

Solvolysis Rates and Deuterium Isotope Effects in 2,2,2-Trifluoroethanol–Water Mixtures

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Abstract: 2,2,2-Trifluoroethanol (TFE)–water is a convenient solvent for the precise conductometric measurement of solvolysis rates. A comparison of results in TFE–water with those in ethanol–water gives a useful indication of the role of changing nucleophilicity in solvolysis reactions. It has been found that the α - and β -deuterium effects in 1-phenylethyl chloride, which in ethanol–water are at or near a maximum characteristic of a limiting reaction, are not much changed in TFE–water. However, for *t*-butyl- d_9 chloride the isotope effects are larger in TFE solutions than in ethanol–water. This is explained on the basis of the incursion of some rate-determining elimination from an ion pair in the TFE solvents. *p*-Methylbenzyl- α - d_2 chloride, and isopropyl- α - d (and - β - d_6) *p*-bromobenzenesulfonates also show larger effects in TFE–water solvents than in ethanol–water. These results are interpreted in terms of some nucleophilic attack of solvent molecules occurring in the rate-determining steps in the ethanol–water solvents.

In studying the mechanisms of nucleophilic solvolytic substitution, measurements previously have been made of the rate effects of α - and β -deuterium substitution using precise conductance methods in ethanol–water solvent mixtures.^{1–3} We felt it would be useful in making mechanistic interpretations if such measurements could be extended to include results in a solvent system of appreciably smaller nucleophilicity. Formic acid and acetic acid have traditionally been used as relatively nonnucleophilic solvents for mechanistic studies of solvolysis, but because of their acidity they show too much dissociation, in mixtures with water, for the conductance method to be useful for the accurate measurement of solvolysis rates. The conventional methods of rate measurement in these solvents also appeared not to be capable of the accuracy we believed necessary for the isotope effects to yield really useful mechanistic information. Our attention was therefore drawn to 2,2,2-trifluoroethanol, which to our knowledge, had first been used for solvolysis studies by Scott.⁴ He reported the low specific conductance of this solvent, and its ability to support dissociation of a salt, potassium chloride. He also reported that *t*-butyl bromide solvolyzed about seven times faster in 2,2,2-trifluoroethanol than in 80 vol % ethanol and that while the solvolysis was reversible in the pure solvent it went to completion if small amounts of water were present; in small proportions added water accelerated the solvolysis rate only slightly.

Ballinger and Long⁵ reported the most recent measurements of the dissociation constant of trifluoroethanol in water and Mukherjee and Grunwald⁶ have determined the dielectric constant. After our work had started Murto and Heino⁷ reported data on the densities, partial molar volumes, viscosities, and dielectric constants of trifluoroethanol–water mixtures.

(1) B. L. Murr, Jr., and V. J. Shiner, Jr., *J. Am. Chem. Soc.*, **84**, 4672 (1962).

(2) V. J. Shiner, Jr., B. L. Murr, and G. Heinemann, *ibid.*, **85**, 2413 (1963).

(3) V. J. Shiner, Jr., W. E. Buddenbaum, B. L. Murr, and G. Lamaty, *ibid.*, **90**, 418 (1968).

(4) F. L. Scott, *Chem. Ind. (London)*, 224 (1959).

(5) P. Ballinger and F. A. Long, *J. Am. Chem. Soc.*, **81**, 1050 (1959).

(6) J. Mukherjee and E. Grunwald, *J. Phys. Chem.*, **62**, 1311 (1958).

(7) J. Murto and E.-L. Heino, *Suomen Kemistilehti*, **39B**, 263 (1966).

Recently Trahanovsky and Doyle⁸ have found that 2,2,2-trifluoroethanolysis of 5 hexenyl *p*-nitrobenzenesulfonates gives very high yields of cyclization products, consistent with its good ionizing ability and very low nucleophilicity.

Results

Trifluoroethanol. Table I summarizes some physical constants for trifluoroethanol, ethanol, and water. The specific resistances are those obtained in routine solvent preparations in the present work and do not necessarily correspond to that of the pure solvents alone. Nevertheless, the high specific resistance of the aqueous solutions indicates little ionization, consistent with the measured pK_a value. Solvent dissociation to the extent of about 10^{-6} *M* is not extensive enough to interfere with conductometric measurement of solvolysis reaction rates which produce strong acid and are measured in the range 10^{-4} to 10^{-3} *M*.

Table I. Comparison of Some Physical Constants of 2,2,2-Trifluoroethanol (TFE) with Corresponding Values for Ethanol and Water

	TFE	Ethanol	Water
Boiling point, 760 torr, deg	73.5	78.5	100
Dielectric constant (25°C) ^a	26.5	25.0	78
Specific resistance, ohms	2×10^8	1×10^9	1×10^7
With 3% H ₂ O	3×10^7		
With 30% H ₂ O	7×10^8		
pK_a^b	12.37	16.0	15.8

^a Reference 6. ^b Reference 5.

