20.0	−4.6
	70% EtOH	25.1	$4.19 \pm 0.03 \times 10^{-3}$		
		9.7	$6.49 \pm 0.20 \times 10^{-4}$		
		−8.6[a]	6.20×10^{-5}	19.7	−3.3
	60% EtOH	25.1	$1.27 \pm 0.01 \times 10^{-2}$		
		9.7	$2.11 \pm 0.03 \times 10^{-3}$		
		−8.6[a]	2.21×10^{-4}	18.9	−3.7
	97% TFE	−14.1	$3.02 \pm 0.12 \times 10^{-3}$		
		−8.6	$6.76 \pm 0.07 \times 10^{-3}$	19.4	0.0
	85% TFE	−14.1	$3.25 \pm 0.07 \times 10^{-3}$		
		−8.6	$8.50 \pm 0.20 \times 10^{-3}$	23.3	0.0
	70% TFE	−14.1	$3.29 \pm 0.18 \times 10^{-3}$		
		−8.6	$1.14 \pm 0.03 \times 10^{-2}$	30.3	0.0
	60% TFE	−14.1	$3.76 \pm 0.17 \times 10^{-3}$		
		−10.0	$1.09 \pm 0.01 \times 10^{-2}$		
		−8.6[a]	1.99×10^{-2}		
3-methyl-2-butyl tosylate	80% EtOH	45.0	$5.39 + 0.08 \times 10^{-5}$		
	60% EtOH	45.0	$2.35 \pm 0.04 \times 10^{-4}$		
	97% TFE	45.0	$1.43 \pm 0.04 \times 10^{-4}$		
	60% TFE	45.0	$4.42 \pm 0.01 \times 10^{-4}$		
cyclooctyl tosylate	80% EtOH	50.0	$2.05 + 0.02 \times 10^{-3}$		
		30.2	$2.38 \pm 0.03 \times 10^{-4}$		
		25.0[a]	1.30×10^{-4}	20.5	−7.6
	70% EtOH	50.0	$4.31 \pm 0.01 \times 10^{-3}$		
		30.2	$5.24 \pm 0.03 \times 10^{-4}$		
		25.0[a]	2.89×10^{-4}	20.1	−7.5
	60% EtOH	25.0	$6.20 \pm 0.18 \times 10^{-4}$		
	50% EtOH	25.0	$1.71 \pm 0.00 \times 10^{-3}$		
	97% TFE	25.0	$5.16 \pm 0.01 \times 10^{-3}$		
	85% TFE	25.0	$5.28 \pm 0.03 \times 10^{-3}$		
	70% TFE	25.0	$5.80 \pm 0.06 \times 10^{-3}$		
	60% TFE	25.0	$6.50 + 0.06 \times 10^{-3}$		
pinacolyl tosylate	85% TFE	55.0	$2.75 \pm 0.06 \times 10^{-3}$		
		30.0	$1.66 \pm 0.01 \times 10^{-4}$		
		25.0[c]	8.98×10^{-5}	21.6	−4.7
	90% EtOH	74.95	$6.79 \pm 0.08 \times 10^{-4}$		
		50.0	$4.57 \pm 0.01 \times 10^{-5}$		
		25.0[c]	1.96×10^{-6}	23.5	−5.8
	70% EtOH	55.0	$7.58 + 0.03 \times 10^{-4}$		
		30.0	$3.54 \pm 0.06 \times 10^{-5}$		
		25.0	1.80×10^{-5}		
	60% EtOH	55.0	$1.62 \pm 0.02 \times 10^{-3}$		
		30.0	$8.36 \pm 0.05 \times 10^{-5}$		
		25.0	4.35×10^{-5}	22.8	−1.9

[a] Calculated from rates at other temperatures. [b] EtOH = aqueous ethanol; TFE = aqueous trifluoroethanol. Ethanols are volume percent, trifluoroethanols are weight percent.

Table II. Solvolysis Rate Constants (−log k) of Alkyl Derivatives in Aqueous Ethanols (E) and Aqueous Trifluoroethanols (T) (at 25 °C Unless Otherwise Noted)

compd	90E	80E	70E	60E	50E	97T	85T	70T	60T	50T
1-adamantyl bromide[a]	7.61	6.29	5.81	5.14	4.54	4.02	3.97	3.75	3.64	3.46
p-methylbenzyl chloride		5.99	5.69	5.28		5.06	4.89	4.59	4.44	
p-methoxybenzyl[b] chloride	5.44	4.77	4.21	3.66		2.17	2.07	1.94	1.70	
tert-butyl chloride[c,d]	5.78	5.03	4.44	3.91	3.38	3.88	3.68[f]	3.37	3.13	2.80[f]
tert-butyl bromide[e,f]	4.18[e]	3.45[e]	2.88[e]	2.42[e]	1.89[e]	2.57[f]	2.31[f]	1.95[f]		
cyclooctyl tosylate		3.89	3.54	3.21	2.77	2.29	2.28	2.24	2.19	
3-methyl-2-butyl tosylate[g]		4.27		3.63		3.84			3.35	
pinacolyl brosylate	5.71	5.20[h]	4.74	4.36	4.00[h]	4.10[h]	4.05	3.97[h]		3.78[h]
p-nitrobenzyl brosylate	4.60	4.37	4.22			6.51[j]		5.25[j]		
p-trifluoromethylbenzyl brosylate	4.27	4.04	3.87				4.90[j,k]	4.65		
benzyl brosylate[i]	3.08	2.76				2.81	2.48[k]			

[a] Reference 1. [b] At −8.6 °C. [c] Reference 39. [d] V. J. Shiner, Jr., W. Dowd, R. D. Fisher, S. R. Hartshorn, M. A. Kessick, L. Milakofsky, and M. W. Rapp, *J. Am. Chem. Soc.*, **91**, 4838 (1969). [e] E. Grunwald and S. Winstein, *ibid.*, **70**, 846 (1948). [f] Reference 38. [g] At 45.0 °C. [h] V. J. Shiner, Jr., R. D. Fisher, and W. Dowd, *J. Am. Chem. Soc.*, **91**, 7748 (1969). [i] V. J. Shiner, Jr., M. W. Rapp, and H. R. Pinnick, Jr., *ibid.*, **92**, 232 (1970); V. J. Shiner, Jr., personal communication. [j] Obtained from the rate constant at 45 °C by dividing by eight. [k] 80% TFE.

