One part of the reaction mixture (2 mL) was quenched with H_2O and the other (25 mL) with D_2O followed by water. Usual workup gave from the first part a mixture (0.02 g) of **11** and **12** in a ratio of 66:34 (NMR), and from the second only **11** (0.256 g). The total yield of **11** and **12** was 89%.

Reaction of 3-(Hydroxymethyl)quinoline with 1.0 Equiv and 1.5 Equiv of *n*-Butyllithium. The *n*-butyllithium used was from the same stock as above. A solution of 3-(hydroxymethyl)quinoline (**12**) (0.318 g, 2 mmol) in dry THF (25 mL) was cooled to −78 °C. *n*-BuLi (~2 mmol in 3.3 mL of ether) was added to the cooled solution over a period of 10 min. The reaction mixture was stirred for a further period of 10 min and quenched with D_2O. Usual workup and isolation gave a compound (mp 84 °C). The ratio of the C_2-H at δ 8.95 and methylene proton signal at δ 4.91 were in the ratio 1:2, indicating that the compound was only **12** (0.27 g, 85%) and no **11** was present.

The experiment was repeated by adding 5 mL of *n*-BuLi over a period of 10 min. Stirring for an additional 10 min, followed by treatment with D_2O and aqueous workup, gave **16** (0.172 g, 40% as a thick liquid). ^1H NMR ($CDCl_3$): δ 8.3–7.3 (5 H, m, Ar-*H*), 4.85 (2 H, s, $ArCH_2OH$), 2.9 (2 H, t, J = 7 Hz, $ArCH_2R$), 1.4–2.0 (5 H, m, exch $ArCH_2CH_2C-H_2CH_3$, $ArCH_2OH$), 1.0 (3 H, t, CH_3). Anal. Calcd for $C_{14}H_{17}NO$: C, 78.1; H, 7.96. Found: C, 78.07; H, 7.67. IR: 3300 cm^{-1}. Workup also gave a compound (mp 84 °C) whose NMR had the C_2-H proton signal at δ 8.95 and the methylene proton signal at δ 4.91 in the ratio 1:2, indicating it was only **12** (0.150 g, 47%) with no **11** being present.

Reaction of the Formate Ester (19) of 2-Iodo-3-(Hydroxymethyl)-quinoline with *n*-Butyllithium. A solution of the formate ester (**19**) of 2-iodo-3-(hydroxymethyl)quinoline (0.940 g, 3 mmol) in dry THF (50 mL) was cooled to −78 °C. *n*-BuLi (6 mmol in ether) was added to the cooled solution dropwise over a period of 15 min when a deep red coloration resulted. Stirring for a further period of 2 h at −78 °C, quenching with saturated NH_4Cl (15 mL), separating the THF layer, and extracting the aqueous layer with ethyl acetate (10 mL) gave in the combined organic extracts after drying (Na_2SO_4), concentration, and column chromatography of the residue over silica gel, using chloroform/methanol (98:2) as eluant, first 2-formyl-3-(hydroxymethyl)quinoline (**21**) (0.316 g, 56%), mp 155 °C (2% methanol/chloroform) and then 3-(hydroxymethyl)quinoline (**12**) (0.146 g, 30%). **21**: ^1H NMR ($CDCl_3$) (keto/lactol 1:10): δ 10.61 (1 H, s, C*H*O), 8.43–7.5 (10 H, m, Ar-*H*), 6.77 (2 H, brs, exch OH, keto and lactol), 6.57 (1 H, s, C*H*OH lactol), 5.43 (2 H, q, J = 13 Hz, $ArCH_2O$, lactol), 5.17 (2 H, q, $ArCH_2OH$, keto). Anal. Calcd for $C_{11}H_9NO_2$: C, 70.58; H, 4.85. Found: C, 70.49; H, 4.80) IR: 3150 cm^{-1}.

Reaction of the Benzoyl Ester (20) of 2-Iodo-3-(hydromethyl)quinoline with n-Butyllithium. A solution of the benzoyl ester (**20**) of 2-iodo-3-(hydroxymethyl)quinoline (1.012 g, 2.6 mmol) in dry THF (50 mL) was cooled to −78 °C. *n*-BuLi (5.2 mmol in ether) was added to the cooled solution dropwise over a period of 15 min when a deep red coloration resulted. Stirring for a further period of 30 min at −78 °C and workup as above gave, on crystallization, 2-benzoyl-3-(hydroxymethyl)quinoline **22** (0.493 g, 72%), mp 94–95 °C (40% EtOAc/hexane). ^1H NMR ($CDCl_3$): δ 8.43–7.37 (10 H, m, Ar*H*), 4.81 (2 H, s, $ArCH_2OH$), 3.67 (1 H, brs, exch OH). Anal. Calcd for $C_{17}H_{13}NO_2$: C, 77.55; H, 4.98. Found: C, 77.45; H, 5.28. IR: 3330, 1665 cm^{-1}.