The trifluoroethanol purification procedure which we have used involves preliminary fractional distillation from aqueous bicarbonate solution yielding solvent containing from 0.1 to 0.3 % by weight of water. This material is then redistilled from sufficient phosphorus pentoxide to react with about 0.5 % water. This second distillate was found by Karl Fischer titration to contain less than 0.03 wt % of water. It is collected during the

(8) W. S. Trahanovsky and M. P. Doyle, *Tetrahedron Letters*, 2155 (1968).

distillation in a small conductance cell and only fractions showing specific resistance greater than 2×10^8 ohms are retained for kinetic studies; usually about 80% of the distillate is satisfactory by this criterion. Pot residues, foreshots, and spent kinetic reaction mixtures can all be recycled in the purification procedure without deterioration of product quality, so losses are minimal.

Conductance parameters have been measured for hydrogen chloride and for *p*-bromobenzenesulfonic acid in various trifluoroethanol-water mixtures. These were found to follow satisfactorily the limiting conductance law in the concentration range below about 2×10^{-3} M for solvents containing 3% or more of water. Strong nonlimiting behavior was observed in pure trifluoroethanol apparently because it is not basic enough to ionize the acids. The conductance parameters are given in Table II.

Table II. Conductance Parameters in 2,2,2-Trifluoroethanol-Water Mixtures

Hydrogen Chloride at 25°				
Wt % H ₂ O	Λ_0	S_α		
3	32.13	100.0		
6	35.6	95.0		
10	42.4	93.2		
20	64.1	90.2		
30	79.8	89.0		
40	106.8	84.0		
100 ^a	426.2	157.6		
<i>p</i> -Bromobenzenesulfonic Acid				
Wt % H ₂ O	Λ_0 (25°)	S_α (25°)	Λ_0 (45°)	S_α (45°)
3	31.79	122.0	50.5	230.0
10	41.05	112.5	64.8	201.9
20	54.70	100.8	85.5	195.0
30	78.17	71.6	118.6	155.0
50 ^b	145.0	33.3		

^a Reference 1. ^b Values obtained by "kinetic" method. All other values obtained by gravimetric method (see Experimental Section).

***t*-Butyl Chloride.** The rates of solvolysis of *t*-butyl chloride were measured in various trifluoroethanol-water mixtures using the conductometric procedure published earlier.¹ The rate constants and derived *Y* values⁹ are given in Table III. The solvolysis rate con-

Table III. Rate of *t*-BuCl Solvolysis in TFE-H₂O and *Y* Values,^a 25°

Wt % H ₂ O	$k, 10^{-4} \text{ sec}^{-1}$	<i>Y</i>
0 ^b	1.04 ^b	1.045 ^b
3	1.319	1.148
6	1.422	1.181
10	1.648	1.245
20	2.713	1.461
30	4.271	1.659
40	7.347	1.894
50	15.70	2.229
60 ^b	36.8 ^b	2.60 ^b

^a *Y* values based on k value of 9.376×10^{-6} for 80 vol % EtOH-20% vol H₂O. ^b In these experiments the rates were measured by following the change in nmr peak intensities with time.

(9) S. Winstein, A. H. Fainberg, and E. Grunwald, *J. Am. Chem. Soc.*, **79**, 4146 (1957).

stant for *t*-butyl chloride in 80 vol % ethanol, $9.376 \times 10^{-6} \text{ sec}^{-1}$, measured earlier¹ was used in the calculation of *Y*. The rates, measured in a cell with a volume of about 80 ml, were reproducible to within about $\pm 0.3\%$. With a larger cell similar to that used in the studies with ethanol solvent, similar reproducibility, around $\pm 0.03\%$, could probably be obtained.

Table IV lists the *Y* values of some other commonly used pure solvents and 2,2,2-trifluoroethanol which is seen to fit nicely into an otherwise large gap in the series between methanol and formic acid. Trifluoroethanol-water (97:3, wt %) has a *Y* value (1.148) conveniently close to that for 60 vol % ethanol (1.124), while 70% trifluoroethanol and 50 vol % ethanol have very similar *Y* values, 1.659 and 1.655, respectively.

Table IV. *Y* Values of Pure Solvents^a

Water	3.493
Formic acid	2.054
2,2,2-Trifluoroethanol	1.045
Methanol	-1.09
Acetic acid	-1.639
Ethanol	-2.03

^a Except for trifluoroethanol, these are taken from A. H. Fainberg and S. Winstein, *J. Am. Chem. Soc.*, **78**, 2770 (1956).