Table III. Statistical Criteria

parameter	k_s	limiting
slope	slope (E) < slope (T)	slope (E) = slope (T)
intercept	int (E) < int (T)	int (E) = int (T)
correlation coefficient	R (E) − R (E + T) ≥ 0.30	R (E) − R (E + T) ≤ 0.01
standard deviation	SD (E + T) > SD (E) and > SD (T) and ≥ 0.20	(a) SD (E + T) < SD (E) and < SD (T) or (b) SD (E + T) ≤ 0.10

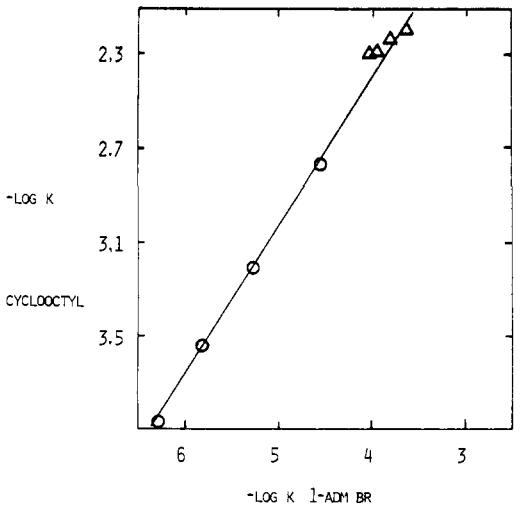


Figure 1. The EtOH-TFE plot for cyclooctyl tosylate. (As for all EtOH-TFE plots in this paper, circles are used to designate aqueous ethanols and triangles are used to designate the aqueous trifluoroethanols.)

kinetic isotope effects for cleavage of a remote carbon-hydrogen bond would be comparable to those observed for β carbon-hydrogen cleavage.[29] These data therefore suggest that the kinetic effects of remote deuterium substitution in cyclooctyl derivatives are secondary effects, and that transannular hydride shifts in cyclooctyl solvolysis occur after rate-limiting ionization. Support for this interpretation comes from the magnitude of the α-d, which at 1.18 is larger than generally observed for k_Δ or k_s processes.[31] On the other hand, the k_H/k_D of 1.12 for the trans-5-deuterium is disturbingly large for a remote secondary effect. Parker and Watt suggested that these data could be accounted for in terms of competitive k_s and k_Δ processes, if the primary effect were 2.0 and the fraction of the reaction proceeding by the anchimerically assisted process were 22%.[24b] However, as we show below, a k_s process is not important for cyclooctyl tosylate solvolysis, so this suggestion can be eliminated. Alternatively, the kinetic effect of the trans-5-deuterium could be the result of a k_Δ process occurring in competition with the k_c process. Such a competition has never been demonstrated, however.

Parker and Watt[24b] also measured the product distribution resulting from deuterium substitution in the 5 position of cyclooctyl tosylate. They observed 40% hydride shift for trans 5-H and 4% hydride shift for trans 5-D (note that in both cases a 1,5-D shift represents a degenerate rearrangement and cannot be detected). The 40% trans-5-H shift and the large trans-5-D kinetic isotope effect are consistent with a k_Δ process. Again, however, the data are inconclusive, since there could be a preference for migration of the trans hydride in a tight ion pair formed in a rate-determining k_c process. Reaction by a k_c pathway is further indicated by the 4% cis hydride migration in the *trans*-5-deuteriocyclooctyl tosylate.

We have applied the EtOH-TFE method to cyclooctyl tosylate solvolysis (Figure 1). Examination of the plot shows a good linear correlation consistent with nucleophilic solvent assistance being very small for this reaction. Application of the statistical criteria supports this conclusion. Adding the TFE points to the ethanol points results in no change in correlation coefficient and only a slight increase in standard deviation. The slope and y-intercept criteria are not applicable since the data fall neither into the k_s nor the lim category. As noted in the previous paper, such a result is not uncommon and is probably due to the small variation in rates for limiting substrates in aqueous TFEs.

To verify that the k_s mechanism is not occurring, the effect of sodium azide on the products of aqueous ethanolysis at 25 °C of cyclooctyl tosylate was determined. A twofold excess of sodium azide (0.04 M) was added to cyclooctyl tosylate (0.02 M) in 70% ethanol containing lutidine (0.022 M). Product analysis by titration and gas chromatography revealed the absence of alkyl azide (<1%), and analysis by gas chromatography showed that the relative amounts of cyclooctene, cyclooctanol, and cyclooctyl ethyl ether were unchanged in the presence of azide. These results are inconsistent with operation of the k_s mechanism.[32] Furthermore, while cyclooctyl tosylate has an m value (0.67) intermediate between values expected for k_s and k_c substrates, its $(k_{EtOH}/k_{AcOH})_Y$ value of 0.40 is consistent with reaction by a limiting mechanism.[9,10]

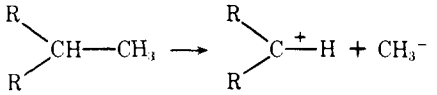
It is important to ask why cyclooctyl tosylate reacts by a limiting mechanism in nucleophilic solvents such as aqueous ethanol when the closely related cyclopentyl, cyclohexyl, and cycloheptyl derivatives do not. We believe that the answer lies

Table IV. Statistical Analyses and Mechanistic Conclusions[a]

compd	criterion	ethanol	TFE	E + T	mechanistic assignment
cyclooctyl tosylate	*n*	4	4	8	
	m	0.62 ± 0.04	0.25 ± 0.04	0.67 ± 0.03	
	b	−0.03 ± 0.19	1.30 ± 0.15	−0.29 ± 0.12	
	R	1.00	0.98	1.00	lim
	SD	0.05	0.01	0.07	lim
tert-butyl chloride	*n*	5	5	10	
	m	0.79 ± 0.06	1.84 ± 0.10	0.64 ± 0.07	k_s
	b	−0.16 ± 0.34	−3.56 ± 0.39	0.86 ± 0.34	k_s
	R	0.99	1.00	0.96	
	SD	0.13	0.05	0.28	k_s
tert-butyl bromide	*n*	5	3	8	
	m	0.75 ± 0.05	2.10 ± 0.55	0.53 ± 0.09	k_s
	b	−1.46 ± 0.31	−5.93 ± 2.15	−0.02 ± 0.49	k_s
	R	0.99	0.97	0.92	
	SD	0.12	0.11	0.33	k_s
p-methoxybenzyl chloride	*n*	4	4	8	
	m	0.72 ± 0.09	1.09 ± 0.21	1.00 ± 0.07	k_s
	b	0.05 ± 0.57	−2.21 ± 0.83	−1.77 ± 0.35	k_s
	R	0.99	0.96	0.99	lim
	SD	0.16	0.07	0.25	k_s
p-methylbenzyl chloride	*n*	3	4	7	
	m	0.62 ± 0.004	1.55 ± 0.15	0.51 ± 0.06	k_s
	b	2.11 ± 0.02	−1.20 ± 0.59	2.78 ± 0.28	k_s
	R	1.00	0.99	0.97	
	SD	0.003	0.05	0.16	
benzyl brosylate	*n*	2	2	4	
	m	0.24	6.60	0.11 ± 0.06	(k_s)
	b	1.24	−23.72	2.19 ± 0.34	(k_s)
	R			0.78	
	SD			0.19	
p-trifluoromethylbenzyl brosylate	*n*	3	2	5	
	m	0.21 ± 0.04	1.14	−0.18 ± 0.11	(k_s)
	b	2.67 ± 0.25	0.39	5.35 ± 0.62	(k_s)
	R	0.98		0.70	
	SD	0.05		0.35	(k_s)
p-nitrobenzyl brosylate	*n*	3	2	5	
	m	0.20 ± 0.03	4.67	−0.41 ± 0.24	(k_s)
	b	3.06 ± 0.19	−12.25	7.23 ± 1.35	(k_s)
	R	0.99		0.70	
	SD	0.04		0.77	(k_s)
3-methyl-2-butyl tosylate	*n*	2	2	4	
	m	0.56	1.29	0.26 ± 0.13	(k_s)
	b	0.77	−1.34	2.51 ± 0.65	(k_s)
	R			0.81	
	SD			0.28	
pinacolyl brosylate	*n*	5	4	9	
	m	0.57 ± 0.05	0.55 ± 0.05	0.46 ± 0.04	lim
	b	1.45 ± 0.28	1.90 ± 0.19	2.15 ± 0.19	lim
	R	0.99	0.99	0.98	lim
	SD	0.11	0.02	0.14	