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Mechanism of Solvolysis of 1-(1-Adamantyl)ethyl Sulfonates

F. P. Wilgis,† T. E. Neumann, and V. J. Shiner, Jr.*

Contribution from the Department of Chemistry, Indiana University, Bloomington, Indiana 47405. *Received October 13, 1989*

Abstract: In contrast to the pinacolyl (3,3-dimethyl-2-butyl) sulfonate esters, the solvolyses of 1-(1-adamantyl)ethyl sulfonates produce significant proportions of unrearranged substitution products indicating that a strong steric bias exists against what is, for the pinacolyl esters, a facile rearrangement of the secondary cation to the tertiary cationic isomer. In addition, the α-*d* and β-d_3 isotope rate effects vary with solvent. This is a strong indication of a change in mechanism which can only occur if internal return is significant. The unusually small isotope effects in trifluoroethanol/water solvents indicate that a proportion of the reaction proceeds through a transition state having the rearranged structure. Observations of extensive oxygen scrambling during solvolysis confirm the existence of internal return. The solvolytic substitutions starting with either the chiral secondary sulfonate or the chiral tertiary heptafluorobutyrate reveal that the rearrangement in both directions is stereospecific as is the unrearranged substitution from the tertiary ester which gives retained chirality. The unrearranged substitution product from solvolysis of the secondary ester, although predominantly of retained configuration, contains a proportion of the inverted enantiomer which increases with solvent nucleophilicity to a maximum of 50% found in ethanol. A steady-state analysis based on a mechanism which involves equilibrating secondary and tertiary carbocations successfully correlates the observed isotope effects with the product yields and the isotope effects expected for the various single steps. Since the steady-state treatment gives unassisted ionization rates which are 2.3 (80E) to 7.7 (97T) times faster than those for the pinacolyl analogue, it seems clear that the ionization rates of the latter are also unassisted.

Some years ago it was suggested that 3,3-dimethyl-2-butyl (pinacolyl) sulfonate esters **1** are useful reference reactants for the estimation of unassisted ionization rates of secondary sulfonate esters in the absence of internal return.[1] The magnitude and constancy of the observed secondary deuterium rate effects in a wide range of solvents of varying nucleophilicity and ionizing power indicate that pinacolyl sulfonates solvolyze by unassisted, irreversible ionization followed by rapid Wagner–Meerwein rearrangement to the more stable tertiary ion; that is rearrangement of the secondary to the tertiary cation in the ion pair is faster than ion recombination. Consistent with this interpretation are the facts that all of the products have rearranged structures[2] and that no ^{18}O scrambling can be detected in recovered unreacted ester.[3] Since internal return and S_N2 attack are insignificant for this ester,[4] the comparison of its solvolytic rates and isotope effects

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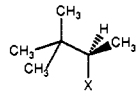
Table I. Products from the Solvolysis of α-Deuterated 1-(1-Adamantyl)ethyl Sulfonates (2a,b) at 25 °C[a]

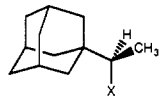
solvent[b]	leaving group[c]	elimination[d]	unrearranged substitution[e]	rearranged substitution[f]
98H	OPms	4.0	32.0	64.0
90H	OPms	4.0	26.0	70.0
80H	OPms	7.0	27.0	66.0
97T	OBs	3.2	27.9	68.9
80T	OBs	4.0	37.0	59.0
70T	OBs	4.1	35.5	60.4
60E	OBs	9.3	43.1	47.6
70E	OBs	10.4	43.0	46.6
80E	OBs	14.6	45.7	39.6

[a] Expressed as a percentage of total product mixture. Determinations were made with use of Varian HR-220 and Nicolet 360 spectrometers operating at 33 and 55 MHz (^{2}H NMR), respectively. Error is approximately 2–3%. [b] 80E is 80 vol % ethanol/20 vol % water; 70T is 70% 2,2,2-trifluoroethanol/30% water, and 98H is 98% 1,1,1,3,3,3-hexafluoro-2-propanol/2% water, etc. Solutions were 0.1 M in the starting ester and buffered with 2,6-lutidine. [c] OPms is pentamethylbenzenesulfonate,[33] and OBs is *p*-bromobenzenesulfonate. [d] The 1-*d* alkene of product **9**. [e] The α-*d*-substituted **2c**, **2d**, and **2e**. [f] The β-d_1-substituted **3b**, **3c**, and **3d**.