In another set of experiments the product ratios for the *t*-butyl chloride solvolyses were determined by nmr measurements. It was found that the products were not normally stable to the reaction conditions but were stable in the presence of 0.1 M pyridine. The rates, measured by the nmr method, were not appreciably changed by the addition of pyridine at this concentration. The product yields are given in Table V. The last column shows that water is two to three times as effective, on a molar basis, as trifluoroethanol in forming substitution product.

Table V. Products of Solvolysis of *t*-Butyl Chloride in 2,2,2-Trifluoroethanol-Water Mixtures, 25°

Wt % H ₂ O	% isobutene	% <i>t</i> -butyl trifluoroethyl ether	% <i>t</i> -butyl alcohol	k_a/k_e^a
1	33.0	56.0	10.0	3.2
3	30.4	45.6	24.0	3.1
6	28.7	41.8	29.5	2.0
9	27.4	35.8	36.7	2.0
20	21.5	19.9	58.6	2.1
30	17.5	14.5	68.0	2.0
40	14.3	9.4	76.2	2.2
60	4.0	0	96.0	...

^a Molar reactivity ratio of water and trifluoroethanol in forming their respective substitution products.

The β -deuterium isotope effects in *t*-butyl chloride solvolysis have also been measured. These are included in Table VI with other values from the literature for purposes of comparison. Frisone and Thornton¹⁰ have argued that the slightly smaller isotope effect in the acetic acid-formic acid mixture and the slightly larger effect in the pyridine-water mixture over that for the ethanol-water solvent of the same *Y* value (see Table

(10) G. J. Frisone and E. R. Thornton, *ibid.*, **90**, 1211 (1968).

VI) reflected the increasing strength of binding of the nucleophiles pyridine, water, and carboxylic acid in the transition state as predicted from the "parallel effect."

Table VI. Isotope Effects on Solvolysis of *t*-Butyl- d_9 Chloride

Solvent and Composition	k_H/k_{D_9}	Y_{73}	Olefin fraction
97 wt % trifluoroethanol-H ₂ O	2.616	1.148	0.30
70 wt % trifluoroethanol-H ₂ O	2.493	1.659	0.17
60 vol % ethanol-H ₂ O ^a	2.405	1.124	
54 vol % ethanol-H ₂ O ^b	2.35 ± 0.03	1.431	0.083
50 vol % ethanol-H ₂ O ^c	2.386	1.655	
51 vol % pyridine-H ₂ O ^b	2.46 ± 0.03	1.43	0.128
29 vol % acetic acid ^b -71 % formic acid	2.30 ± 0.05	1.43	0.118

^a Reference 2. ^b Reference 10. ^c L. Hakka, A. Queen, and R. E. Robertson, *J. Am. Chem. Soc.*, **87**, 161 (1965).

It is seen in Table VI that the β -deuterium isotope effects are larger in trifluoroethanol-water than in ethanol-water mixtures of similar Y value. This trend with respect to nucleophilicity is *opposite* to that observed by Frisone and Thornton. These results, however, do not necessarily conflict with the earlier authors' interpretation because in the present comparison the olefin fractions are much larger in trifluoroethanol, whereas they were nearly the same in all of the solvents compared in the earlier work. The fact that the olefin fraction is larger in our less nucleophilic solvent rules out any significant E2 contribution but is consistent with the observations of Cocivera and Winstein¹¹ who found much larger yields of isobutene from solvolysis of *t*-butyl chloride in ethanol or acetic acid than in water; in the first two solvents (but not in water) the olefin yield also decreased markedly with leaving group in the order: Cl > Br > I > SMe₂. This behavior was attributed to proton loss in the elimination in ethanol and acetic acid, occurring in large part from an ion pair rather than from the free carbonium ion of the classical E1 mechanism. The fact that the larger olefin fraction in trifluoroethanol solvent is accompanied by a larger β -deuterium effect strongly suggests that elimination from an ion pair in this solvent may be rate determining and therefore, that an important reaction of these ion pairs is recombination to form starting material. It is known from product yields that elimination of β -deuterium in a carbonium ion intermediate is slower than hydrogen elimination by a factor of about 2.^{12,10} The larger isotope effects in trifluoroethanol solvolysis can be explained quantitatively on the basis of rate-determining elimination competing with another process leading to substitution product at a *reversibly formed* ion-pair stage with the assumption of reasonable isotope effects on the ion-pair equilibrium ($k_H/k_{D_9} \sim 2.4$), the elimination ($k_H/k_{D_9} \sim 1.7$), and the competing process leading to substitution ($k_H/k_{D_9} \sim 1.0$). This would be an important conclusion because there is no other direct evidence for a large amount of ion-pair return in the solvolysis of *t*-butyl chloride. It must be stressed that there are other possible interpretations for the larger isotope effects in the solvolysis of *t*-butyl- d_9 chloride in trifluoroethanol and that the one based on ion-pair return and rate-determining elimination is not yet conclusively es-

(11) M. Cocivera and S. Winstein, *J. Am. Chem. Soc.*, **85**, 1702 (1963).
 (12) V. J. Shiner, Jr., *ibid.*, **75**, 2925 (1953).

tablished. Additional experiments designed to confirm or eliminate this explanation are currently in progress.