[a] Where *n* is the number of solvents used in the linear regression analysis, *m* is the slope, *b* is the intercept, *R* is the correlation coefficient, and SD is the standard deviation.

in the effects of strain on ionization. Some years ago Brown suggested that the solvolysis of medium-ring derivatives was accelerated by relief of angle strain (I-strain),[33] but this model was based on the assumption that all secondary cyclic compounds reacted by a simple k_c mechanism, an assumption later found to be incorrect. Changes in strain energies upon ionization can be calculated by the molecular mechanics method developed by Schleyer.[34] In Table V we have given strain energies for several compounds including cyclic systems containing five to eight carbons, and we have given δ strain values for the process shown in eq 1. Suitable hydrocarbon models for



(1)

Table V. Strain Energies Determined by the Schleyer Molecular Mechanics Method[34] for a Series of Carbocations and the Corresponding Hydrocarbon Models for Solvolytic Precursors

R =	strain energies, kcal/mol RCH₃	strain energies, kcal/mol R⁺	δ(strain)
2-propyl	−0.88[a]	0.30	1.18
tert-butyl	−1.43[a]	0.0[b]	1.43
cyclopentyl	6.53	6.85	0.32
cyclohexyl	0.87[a]	2.95	2.08
exo-2-norbornyl	17.05	20.08	3.03
7-norbornyl	18.77[a]	30.79	12.02
2-adamantyl	8.56[a]	9.21	0.65
cyclooctyl	13.86[c]	10.80[d]	−3.06

[a] Reference 34. [b] By definition. [c] Position 2 of boat-chair conformation. [d] Position 3 of boat-chair conformation.

nonhydrocarbon leaving groups are required (the molecular mechanics methods have not been developed to the point where sulfonate groups can be directly treated).[35] In his calculations[34] Schleyer modeled halide and benzoate leaving groups with hydrogen. There is evidence[36] that hydrogen is too small for this purpose and that a methyl group is more sterically similar to an arenesulfonate leaving group; consequently, we have used a methyl group as the group model in the calculations reported here. Of the compounds considered in Table V, the cyclooctyl system is unique in that it is the only system showing a relative relief of strain upon ionization.[37] Thus we conclude that for most acyclic and monocyclic derivatives, simple ionization is disfavored by strain and electronic factors so that reaction by nucleophilic attack dominates. Yet there are certain secondary substrates, such as cyclooctyl tosylate, for which strain factors can shift the balance such that reaction occurs without nucleophilic solvent assistance even when there are no obvious barriers to nucleophilic approach. Relative to the much-debated solvolyses of the secondary derivatives **1-4**, the present work does show that unassisted (by either solvent or neighboring group) ionization is not energetically prohibitive for secondary derivatives, and there is no a priori reason for excluding this process for these compounds.

***tert*-Butyl Chloride and Bromide.**[38] One of organic chemistry's most useful linear free energy relationships has been the Winstein-Grunwald mY relationship, eq 2, for calculation of

$$\log k/k_0 = mY \qquad (2)$$

solvolysis rates in different solvents; in this equation, k is the rate constant for the solvolysis of a substrate in some solvent of ionizing power Y, and k_0 is the rate constant for solvolysis of the substrate in 80% ethanol (for which Y is defined as zero); m is the measure of substrate response to changes in solvent ionizing power.[39] The relationship is based on the solvolysis of *tert*-butyl chloride as a model k_c substrate. However, recent studies have shown that there may be difficulties associated with the use of *tert*-butyl chloride as a model k_c substrate in all solvents. Schleyer and his co-workers[40] plotted the rate constants for *tert*-butyl chloride solvolysis in a larger series of solvents against the corresponding rate constants for the solvolysis of 1-adamantyl bromide, a compound which must react by a k_c mechanism, and found an excellent correlation for all solvents except aqueous trifluoroethanols. Similarly, Sunko and his co-workers[41] found that the solvolyses of several substrates gave abnormally low m values in aqueous TFE.

Shiner has determined the β-deuterium isotope effects for trifluoroethanolysis of *tert*-butyl chloride and has concluded that rate-determining elimination is important in this solvent.[42] Thus it appears that there may be a bimolecular contribution to reaction of *tert*-butyl chloride in some solvents which would reduce the usefulness of the original mY relationship.