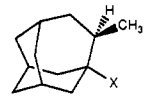
with those for other secondary sulfonate esters helps one to distinguish among causes for changes in rate due to such factors as nucleophilic attack, internal return, participation during ionization and participation after ionization.[1,5] However, this mechanistic analysis still attracts criticism, particularly concerning the question whether methyl migration occurs concomitantly with or subsequent to ionization[6] and whether solvent nucleophilicity assists ionization.[7] To provide a more extensive body of information to resolve this problem we undertook an investigation of the solvolysis of 1-(1-adamantyl)ethyl sulfonates **2a,b**, pinacolyl analogues which are biased against rearrangement by the large increase in strain involved in the conversion of the adamantyl to the homoadamantyl ring system (**3**).[8]



1, X = OBs



2a, X = OBs
b, X = OPMs
c, X = OH
d, X = OCH_2CH_3
e, X = OCH_2CF_3
f, X = $O_2CC_3F_7$



3a, X = $O_2CC_3F_7$
b, X = OH
c, X = OCH_2CH_3
d, X = OCH_2CF_3

OBs = *p*-Bromobenzenesulfonate OPMs = Pentamethylbenzenesulfonate

Table II. Products from the Solvolysis of β-d_3 Substituted 1-(1-Adamantyl)ethyl Sulfonates (2a,b) at 25 °C[a]

solvent[b]	leaving group[c]	elimination[d]	unrearranged substitution[e]	rearranged substitution[f]
98H	OPms	3.0	37.0	60.0
90H	OPms	3.0	32.0	65.0
80H	OPms	3.0	33.0	64.0
97T	OBs	3.0	33.0	64.0
80T	OBs	2.0	31.0	67.0
70T	OBs	2.5	32.5	65.0
60E	OBs	3.3	43.7	53.0
70E	OBs	4.2	44.8	51.0
80E	OBs	5.1	45.9	49.0

[a–c] See footnotes in Table I. [d] The β-d_2 substituted alkene **9**. [e] The β-d_3 substituted **2c**, **2d**, and **2e**. [f] The γ-d_3 substituted **3b**, **3c**, and **3d**.

Table III. Stereochemical Results from the Solvolysis of (*R*)-1-(1-Adamantyl)ethyl Brosylate (2a) at 25 °C[a]

		unrearranged[c] substitution		rearranged[c] substitution	
solvent[b]	unreacted *R*OBs[c] (2a)	alcohol (2c)	ether (2d,e)	alcohol (3b)	ether (3c,d)
97T		83% ret	100% ret	97% inv	98% inv
70T		80% ret		95% inv	
60E		56% ret		100% inv	
70E		47% ret		99% inv	
80E	98% ret	51% ret	45% ret	100% inv	100% inv
90E	100% ret	41% ret	24% ret	100% inv	100% inv
100E	97% ret		0% ret		100% inv

[a] The optical purities of the ester and each of the products were determined by comparison of the intensities of the enantiomeric methyl doublets that appear in the ^{1}H NMR spectrum in the presence of (*S*)-(+)-2,2,2-trifluoro-1-(9-anthryl)ethanol. The enantiomeric excess of the starting ester is 40%. [b] Solvents are as noted in Table I. [c] The values in the table are the observed enantiomeric excess expressed as a percentage of the enantiomeric excess of the starting ester. Thus 51% ret corresponds to 51% of the original ee being retained (net retention of stereochemistry) with 49% being loss due to 24.5% inversion.