1-Phenylethyl Chloride. The α - and β -deuterium effects on the rate of solvolysis of 1-phenylethyl chloride in a trifluoroethanol-water solvent have also been measured. These are of special interest since extensive correlations of effects in this and a number of related ring-substituted compounds have been made earlier.³ The results together with some of the effects already reported³ are listed in Table VII. In the earlier work it

Table VII. Isotope Effects in Solvolysis of 1-Phenylethyl Chloride, 25°

Solvent	$k_H, 10^{-5} \text{ sec}^{-1}$	$k_H/k_{\alpha-D}$	$k_H/k_{\beta-D_3}$
80 vol % ethanol-H ₂ O ^a	1.0019	1.146	1.223
70 vol % ethanol-H ₂ O ^a	3.4403	1.149	1.225
60 vol % ethanol-H ₂ O ^a	10.865	1.151	1.226
50 vol % ethanol-H ₂ O ^a	36.20	1.153	1.224
97 wt % trifluoroethanol-H ₂ O	67.30	1.158	1.219

^a Reference 1.

was concluded from substituent and solvent influences that α -*d* effects near 1.15 (25°) were characteristic of a limiting solvolysis in this system. The small variation in this α -*d* effect with a wide range of electron-releasing ring substituents leads to the conclusion that the force constants constraining the α -hydrogen (or deuterium) in the transition state in the reactions were largely independent of the *electrophilicity of the carbonium ion*. The difference between the isotope effects for chloride and bromide leaving groups was shown on the basis of reasonable model calculations to be largely attributable to force constant differences in the initial states.¹³ This leads to the conclusion that the transition state force constants constraining the α -hydrogen were largely independent of the nucleophilicity of the leaving group. The present result indicated at most a very small variation in these force constants with nucleophilicity of solvent. These three conclusions are, of course, mutually interdependent and consistent. They lead to a picture of the transition state in which there is no appreciable covalent binding between the central carbon atom and either leaving or incoming group. This is consistent with the rate-determining step being the conversion of one type of ion pair to another. The small changes in α - and β -deuterium rate effects in α -phenylethyl chloride with solvent also suggest that in the absence of mechanistic changes solvent influences on the isotope effects are small. The yields of styrene in all of these 1-phenylethyl chloride solvolyses are in the range from 1 to 3%. This strengthens the need for a mechanistic interpretation, such as the one given above, for the larger β -deuterium effects and larger isobutene yields in the *t*-butyl chloride solvolysis in trifluoroethanol-water as compared to ethanol-water.

***p*-Methylbenzyl Chloride.** Table VIII summarizes results on the solvolysis of *p*-methylbenzyl chloride. We believe that the relatively high and relatively constant values of the α -*d* effect for *p*-methylbenzyl chloride in trifluoroethanol-water solvents indicates that these solvolyses are near limiting. Thus, they are following

(13) V. J. Shiner, Jr., M. W. Rapp, E. A. Halevi, and M. Wolfsberg, *ibid.*, **90**, 7171 (1968).

essentially the same mechanism that α -phenylethyl chloride does in the same solvent and in aqueous ethanol as well. However, in aqueous ethanol *p*-methylbenzyl chloride shows a much smaller effect, consistent with a large amount of nucleophilic character. It should be noted that these numbers cannot be correlated on the basis of the Frisone-Thornton "parallel effect"¹⁰ if both are following some generalized substitution mechanism and differ only in transition-state bond strengths to the different nucleophiles, *e.g.*, in opposition to the proposed rule ethanol, the stronger base, gives a stronger transition-state bond (low α -*d* effect) while trifluoroethanol, the weaker base, shows a weaker bond (large α -*d* effect). Since the temperature dependence of α -deuterium effects appears to be normal, the 50% ethanol value would be expected to be about 1.085 at 25°.