To test this idea, we have applied the EtOH-TFE probe to the solvolysis of *tert*-butyl chloride and bromide (Figure 2, Table IV). Typical "k_s plots" are observed! However, as indicated by a variety of other mechanistic criteria,[5,9,10] the *tert*-butyl halides clearly do not solvolyze with nucleophilic solvent assistance. In an earlier paper on this topic[40] it was pointed out that the observed rates for *tert*-butyl chloride in aqueous trifluoroethanol were *slower* than predicted by comparison with 1-adamantyl bromide solvolysis rates. This suggests that in the less aqueous (and therefore less nucleophilic) TFEs solvent attack on the ion pair becomes slower than formation of the ion pair; i.e., ionization occurs at the rate predicted by comparison with 1-adamantyl bromide, but TFE is sufficiently weakly nucleophilic and basic that the solvent capture of the ionization product becomes rate determining. In other words, ion pair return may become important for reactive tertiary halides such as *tert*-butyl chloride and bromide in such nonnucleophilic solvents as the less aqueous TFEs.[9,10,42]

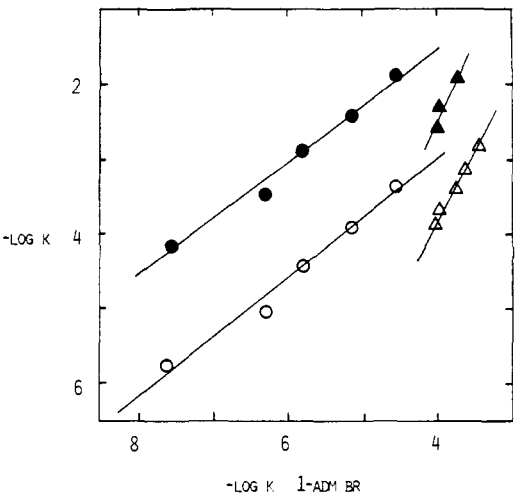


Figure 2. The EtOH-TFE plot for (a) *tert*-butyl bromide (filled symbols) and (b) *tert*-butyl chloride (open symbols).

This "k_s behavior" of the *tert*-butyl halides also indicates that the ethanol-TFE method is subject to limitations and that mechanistic conclusions based on this method should be used in conjunction with other mechanistic criteria.

In view of the mechanistic variability for *tert*-butyl chloride solvolysis, we reemphasize the earlier proposal[40] that solvent Y values be based on a more certain limiting model such as 1-adamantyl bromide[40] or 2-adamantyl tosylate.[10] If Y values from 1-adamantyl bromide solvolysis[40] are used, essentially normal (i.e., comparable to those of similar substrates)[10] m values are found for the substrates Sunko noted[41] as giving low m values with *tert*-butyl chloride Y values; for example, for 7-methyl-7-norbornyl tosylate m = 0.062 (*tert*-butyl chloride Y), m = 0.61 (1-adamantyl bromide Y).

Benzyl Chlorides. The solvolysis of benzyl derivatives, as of other aryl carbinyl derivatives, has long been of interest, primarily because variation of the aryl group results in variation of the stability of the solvolytic transition state.[43] It has frequently been assumed that these reactions are well understood and therefore suitable for use as model reactions to develop various techniques. In particular, the solvolyses of benzyl or arylmethyl compounds have been used for the development of molecular orbital methods[44] and for gaining an understanding of kinetic isotope effects including deuterium,[45] carbon (at the reactive site),[46] chlorine (leaving group),[47] and sulfur (leaving group).[48] Rather than being well understood there is, in fact, serious question concerning the molecularity of the rate-determining step for these solvolyses.

There can be little question that the parent benzyl derivative and those substrates containing deactivating ring substituents react by a k_s mechanism. For example, in Table VI we have presented some of the common measures of nucleophilic solvent assistance for benzyl tosylate and two typical k_s substrates, ethyl and 2-propyl tosylates. As can be seen, the susceptibility to nucleophilic attack of benzyl tosylate is quite comparable to that of 2-propyl tosylate. The difficulty with assigning mechanism for the benzyl series comes in determining the extent of involvement of solvent as nucleophile in the more activated members of the series, and in identifying the particular ion pairs involved.[48,49] We will concentrate on only the former task in the present work.

The solvolysis of ring-substituted benzyl derivatives gives curved Hammett plots[50] typical of those observed when there is a change of mechanism along a series.[51] Okamoto and Brown[50] have interpreted these curved Hammett plots as showing a change from an S_N2 mechanism for the deactivated benzyl compounds to an S_N1 mechanism for the activated compounds. However, this need not be the case. Rather, the

Table VI. Measures of Nucleophilic Involvement in Benzyl Tosylates Solvolysis

substrate	$(k_{EtOH}/k_{AcOH})_Y$	Q^c	α-$k_H/k_D{}^d$	product stereochem
ethyl-OTs	80[a]	0.12	1.02[e]	100% inv[h]
benzyl-OTs	30[a]	0.51	1.074[f]	~98% inv[i]
2-propyl-OTs	7.8[b]	0.48	1.098[g]	100% inv[j]

[a] A. Streitwieser, Jr., "Solvolytic Displacement Reactions", McGraw-Hill, New York, N.Y., 1962, p 64. [b] Reference 6. [c] Reference 10. [d] For brosylates in 80% ethanol, except for ethyl which is in methanol. [e] E. S. Lewis, J. C. Brown, and W. C. Herndon, *Can. J. Chem.*, **39**, 954 (1961). [f] Reference 45. [g] V. J. Shiner, Jr., R. D. Fisher, and W. Dowd, *J. Am. Chem. Soc.*, **91**, 7748 (1969). [h] For 1-butyl-*1-d* *p*-nitrobenzenesulfonate: A. Streitwieser, Jr., and T. D. Walsh, *J. Am. Chem. Soc.*, **87**, 3686 (1965). [i] A. Streitwieser, Jr., and J. Wolfe, *ibid.*, **81**, 4912 (1959). [j] For several secondary derivatives; see ref 4 and 9.

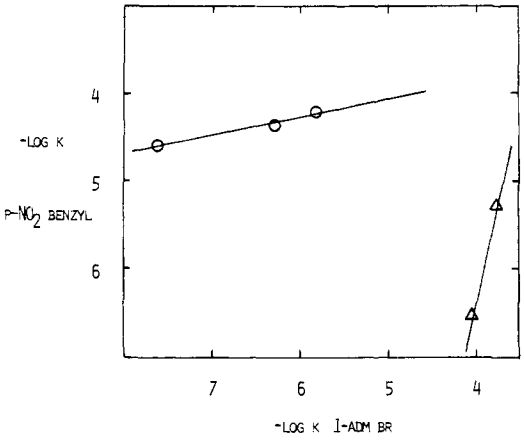


Figure 3. The EtOH-TFE plot for *p*-nitrobenzyl brosylate.

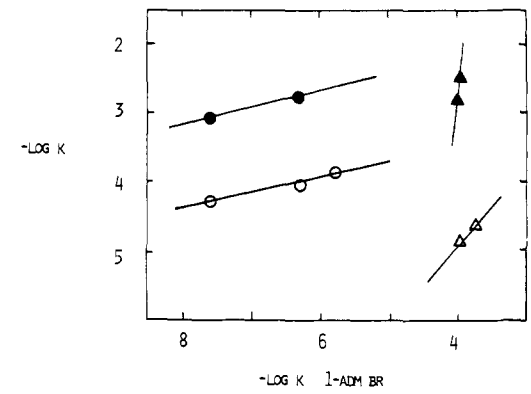


Figure 4. The EtOH-TFE plot for (a) *p*-trifluoromethylbenzyl brosylate (filled symbols) and (b) benzyl brosylate (open symbols).