A preliminary communication reported both α-*d* and β-d_3 rate effects and product analyses for the α-*d*-substituted ester of **2a** and **2b** in nine solvents.[9] In order to explain the yields of unrearranged products as well as both the magnitude and variation of the observed isotope effects with solvent changes, we postulated a mechanism which involves not only internal return of the unrearranged secondary ion pair but also reverse rearrangement of the tertiary ion pair to the secondary ion pair occurring in competition with further reaction of the tertiary ion. In further support of this mechanism with some additional modifications we now report new results from the solvolysis of **2a** and of an ester of the isomeric tertiary alcohol (**3a**); these include product studies, an examination of stereochemical results, isotope rate effects, oxygen-18 equilibration studies, and a detailed description of a steady-state analysis of the proposed mechanism.

Results and Discussion

Tables I and II give the product yields for both the α-*d*- and β-d_3-substituted esters of **2a** and **2b** in nine solvents listed in order of increasing nucleophilicity. The identity and relative yields of the products were determined by analysis of the spent reaction mixtures after solvolysis of the deuterated esters for 10 half-lives using ^{2}H NMR at 33 and 55 Mhz. The data in Table I were reported earlier and are reproduced here in order to document the minor corrections made due to the use of the higher resolution 55-MHz ^{2}H NMR. While the major products in the fluorinated solvents are of rearranged substitution, there is still an appreciable yield of unrearranged substitution and small yield of unrearranged elimination.

In comparison with the pinacolyl analogue which gives no observable yield of unrearranged product one consequence of the

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Table IV. Deuterium Isotope Effects[a] and Solvolysis Rates[b] for 1-(1-Adamantyl)ethyl Sulfonates (**2a,b**) at 25 °C

solvent[c]	leaving group[d]	α-d[e]	β-d_3[f]	d_4[g]	k_H	k_H/k_{pin}[h]
98H	OPms	1.116	1.120		178.5	
90H	OPms	1.113	1.135		43.58	
80H	OPms	1.120	1.146		39.17	
97T	OBs	1.111	1.120	1.253	29.97	3.77
80T	OBs	1.119	1.153	1.275	33.00	
70T	OBs	1.122	1.151	1.276	36.71	3.45
60E	OBs	1.144	1.205	1.363	3.485	0.84
70E	OBs	1.145	1.225	1.388	1.406	0.81
80E	OBs	1.147	1.256	1.427	0.513	0.81

[a] The reproducibilities of the isotope effects are 0.004 and less. [b] First-order rate constants in units of 10^{-5} s^{-1}. [c,d] Solvents and leaving groups are as noted in Table I. [e] $k_H/k_{\alpha\text{-}d}$. [f] $k_H/k_{\beta\text{-}D_3}$. [g] $k_H/k_{\alpha\text{-}d,\beta\text{-}d_3}$. [h] Rate ratio relative to pinacolyl brosylate (**1**).

steric bias against rearrangement is evident: unrearranged products are obtained in significant proportions in all solvents and their yields generally are larger in more nucleophilic and more basic solvents.

In Table III are shown in stereochemical results of substitution from the solvolysis of *R*-enriched 1-(1-adamantyl)ethyl brosylate (**2a**, 40% ee) in the various solvents listed in order of increasing nucleophilicity. The solvolysis products and in some cases the unreacted ester, isolated from buffered reaction mixtures after 2–10 half-lives, were purifed by HPLC and their optical purities determined from the intensities of the enantiomeric methyl doublets that appear in the ^1H NMR spectrum in the presence of the chiral solvating reagent (*S*)-(+)-2,2,2-trifluoro-1-(9-anthryl)ethanol (TFAE).[10] In the spectrum of the starting ester and the alcohol from which the ester was prepared, the dominant doublet corresponding to the *R* configuration was the signal occurring at lower field. The values that appear in the table for each product are the observed enantiomeric excesses expressed as a percentage of the enantiomeric excess of the starting ester.

The rearranged products are formed stereospecifically in all solvents. Since attack by the rearranging carbon is expected to occur backside to the leaving group, the observed 100% stereospecific result is assumed to be inversion. In 80E, 90E, and 100E the isolated unreacted ester retains the chiral purity that it had at the start of solvolysis. Thus, **2a** does not racemize during solvolysis. The unrearranged substitution products are mainly of retained configuration but contain increasing proportions of the inverted product as solvent nucleophilicity increases. Since the unreacted ester does not racemize, rearranged products are chirally pure, and S_N2 attack by solvent is highly unlikely (vide infra), the inverted product must arise from backside attack by solvent on the unrearranged secondary tight ion pair. These observations rule out a bridged ion as a single intermediate cationic species because bridging would prevent backside attack and result in unrearranged product of retained configuration.