Table VIII. Isotope Effects in Solvolysis of *p*-Methylbenzyl- α -*d*₂ Chloride

Solvent	$k_H, 10^{-5}$ sec ⁻¹	Temp, °C	$(k_H/k_{D_2})^{1/2}$
50 vol % ethanol	6.999	45	1.080
70 wt % trifluoroethanol	1.601	25	1.140
94 wt % trifluoroethanol	0.686	25	1.145
97 wt % trifluoroethanol	0.644	25	1.143

Isopropyl *p*-Bromobenzenesulfonate. Table IX shows rates and isotope effects for the solvolysis of isopropyl *p*-bromobenzenesulfonate in various trifluoroethanol-water mixtures. The effects measured in solvents with relatively high water content are very close to the values reported for isopropyl *p*-toluenesulfonate by Robertson and coworkers for water solutions.¹⁴ The abnormal temperature dependence of the β effect reported earlier¹⁵ is also apparent in our results. In addition, however, we find a near normal temperature dependence of the α effect. The effects both increase with increasing concentration of trifluoroethanol but show no indication of any leveling off. This is consistent with the view of this type reaction in aqueous solvents as being nucleophilic, probably involving nucleophilic attack on the tight ion pair.¹⁶ In trifluoroethanol either some "limiting" character is incurred or the weaker nucleophile is more loosely bound in the transition state.

Table IX. Solvolysis of Isopropyl *p*-Bromobenzenesulfonate in Trifluoroethanol-Water Mixtures

Wt % H ₂ O	Temp, °C	$k_H, 10^{-5}$ sec ⁻¹	$k_H/k_{\alpha-D}$	$k_H/k_{\beta-D_6}$
3	45	2.041		1.579
30	45	13.68	1.122	1.553
30	25	1.141	1.140	1.537
50	25	2.848	1.122	

The products of solvolysis of isopropyl *p*-bromobenzenesulfonate in various trifluoroethanol-water mixtures have been measured by nmr techniques. These are given in Table X. The selectivity factors, k_a/k_e , for

(14) K. T. Leffek, J. A. Llewellyn, and R. E. Robertson, *Can. J. Chem.*, **38**, 1505, 2171 (1960).

(15) K. T. Leffek, R. E. Robertson, and J. E. Sugamori, *ibid.*, **39**, 1989 (1961).

(16) H. Wiener and R. A. Sneen, *J. Am. Chem. Soc.*, **87**, 292 (1965).

Table X. Products of Solvolysis of Isopropyl *p*-Bromobenzenesulfonate in Trifluoroethanol-Water Solvents, 25°

Wt % H ₂ O	% propene	% alcohol	% ether	k_a/k_e
1	2.2	5.2	92.6	1.0
3	2.9	31.2	65.8	2.7
10	2.0	56.7	41.3	2.2
20	1.2	68.2	31.3	1.5
30	1.1	98.9	Trace	
40	0.5	99.5		
60		100		

isopropyl *p*-bromobenzenesulfonate are similar to those given earlier for *t*-butyl chloride. Since the pK_a 's of trifluoroethanol and water differ by about 3 units the effective Brønsted " α " in these nucleophilic selectivities is only around 0.1, indicating a small degree of nucleophilic attachment in the product-determining step.

Experimental Section

Trifluoroethanol. 2,2,2-Trifluoroethanol was purchased from Halocarbon Products Corp., Hackensack, N. J. It was determined that the solvent could be recovered from the partially aqueous spent kinetic reaction mixtures and from foreshots and distillation flask residues from previous purifications. Approximately 2 l. of new or recovered trifluoroethanol and 1 l. of water was brought to pH 8-9 by addition of potassium carbonate, and fractionally distilled through a 2.4 × 100 cm vacuum-jacketed column packed with ³/₃₂ in. glass helices using a reflux ratio of about 20/1. Material boiling from 73.5-74.5° was collected and was found by Karl Fischer titration to contain 0.28% water. Enough phosphorus pentoxide was added to react with 0.5% water and the solvent distilled again through a 2.4 × 100 cm vacuum-jacketed column filled with ³/₃₂ in. stainless steel helices. Material was collected at a reflux ratio of about 40/1 in an 80-ml conductance cell that, after each filling, siphoned into a large volume receiver. The receiver was fitted with a siphon and ground-glass stopcock for draining off the pure trifluoroethanol for use as needed. All of the normal precautions used in the preparation and handling of conductance solvents^{1,3} had to be followed except that the distillation did not need to be protected from the air. The distillation head, the cell, the receiver, and all containers had to be rinsed several times each with hot nitric acid, hot conductance water, and hot conductance grade trifluoroethanol. To facilitate rinsing, all receivers were equipped with male ground-glass joints and capped with female joints. Only material having specific resistance, in the collector cell, higher than 2 × 10⁹ ohms was used for conductance measurements. The highest specific resistance observed was 4 × 10⁹ ohms. Usually the first two or three fillings of the monitor cell were of lower resistance and were collected separately for recycling in the purification process. In later purifications, the product from the first distillation was dried by passing it through a 2 × 50 cm column of 5 Å molecular sieves. Only a few grams of phosphorus pentoxide was added per liter of this predried product before the final distillation. The final product contained less than 0.03% water by Karl Fischer titration and had a density at 25° of 1.3837 g/ml (neglecting buoyancy corrections). Densities at 25° were determined for several aqueous solutions as follows: 0.65 mol % water, 1.3834; 2.50 mol % water, 1.3822; 6.67 mol % water, 1.3798; 10.55 mol % water, 1.3761. The decrease in density is roughly linear in mole per cent water.