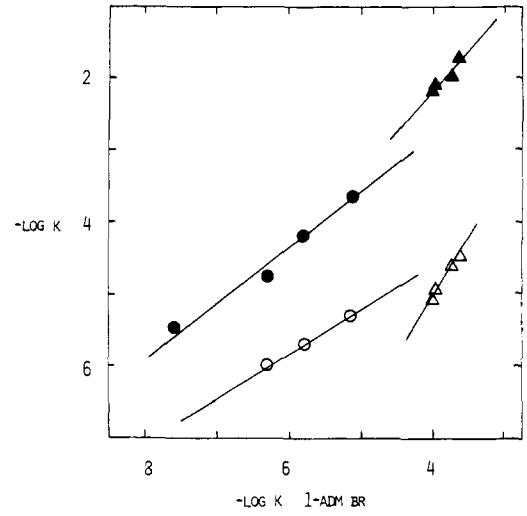


Figure 5. The EtOH-TFE plot for (a) *p*-methylbenzyl chloride (open symbols) and (b) benzyl brosylate (filled symbols).

curved plots could result from an inability of the Hammett equation to linearly correlate reaction by a single reaction (e.g., a k_s mechanism in which k_s/k_c varies); Hammond has suggested that this is the case.[52] Several recent works also support the constancy of mechanism throughout the series. For example, Shiner has studied the α-*d*'s for ring-substituted benzyl brosylates and has found that, although there is a steady increase in α-*d* with increasingly activating substituents, the isotope effects in aqueous ethanols never reach the maximum values expected for a k_c process; such maxima are reached in more limiting aqueous TFEs, however.[45,49] Shiner's results show that, although ion pairs may be involved, nucleophilic solvent assistance in nonlimiting solvents is important even for the activated substrates. Similarly, Thornton[48] has found constant sulfur kinetic isotope effects for ring-substituted benzyldimethylsulfonium tosylates in water, and has interpreted these results, and the earlier chlorine kinetic isotope effects of Fry,[47b] in terms of a constant k_s mechanism.

Application of the EtOH-TFE method to a series of benzyl derivatives is shown in Figures 3-5. As expected, the parent benzyl derivative and the two deactivated compounds clearly are k_s substrates (Table IV). However, even *p*-methylbenzyl chloride appears to solvolyze with weak nucleophilic solvent assistance in the aqueous ethanols, although it lies on the "S_N1" part of the curved Hammett plots;[50] failure of the Hammett equation to linearly correlate substrates reacting by the same mechanism is indicated. Only the highly activated *p*-methoxybenzyl chloride fails to exhibit clear-cut k_s behavior, and the mechanistic assignments in Table IV are conflicting for this derivative. Our method indicates that there is a large variation in the extent of nucleophilic involvement in the transition states for benzyl solvolysis in nucleophilic solvents. The failure of chlorine and sulfur leaving-group kinetic isotope effects[47,48] to respond to this variation, in our opinion, greatly reduces the utility of those methods.

Support for the results of the EtOH-TFE method was obtained by examination of the effects of added azide on the solvolysis of *p*-methyl- and *p*-methoxybenzyl chlorides (Table VII). Application of the equation

$$1 - 1/(\text{rate enhancement from azide}) = \% RN_3/100 \quad (3)$$

to the azide results shows the rate-product correlation expected for a bimolecular reaction.[32] Thus both *p*-methyl- and *p*-methoxybenzyl chlorides appear to react with azide ion by an S_N2 mechanism (although Sneen interprets these same data in terms of an ion-pair mechanism—discussion of the Sneen mechanism and the simple S_N2 alternative is given in ref 32, 54, and 55). While observation of an S_N2 mechanism for reaction with the strong nucleophile azide does not require that reaction with the weak nucleophile water will also take place by an S_N2 mechanism, we believe that these results, taken together with the EtOH-TFE results, clearly demonstrate the importance of nucleophile solvent assistance in the solvolysis of both activated and deactivated benzyl halides.

3-Methyl-2-butyl and 3,3-Dimethyl-2-butyl Tosylate. One of the classic concerns of physical organic chemistry has been to determine the effects of β substitution on the major classes of organic reactions. For the solvolysis of secondary alkyl derivatives this concern has focused on the rate variations along the series 2-propyl, 2-butyl, 3-methyl-2-butyl, and 3,3-dimethyl-2-butyl (pinacolyl), **5**.

Table VII. Rates and Products for the Reaction of *p*-Methoxy- and *p*-Methylbenzyl Chlorides with Sodium Azide

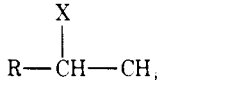
substrate	$[NaN_3]$, M	$k \times 10^4$, s^{-1}	% RN_3 exptl	% RN_3 calcd[a]
p-methyl[b]	0.0	2.37		
	0.02	6.24 ± 0.58	67	62 ± 3
p-methoxy[c]	0.0	2.71		
	0.0198	3.56	29.9	29.8
	0.0312	4.07	40.3	40.2
	0.0399	4.34	46.3	46.3

[a] From eq 3. [b] At 75 °C in 70% ethanol. [c] At 25 °C in 70% acetone: R. A. Sneen and J. W. Larsen, *J. Am. Chem. Soc.*, **91,** 6031 (1969).

Table VIII. Solvolysis Rate Constants for Secondary Tosylates at 25 °C[a]

	$k \times 10^5$, s^{-1}				
ROTs, R =	CF_3C-OOH	97% TFE[c,d]	HCOO-H	AcOH	80% EtOH
2-propyl	2.49	0.0692	2.38	0.0077	0.294
2-butyl	14.6	0.184	5.50	0.0134	0.381
2-pentyl	19.0		5.35	0.011	0.312
3-pentyl	76.8	0.532	14.08	0.0234	0.634
4-heptyl	115		13.2	0.0209	0.447
3-methyl-2-butyl	173[b]	1.62	28.5[c,e]	0.0483[c,e]	0.710[f]
pinacolyl	409	2.66	31.8	0.0191	0.212[c,d]

[a] Unless otherwise noted taken from ref 9, Table III. [b] J. M. Harris, unpublished results. [c] Calculated from the rate for the brosylate assuming a OBs/OTs of three: D. D. Roberts, *J. Org. Chem.*, **37,** 1510 (1972). [d] Reference 49, Table 2-20. [e] S. Winstein and H. Marshall, *J. Am. Chem. Soc.*, **74,** 1120 (1952). [f] Reference 57.