In Table IV are listed solvolysis rates, α-d, β-d_3, and d_4 (α-d,β-d_3) isotope rate effects and rates relative to pinacolyl brosylate for the title ester in nine solvents. The majority of the isotope effect data in the table were reported earlier[9] but are given here to show their relation to the more recently measured d_4 effects. The rate constants at 25 °C were determined either conductometrically or spectrophotometrically, with the reported rates being the average of several determinations.

Bentley et al. were the first to show that the α-d effect for solvolysis of **2a** in 97T was unusually low, and in support of an alternative mechanism which neglects internal return they attributed the lowered effect to initial state strain.[6f] It has been recognized for some time that steric crowding tends to increase vibrational frequencies and H/D fractionation factors.[11] However, in a limiting solvolysis the transition state is expected to be less crowded than the initial state, leading to the conclusion that sterically hindered reactants should show larger rather than smaller α-d effects. Further the data show that both the α-d and β-d_3 isotope effects are lower in the more ionizing solvents and that they vary in a roughly parallel way with solvent changes, strongly suggesting that they are caused by a common origin which could not be initial state steric strain in the β-d_3 case. One possible complication which can be readily rejected is that the isotope effects are directly influenced by solvent changes even though the mechanism does not change. H/D fractionation factors are known not to be strongly influenced by solvent. It has been shown that pinacolyl and 2-adamantyl sulfonate esters, which react by different, solvent-independent mechanisms, show isotope effects that are largely unaffected by solvent changes.[1a,c] An additional possibility which can also be discarded is the suggestion that the reaction is subject to "nucleophilic solvation" which has been suggested for pinacolyl sulfonate esters,[7] despite their neopentyl-type structure and low S_N2 reactivity with strong nucleophiles. This effect cannot cause the variation in isotope effects because the larger isotope effects, which could correspond to lesser nucleophilic involvement, are in the more nucleophilic solvents. In addition, a plot of the log of the rate constants for **2a** vs those for 2-adamantyl tosylate in the same solvents, according to the "ethanol/trifluoroethanol" method of Raber and Harris,[12] is linear with a slope (m) of 0.96 (Figure 1).

The only known cause for such variations in isotope effects as are noted here is a change in the rate-determining step.[13] Since the observation of inverted substitution strongly implicates the secondary ion pair as an intermediate, internal return from this ion pair must be occurring.

In order to confirm the occurrence of internal return, we have examined the solvolysis of a sample of **2a** in which both sulfonyl oxygens were labeled to the extent of 91.0% with ^{18}O. Oxygen-18 labeled **2a** was prepared from the alcohol and ^{18}O enriched (91.0%) *p*-bromobenzenesulfonyl chloride by a modified Tipson procedure.[14] Unreacted sulfonate ester was recovered after solvolysis for approximately 1 half-life in buffered 97T and 80E and its ^{18}O incorporation at the α-carbon determined by the convenient NMR method introduced by Risley and Van Etten[15] which makes use of the $^{16}O/^{18}O$ isotopic effect on the chemical shift of the attached ^{13}C resonance. The observed percentages of ^{18}O at the α-carbon were used to calculate equilibration rates (k_{eq}) with the use of standard methods.[16]

In Table V are shown the results for oxygen equilibration in each solvent including the percent ^{18}O observed at the α-carbon, the calculated equilibration rate, and the minimum fraction of internal return ($F_{Rel} = k_{eq}/(k_{eq} + k_t)$). Intramolecular oxygen

Table V. Oxygen-18 Equilibration Data for Sulfonyl ^{18}O Labeled 1-(1-Adamantyl)ethyl Brosylate (**2a**) at 25 °C[a]

solvent[b]	k_t[c]	elapsed time (s)	% ^{18}O[d]	k_{eq}[e]	F_{rel}[f]
97T	29.97	2350	19.6	16.5	0.36
		2330	19.3	16.7	0.36
80E	0.513	135900	29.3	0.493	0.49
		135800	29.0	0.479	0.48

[a] The sulfonyl oxygens are labeled to the extent of 91.0% with ^{18}O. Unreacted ester (5 mM) in buffered solvent was isolated after 1 half-life and the % ^{18}O attached to the α-carbon was determined by ^{13}C NMR. [b] Solvents are as noted in Table I. [c] Observed solvolysis rate in units of 10^{-5} s^{-1}. [d] The % ^{18}O calculated from the relative peak heights of the α ^{13}C–^{16}O and ^{13}C–^{18}O signals in the ^{13}C NMR. [e] The calculated ^{18}O equilibration rate in units 10^{-5} s^{-1}. [f] $F_{rel} = k_{eq}/(k_{eq} + k_t)$ = the minimum fraction of internal return.