Isopropyl *p*-Bromobenzenesulfonates. The hydrogen α -*d* and β -*d*₆ compounds were prepared from the alcohols by the usual Tipson procedure¹⁷ and recrystallized from *n*-hexane, mp 33.0-34.0° uncor. The alcohols were prepared according to published procedures.¹⁸ The nmr spectra agreed with the expected structures and showed 2% or less isotopic impurity.

***t*-Butyl Chloride.** Commercial *t*-butyl chloride was carefully fractionally distilled and a center cut used. *t*-Butyl-*d*₉ chloride was purchased from Merck Sharp and Dohme and used without further purification.

(17) R. S. Tipson, *J. Org. Chem.*, **9**, 235 (1944).

(18) V. J. Shiner, Jr., *J. Am. Chem. Soc.*, **74**, 5285 (1952).

1-Phenylethyl Chloride. This compound and the α -*d* and β -*d*₂ analogs were prepared and purified in the manner reported earlier.³

Ethyl *p*-Methylbenzoate. A sample of 8.8 g (0.065 mol) of *p*-methylbenzoic acid (Eastman Kodak Co.) recrystallized from 60 ml of 1:1 ethanol-water was refluxed with 55 ml (1 mol) of absolute ethanol and 4 ml of concentrated sulfuric acid for 3 hr. Methylene chloride was added after cooling, and 7.8 g (0.048 mol, 74%) of ester was distilled, bp 122° (30 mm); lit.¹⁹ 85° (10 mm) after washing, drying, and distilling off the solvent.

***p*-Methylbenzyl Alcohol.** A sample of 9.5 g (0.058 mol) of ethyl *p*-methylbenzoate was reduced, using the usual procedure for ether-soluble compounds,²⁰ with 1.54 g (0.039 mol, 95% pure) of lithium aluminum hydride. The initially isolated product, still containing some ether, was heated for 15 min with 100 ml of 25% potassium hydroxide to saponify any unreacted ester. The resulting mixture was extracted twice with 50-ml portions of ether and the ether extracts combined, washed, decolorized, and dried over anhydrous Na₂SO₄. After evaporation of the ether, the crude alcohol was recrystallized from ethanol-water, yielding 3.4 g (0.028 mol, 48%) of alcohol melting at 59–60° (lit.²¹ mp 59.5°). The ir spectrum showed no absorption bands due to unreacted ester.

***p*-Methylbenzyl- α -*d*₂ Alcohol.** The procedure was the same as that described for *p*-methylbenzyl alcohol except that lithium aluminum deuteride was used and the pure alcohol was not isolated but was used as the ethereal solution in the preparation of the chloride.

***p*-Methylbenzyl Chloride.** An ether solution of *p*-methylbenzyl alcohol, prepared as described above from 11.0 g (0.087 mol) of *p*-methylbenzoic acid, was not treated with KOH but was concentrated to ~20 ml, mixed with 25 ml of benzene and 1 ml of pyridine, and put in a three-necked, 100-ml, round-bottomed flask. Twelve milliliters (~20 g or 0.16 mol) of freshly distilled thionyl chloride was added dropwise to the cooled solution with stirring over a 30-min period. After the addition was completed, the ether was evaporated and the residue warmed to 70° for 1 hr. The reaction mixture was concentrated to ~25 ml by distillation of material boiling below 85°. The residue was taken up in 75 ml of ether and washed several times with water. The ether solution was decolorized, dried, and concentrated to ~15 ml. This material was distilled under vacuum and 4.77 g (0.034 mol) of product was collected at 101–102° (30 mm) (lit.²² bp 90° (20 mm)); over-all yield from *p*-methylbenzoic acid was 39%. The ir spectrum showed no absorption due to hydroxyl or carbonyl groups; nmr (CCl₄) δ 2.29 (s, 3), 4.44 (s, 2), 7.12 (m, 4), and no other absorption.

***p*-Methylbenzyl- α -*d*₂ Chloride.** *p*-Methylbenzyl- α -*d*₂ alcohol was converted to the chloride by a procedure exactly analogous to that described above for the undeuterated compound. The final distillation yielded 6.6 g (0.047 mol) of *p*-methylbenzyl- α -*d*₂ chloride collected at 114–121° (35–45 mm); the over-all yield from 8.8 g (0.065 mol) of *p*-methylbenzoic acid was 72%. The ir spectrum indicated appreciable alcoholic impurity and the nmr showed both alcohol and chloride methyl groups in ratio of ~1:4. The nmr indicated a complete absence of benzylic hydrogen.