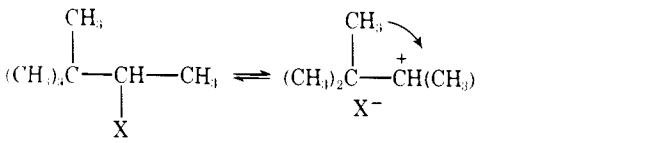


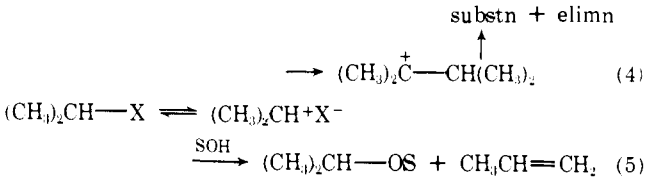
R = Me, Et, *i*-Pr, *t*-Bu

5

In Figure 6 we have presented a plot of rates against the Taft σ^* constants for this series of secondary tosylates in several solvent systems (Table VIII); these constants are generally supposed to provide an evaluation of the ability of substituents to donate electron density to an electron-deficient center, but it should be noted that this interpretation has been challenged.[56] In the present work we are concerned with application of the EtOH-TFE probe to elucidate the patterns evident in Figure 6, but first we must consider previous works pertinent to this task.

Interpretation of Figure 6 is made difficult by changes in mechanism and, potentially, in ion pair return along the series **5**. First we will consider the potential involvement of ion pair return. Shiner has proposed that the faster rate of pinacolyl solvolysis relative to 2-propyl solvolysis is in large part determined by neighboring methyl participation in the pinacolyl derivative effectively eliminating ion pair return, eq 4 and 5.[49]





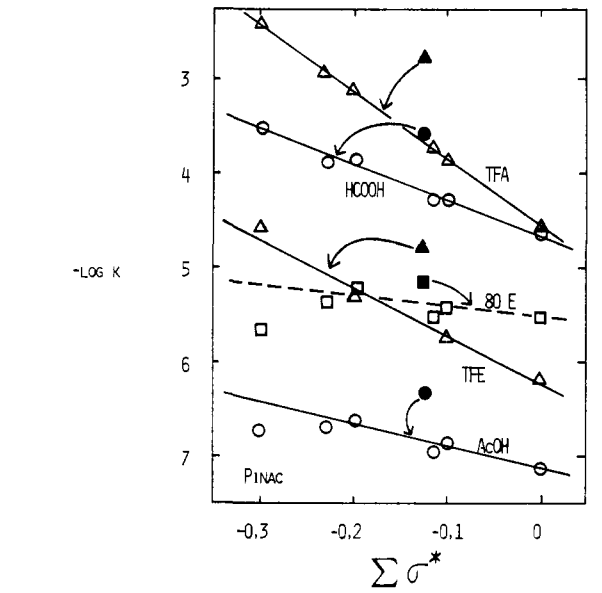
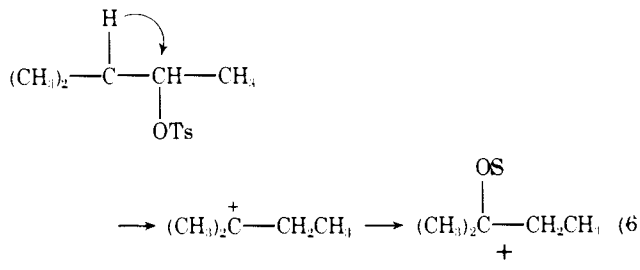


Figure 6. Taft σ^* plots for secondary alkyl tosylates in several solvent systems. The solid points are for 3-methyl-2-butyl tosylate. The arrows indicate the line to which each solid point belongs.

This proposal has been rejected by Schleyer on the basis of the linear σ^* plot (for all but 3-methyl-2-butyl—discussed below) for the secondary series in TFA, and on the basis of 1-adamantyl carbinyl tosylate solvolyzing more rapidly than pinacolyl tosylate in TFA despite the almost total lack of rearrangement in the adamantyl compound.[9,11] According to the Schleyer interpretation the pattern exhibited in Figure 6 (ignoring 3-methyl-2-butyl) can be rationalized by assuming that substitution on **5** is occurring by a k_s process which is retarded by the steric effect and accelerated by the polar effect of the larger alkyl groups; as solvent nucleophilicity is reduced, the steric effect becomes less important, with the result that a linear plot of polar effects (σ^*)[56] against solvolysis rate is observed in trifluoroacetic acid where nucleophilicity is unimportant. This interpretation has been supported by Pross,[57] who observed gradual reductions in k_s/k_c ratios along the series **5** as R becomes larger and as solvent nucleophilicity decreases. Thus it appears that we can discount variations in ion pair return as being a significant factor contributing to the patterns exhibited in Figure 6. Next we will consider changes in mechanism along series **5**.

Although the solvolysis of 2-propyl and 2-butyl and, possibly (below), of pinacolyl tosylates seem best interpreted in terms of a simple k_s process, such is certainly not the case for 3-methyl-2-butyl tosylate. A major component of the solvolysis of 3-methyl-2-butyl tosylate has long been known to be neighboring hydrogen participation, eq 6. That this is the case



is demonstrated by the β-*d*'s for the migrating hydrogen of 2.14, 2.26, and 2.24 in 80% ethanol, acetic acid, and formic acid, respectively;[58] since secondary β-*d*'s are said to be no larger than 1.5, these must be primary isotope effects.[49] A small amount (3%) of unrearranged substitution product is

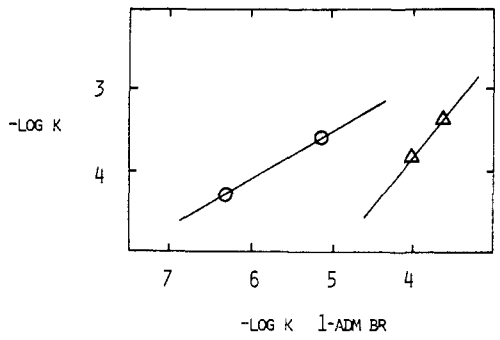


Figure 7. The EtOH-TFE plot for 3-methyl-2-butyl tosylate.