Rate and Product Determination by Nmr. Spectra were taken on a Varian HA-1L-100 nmr spectrometer in both field sweep and frequency sweep modes. The methylene group of trifluoroethanol was used for an internal locking standard. The trifluoroethanol-water solvent mixtures were prepared by weight and Eastman spectro-grade acetonitrile was used as an internal standard. Solid reactants were weighed in an nmr tube before the addition of solvent and internal standard. Liquid samples were added from weight-calibrated microsyringes. The nmr tubes were sealed by use of rubber septum caps. All measurements made were at a probe temperature of 25° with reactant concentrations ranging from 0.02 to 0.05 *N*. For long reactions the tubes were removed from the probe and placed in a 25° thermostat between observations. Reactions were followed from two to three half-lives with three to six points taken per half-life. Rate constants were obtained from plots of log of reactant concentration vs. time and checked where possible with plots of the log of product concentration with time.²³ Pyridine in concentration two to three times that of the reactant was used in the

solvolysis of the halides. This was shown to have no effect on rates but prevented further reaction of the products. Rate constants determined by nmr agree with those determined conductometrically to within 10%.

Product analyses were carried out on reaction mixtures from kinetic reactions after eight to ten half-lives. Product ratios were calculated by peak height measurements and by triangulation because the very high gain levels employed in the spectrometer made normal integration results less accurate. Product yields, determined with reference to the internal standard, varied between 89% and 103%. Individual product analyses were reproducible to ± 2 –3%.

The characteristic peak positions (in δ values) used to follow each reaction were as follows: *t*-butyl chloride, 1.63 (singlet); isobutylene, 1.80 (multiplet); *t*-butyl trifluoroethyl ether, 1.32 (singlet); and *t*-butyl alcohol, 1.37 (singlet).

Conductance Kinetic Procedure. The apparatus, cells, procedure, and calculations have been described previously.³ In the current work, cells with a total volume of about 100 ml were used to conserve solvent. The smaller cells were constructed exactly as before except that the cell compartment was sealed to a 20-mm tube instead of a 1-l. erlenmeyer flask. The cells were sealed with Fisher-Porter No. 25 solvent seal joints to avoid grease and obtain a good seal so that the entire cell including the cap could be immersed in the oil bath. This prevented solvent from condensing in the cap of the cell, which in the older technique extended above the oil level in the bath. The small cells did not give rate constants quite as accurate as those obtained with the larger cells probably because electrolyte which may be desorbed or absorbed on the electrode has more effect on conductance in the smaller volume of solvent. The reproducibility of rate constants with the 100-ml cells was found to be about ± 0.1 %.

Determination of Conductance Parameters of *p*-Bromobenzenesulfonic Acid in H₂O-TFE Mixtures. A. Gravimetric Method. This procedure corresponded closely to the procedure used for HCl in ethanol-water mixtures.¹ However, because of the difficulty encountered in preparation of pure *p*-bromobenzenesulfonic acid, the acid solution was prepared by allowing a known weight of 3,3-dimethyl-2-butyl brosylate to solvolyze in a known weight per cent H₂O-TFE mixture for approximately 12 half-lives. The density of the H₂O-TFE mixtures was determined at 25 and 45° with a calibrated Ostwald pycnometer. Assuming that all the ester was converted to acid, the concentrations (*ca.* 0.02 *M*) of the acid solutions at 25 and 45° were calculated. An example of the procedure is as follows.

A 0.1076-g sample of pinacolyl brosylate was dissolved in 22.1011 g of 29.92 wt % H₂O-TFE. The density of the H₂O-TFE solvent was 1.258 g/ml at 25° and 1.234 g/ml at 45° and the brosylate solution was 0.0191 *M* at 25° and 0.0187 *M* at 45°. Weighed aliquots of this solution were added from a weight buret to a conductivity cell (cell constant 0.3208) containing 138.22 g of 29.92 wt % H₂O-TFE mixture. The resistance of the solution at 25,000 Ω was determined using the apparatus described earlier. The cell was then transferred to the 45° bath and another resistance measurement was taken after thermal equilibrium was reached, as indicated by the absence of any drift in the resistance reading. The cell was replaced in the 25° bath and allowed to come to thermal equilibrium. This second reading at 25° provided a check on the first. This procedure was repeated for four more additions of the acid solutions. The results are given in Table XI. The data in Table XII were evaluated according to the limiting conductance equation (where Λ is the equivalent conductance, and *c* the concentration).

$$\Lambda = \Lambda_0 - S_\alpha \sqrt{c}$$

A plot of Λ vs. \sqrt{c} from Table XII was linear over all acid concentrations (0.8626×10^{-4} to 3.5457×10^{-4} mol/l.). From these plots, the values of Λ_0 and S_α were obtained as the intercept and the slope. The conductance parameters are given in Table II for 3, 10, 20, and 30% H₂O in TFE at 25 and 45°.

B. Kinetic Method. This procedure is based on a modification of method A above, and on the conductance method used for obtaining kinetic measurements. An example of the procedure is as follows.

A conductivity cell (cell constant 0.2873) was filled with 1193.56 g of 30 wt % H₂O-70% TFE mixture. A 0.24382-g sample of isopropyl brosylate was added to this solution (concentration 9.2278×10^{-4} mol/l.). The cell was transferred to the 25° bath. After allowing 20 min for thermal equilibrium to be established, the resistance of the solution was measured as a function of time for approximately two to three half-lives.

(19) R. L. Herbst, Jr., and M. E. Jacox, *J. Am. Chem. Soc.*, **74**, 3004 (1952).

(20) R. F. Nystrom and W. G. Brown, *ibid.*, **69**, 1197 (1947).

(21) J. K. Kochi and G. S. Hammond, *ibid.*, **75**, 3443 (1953).

(22) H. Stephen, W. F. Short, and G. Gladding, *J. Chem. Soc.*, **117**, 510 (1920).

(23) J. A. Pople, W. G. Schneider, and H. J. Bernstein, "High-Resolution Nuclear Magnetic Resonance," McGraw-Hill Book Co., Inc., New York, N. Y., 1959, pp 458–463.

Table XI. Resistance of Solutions of *p*-Bromobenzenesulfonic Acid in 29.92% H₂O-TFE

Wt of solution added, g	R_{25} , ohms	R_{45} , ohms	R_{25} , ohms
0.6288	48,590	32,970	48,580
+0.11619	38,720	26,289	38,720
+0.2875	28,560	19,358	28,560
+0.5078	19,584	13,276	19,584
+1.0871	11,753	7,970	

Table XII. Equivalent Conductance of *p*-Bromobenzenesulfonic Acid in 29.92% H₂O-TFE

Λ		$c \times 10^4$		$\sqrt{c} \times 10^2$	
25°	45°	25°	45°	25°	45°
77.9	117.1	0.863	0.846	0.929	0.920
77.8	116.9	1.084	1.063	1.041	1.031
77.4	116.7	1.477	1.447	1.215	1.203
77.2	116.1	2.161	2.120	1.470	1.456
76.9	115.6	3.614	3.614	1.901	1.883

Table XIII. Conductance Parameters in 2,2,2-Trifluoroethanol-Water Mixtures for *p*-Bromobenzenesulfonic Acid at 25 and 45°

Wt % H ₂ O	25°		45°	
	Λ_0	S_α	Λ_0	S_α
3	31.79	122.0	50.45	200.0
30	78.17	71.6	118.6	135.0
50	145.0	33.3		
60			320.0	35.0

Using the computer program for the determination of the first-order rate constants, the kinetic data were treated in the same manner as before³ for an electrolyte showing limiting behavior except that the conductance parameters (S_α and Λ_0) are guessed, initially. Generally, the plot of the percentage resistance residuals *vs.* time was curved. If the percentage resistance residuals were positive in the first half-life of the reaction and negative in the

second half-life, then the values of Λ_0 are assumed to be at least 10% too large. If the percentage resistance residuals are negative in the first half-life and positive in the second half-life, then the value of Λ_0 is assumed to be at least 10% too large or the value of S_α at least 10% too small. By trial and error variation of either S_α or Λ_0 , the percentage resistance residuals was minimized to less than $\pm 0.2\%$ and any systematic trends eliminated.

This process yielded a set of corrected trial conductance parameters (S_α' and Λ_0') and a corresponding trial calculated concentration of acid at infinite time (C'). The true values of the conductance parameters were calculated from these values and the true concentration of acid at infinite time (C_{exptl}), obtained from the known weight of starting ester, by

$$\Lambda_0 = \Lambda_0' C' / C_{\text{exptl}}$$

$$S_\alpha = S_\alpha' (C' / C_{\text{exptl}})^{1/2}$$

The results are given in Table XIII.

The kinetic method of determining the conductance parameters should be quite satisfactory if the reactions actually follow the first-order rate law and it has the advantage that it uses about 100 points over a concentration range from 10^{-4} to 10^{-3} *M*. It gives conductance parameters that agree reasonably well with those obtained by weight methods and the infinity point of the kinetic run actually serves as a single "weight method" point. Using these parameters reaction rate constants reproducible to $\pm 0.1\%$ were obtained.

For the more polar solvents which show relatively larger values of Λ_0 the kinetic results are not so sensitive to S_α and the errors in its determination are correspondingly larger. We have quoted in the tables the values actually used in the kinetic calculations even though these figures include one or two more figures than are significant.

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