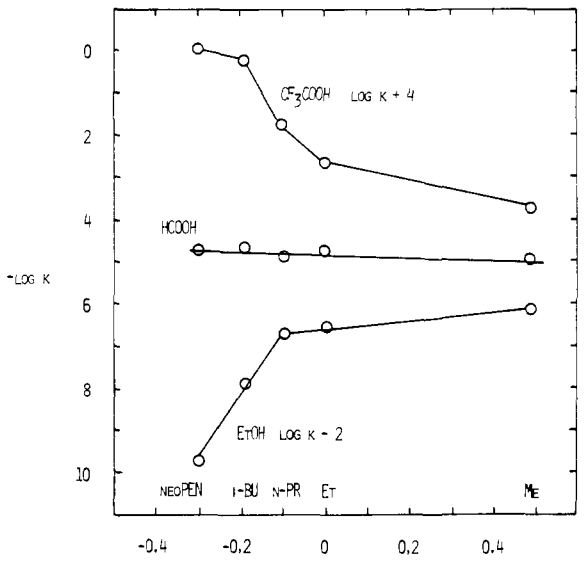


Figure 8. A Taft σ^* plot for a series of primary alkyl tosylates in ethanol, formic acid, and trifluoroacetic acid.[4]

found for acetolysis,[58] indicating that direct nucleophilic displacement is of minor importance. Bimolecular elimination is also implicated by the formation of 4% of 3-methyl-1-butene.[58]

Application of the EtOH-TFE method to the solvolysis of 3-methyl-2-butyl tosylate (Figure 7) indicates that solvent is kinetically involved as a nucleophile in aqueous ethanolysis despite the indications above that such involvement is small. An upper limit to the amount of nucleophilic solvent assistance being detected is provided by the k_s/k_c ratio of 54 for solvolysis of 3-methyl-2-butyl tosylate in 50% ethanol,[57] but these ratios tend to be too large for k_Δ substrates.[2] Thus, although product studies and isotope effect studies indicate essentially limiting behavior for 3-methyl-2-butyl tosylate, the EtOH-TFE method is still able to detect a small amount of nucleophilic solvent assistance in the more nucleophilic solvents. This reinforces the conclusion of the preceding paper[2] that the EtOH-TFE method is capable of detecting nucleophilic solvent assistance when it is only on the order of a single power of ten and perhaps even less.

The solvolysis mechanism of pinacolyl (3,3-dimethyl-2-butyl) derivatives has also been examined extensively, the major question being the importance of neighboring group assistance; acetolysis of the compound does give "largely rearranged" products,[6] so consideration of a k_Δ mechanism is required. Only small γ-deuterium isotope effects are observed, but this has been interpreted as providing support both for and against the intervention of anchimeric assistance.[59] The linear σ^* plot (Figure 6) for secondary trifluoroacetolysis (including pinacolyl) is consistent with solvolysis of pinacolyl without assistance, but it should be noted that this interpretation is not required. For example, similar plots are observed for the solvolysis of primary derivatives (Figure 8), in which there is downward curvature in ethanol but linearity for reaction in the less nucleophilic formic acid. However, for primary derivatives there is competition between k_s and k_Δ processes so that as solvent nucleophilicity decreases, neighboring group assistance becomes increasingly important for branched derivatives; thus upward curvature is observed in trifluoroacetic acid. The point for a single substrate (3-methyl-2-butyl tosylate) in Figure 6 lies above the trifluoroacetolysis line defined by the other alkyls,[13] and this σ^* plot thus reflects the dominance of the k_Δ process over the k_s process for 3-methyl-2-butyl tosylate in this solvent. If neighboring methyl assistance were important for pinacolyl solvolysis then the point for this compound should also be above the line (e.g., as are neopentyl and isobutyl points in Figure 8).

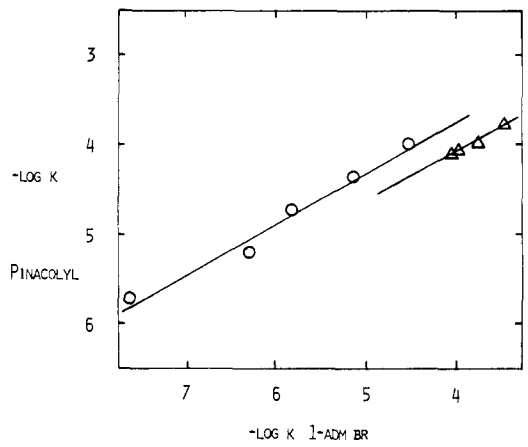


Figure 9. The EtOH-TFE plot for pinacolyl brosylate.

Since pinacolyl solvolyses yield largely rearranged products,[6] the extent of nucleophilic solvent assistance in the solvolysis of this compound must be weak. This interpretation is supported by the observation of the low k_s/k_c ratios for this compound (e.g., $k_s/k_c = 7.9$ in 50% ethanol).[57] In Figure 9 is presented the EtOH-TFE plot for the solvolysis of pinacolyl tosylate. The plot exhibits slightly different correlations for ethanol and trifluoroethanol which would be consistent with the operation of very weak nucleophilic solvent assistance for this reaction. However, statistical analysis (Table IV) of the data reveals that, within experimental error, both lines have the same slope and intercept. Clearly then the EtOH-TFE method is unable to detect any nucleophilic solvent assistance in the reaction of pincolyl tosylate, and we conclude that any such assistance must be small for this compound.

The solvolysis mechanisms of series **5** are now well characterized and interpretation of Figure 9 is therefore possible. The simple secondary alkyls react by a k_s mechanism with the extent of nucleophilic solvent assistance becoming progressively weaker as solvent nucleophilicity[10] decreases. In trifluoroacetic acid this assistance is indicated to be very small.[9,10] 3-Methyl-2-butyl tosylate reacts by competitive k_s and k_Δ mechanisms, resulting in this substrate always being above a line defined by the k_s substrates. Finally, pinacolyl tosylate, being a limiting substrate, lies below the line defined by the k_s substrates in the more nucleophilic solvents, 80% ethanol and acetic acid. In the less nucleophilic solvents the k_s substrates approach a limiting mechanism, so the reactivities of both k_s and k_c substrates should be correlated by σ^*.

Solvolysis in Highly Limiting Solvents. The present utilization of trifluoroethanol provides further justification for the extensive recent interest in the use of highly ionizing, weakly nucleophilic solvents for the study of solvolysis mechanisms. Solvolyses in hexafluoro-2-propanol,[60] trifluoroacetic acid,[9-11,61] fluorosulfuric acid,[63] and sulfuric acid[63] have been

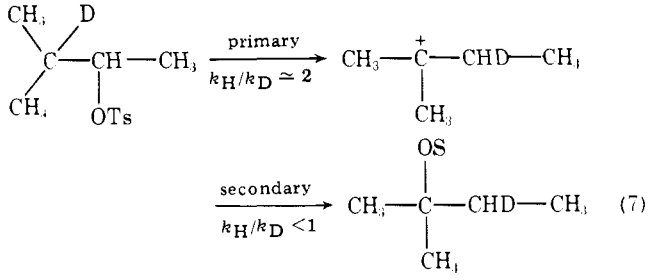
Table IX. Kinetic β-Deuterium Isotope Effects For 3-Deuterio-3-methyl-2-butyl Tosylate

solvent[a]	t, °C	β-k_H/k_D[b]	N[c]	Y[c]
80% ethanol	75	1.681 ± 0.015	0.0	0.0
	45	1.721 ± 0.003		
97% trifluoroethanol	45	1.712 ± 0.062	−2.79	1.83
97% hexafluoro-2-propanol	45	1.731 ± 0.049	−4.27	3.61

[a] 80% ethanol is volume basis, others weight basis. [b] Determined conductometrically and the result of at least three determinations. [c] Reference 10.

of particular interest. One possible difficulty with the use of these solvents is that as the solvent becomes increasingly limiting, a point could be reached where nucleophilic attack on the carbocation intermediate would be slower than carbocation formation. As noted above, Schleyer and his co-workers have considered this possibility and have ruled it out for simple secondary systems.[9-11] Here we consider an alternative test for rate-determining carbocation destruction for 3-methyl-2-butyl tosylate, a substrate not considered by Schleyer and co-workers.

The proposed test can be performed by studying the effects of solvent variation on the deuterium isotope effect of 3-deuterio-3-methyl-2-butyl tosylate solvolysis. As discussed above, this compound solvolyzes to give almost totally rearranged products and large primary β-d's consistent with neighboring hydrogen assistance.[58] We have determined the β-d's for 3-methyl-2-butyl tosylate solvolysis in aqueous ethanol, trifluoroethanol, and hexafluoro-2-propanol (Table IX). If reaction in trifluoroethanol or 1,1,1,3,3,3-hexafluoro-2-propanol continues to involve rate-determining carbocation formation, the β-d will remain large. However, if carbocation destruction becomes rate limiting, the β-d should become a small or even inverse ($k_H/k_D < 1$) secondary effect, eq 7. Ion pair return at



(7)

the stage of the rearranged cation could introduce a perturbation, but the measured isotope effect would nevertheless be a secondary one.

Our results (Table IX) show that the β-d for 3-methyl-2-butyl tosylate solvolysis is the same in trifluoroethanol and hexafluoro-2-propanol as in 80% ethanol. The rate-determining step in each case must be concerted hydride migration and leaving group departure. We conclude that nucleophilic solvent attack on simple alkyl carbocations is a rapid process in solvents of comparable nucleophilicity and ionizing power to hexafluoro-2-propanol.

Experimental Section

The chlorides and arenesulfonates used in this work are well-known compounds which can be purchased or prepared by standard techniques. Physical constants and details of preparation can be obtained from the references given at the beginning of the appropriate section of the text. Rates were determined conductometrically as reported previously,[40] and aqueous ethanols and trifluoroethanols were prepared as previously described.[40] Product analyses for the azide studies (cyclooctyl and benzyl) were preformed by titration.[32,53b] Hexafluoro-2-propanol was washed with base, dried over molecular sieves, and fractionally distilled. 3-Deuterio-3-methyl-2-butanol was prepared by reaction of 2-methyl-2-butene (Aldrich) with BD_3.[65] The NMR spectrum of this compound indicated that there was greater than 90% D per molecule.

Acknowledgment is made to the donors of the Petroleum Research Fund, administered by the American Chemical Society, for partial support of this research.

References and Notes

(1) (a) University of Alabama in Huntsville: (b) University of South Florida.
(2) D. J. Raber, W. C. Neal, Jr., M. D. Dukes, J. M. Harris, and D. L. Mount, *J. Am. Chem. Soc.*, preceding paper in this issue.
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Photoreactions of Charged Benzophenone with Amphiphiles in Micelles and Multicomponent Aggregates as Conformational Probes

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Abstract: Photolysis of mixed micelles composed of sodium dodecyl sulfates (SDS) and benzophenone-4-carboxylate leads to insertion of the benzophenone carbonyl into the SDS chain. Degradative methods are described by which the distribution of functionalization positions can be determined. The data show that attack occurs over almost the entire chain, from C-5 to C-11; with the same benzophenone probe and sodium hexadecyl sulfate attack occurs from C-5 to C-15. The random distribution suggests extensive coiling and folding of the detergent chains. Photolysis of hexadecyltrimethylammonium bromide (CTAB) with benzophenone-4-trimethylenetrimethylammonium bromide confirms this picture. Photolysis of CTAB with benzophenone-4-butyrate below the critical micelle concentration leads to highly selective attack at C-15 ascribed to ion pairs or clusters, while in the concentration region for micelle formation it becomes more random. The reaction of CTAB at micellar concentrations with benzophenone-4-carboxylate, -propionate, -butyrate, and -pentanoate shows that attack on C-15 of CTAB, at the end of the chain, *decreases* as the probe is lengthened. This remarkable finding also suggests folding of the detergent chain. The distribution is characterized by a new parameter, R_f. Studies of this parameter as a function of concentration and with added sterol or dodecanol confirm many of the previous pictures of micellar structures, but show that these structures are not rigid enough to lead to synthetically useful selective reaction.

Introduction

Some years ago we developed the use of benzophenone photochemistry for the selective functionalization of steroids.[1] This then led to the selective halogenation of steroids by the use of rigid free-radical reagents or templates.[2] Although such processes can be quite attractive and synthetically useful, they depend on the rigidity of both the reagent and the steroid substrate in order that significant geometric control of the chemistry ensue. With flexible substrates the attack by the attached benzophenone or phenyliodine dichloride reagents is quite nonspecific.[3] Conformational information, but not useful synthetic transformations, can be obtained.

We decided to explore the selectivity of such reactions for flexible substrates incorporated in micelles. In simple micelles physical studies[4] indicate that the chains are "liquid-like", but this could still allow some ordering relative to flexible chains in solution. Furthermore, at high concentrations amphiphiles can undergo transitions to new phases with considerable ordering of the chains, resembling bilayers.[5] Thus our studies promised to supply information on the amount of ordering attained. It was also possible that synthetically useful selectivity could be achieved if sufficient orientation were present.

As flexible substrates which can form micelles, we have studied cetyltrimethylammonium bromide (CTAB, **1**), sodium cetyl sulfate (CTS, **2**), and sodium dodecyl sulfate (SDS, **3**). The critical micelle concentrations[6] of **1**, **2**, and **3** in H_2O at 25°C are respectively 0.001, 0.0004 (at 35°C), and 0.008 M. As probes or reagents we have used a series of benzophenone carboxylates, including benzophenone-4-carboxylate (**4**), benzophenone-4-acetate (**5**), benzophenone-4-propionate (**6**), benzophenone-4-butyrate (**7**), and benzophenone-4-heptanoate (**8**). Cationic benzophenone-4-trimethylene-*N*-trimethylammonium (**9**) was also used. In addition, 4′-propylbenzophenone-4-carboxylate (**10**), 4′-cyclohexylbenzophenone-4-carboxylate (**11**), and the benzophenone derivative of cyclohex-

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