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(11) (a) Bartell, L. S. *Tetrahedron Lett.* **1960**, 13. (b) Melander, L.; Sanders, W. H., Jr. In *Reaction Rates of Isotopic Molecules*; Wiley: New York, 1980; pp 189–197 and references cited therein.
(12) Raber, D. J.; Neal, W. C., Jr.; Dukes, M. D.; Harris, J. M.; Mount, D. L. *J. Am. Chem. Soc.* **1978**, *100*, 8137.
(13) Harlshorn, S. R.; Shiner, V. J., Jr. *J. Am. Chem. Soc.* **1972**, 9002–9012.
(14) Tipson, R. S. *J. Org. Chem.* **1944**, *9*, 253.
(15) Risley, J. M.; Van Ellen, R. L. *J. Am. Chem. Soc.* **1979**, *101*, 252–253.
(16) Frost, A. A.; Pearson, R. G. *Kinetics and Mechanism*, 2nd ed.; Wiley: New York, 1961; p 186.

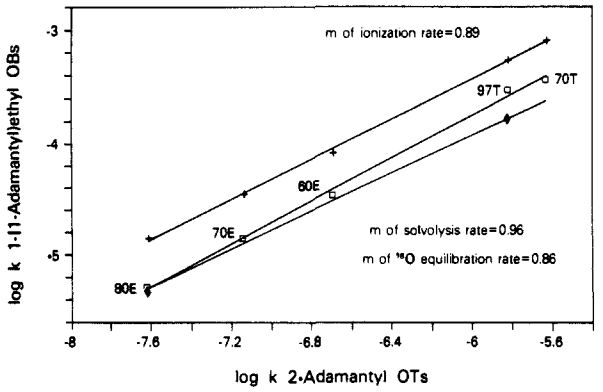


Figure 1. The EtOH/TFE plot of the solvolysis rate (□), the ^{18}O equilibration rate (◆), and the calculated ionization rate (+) for 1-(1-adamantyl)ethyl brosylate.

equilibration which accompanies the solvolysis of carboxylate and sulfonate esters has traditionally been accepted as a minimum measure of the extent of internal return from an ion pair intermediate.[3,6e,17] As we were able to predict from the analysis of the isotope effects, the solvolysis of **2a** shows extensive ^{18}O equilibration resulting from internal return of the secondary tight ion pair. From the minimum estimate of the fraction of internal return (36% in 97T and 49% in 80E) we conclude that the rate-determining step is not ionization but one or more steps involving further reaction of the ion-pair intermediate. In the solvolyses of 2-adamantyl sulfonates, which we had concluded from isotope effects and other criteria involves rate-determining solvent separation of the tight ion pair, Paradisi and Bunnett observed extensive ^{18}O equilibration in all solvents tested.[3] In fact, the minimum estimate of the fraction of internal return in 80E (53%) is similar to that observed here. Recently, doubts have been expressed concerning the intermediacy of ion pairs in solvolysis of secondary sulfonates and it has been proposed that ^{18}O scrambling involves a different mechanism.[6d,18] In rebuttal to these speculations Paradisi and Bunnett showed that the observed equilibration rates from 2-adamantyl ester solvolysis show a large kinetic dependence on solvent polarity.[3b] We, too, note a similar dependence on solvent polarity; the plot of the logarithm of the two measured oxygen equilibration rates vs the logarithm of the solvolysis rates for 2-adamantyl tosylate shows a slope of 0.86 (Figure 1).[19] It is didfficult to reconcile this observation with suggestions that ^{18}O equilibration takes place by a nonionizing mechanism.

It is clear that the unrearranged secondary tight ion pair is a key intermediate in this reaction and that any reasonable mechanism has to involve the partitioning of this ion pair among the following reactions: (1) internal return to covalent reactant, (2) rearrangement, (3) further dissociation to the solvent separated ion pair yielding substitution with retention, (4) backside nucleophilic attack by solvent giving inverted substitution, and (5) elimination. With the rearrangement rate being retarded, in comparison with the pinacolyl analogue, internal return becomes significant and appears to dominate other reactions available to the ion pair. While our ^{18}O equilibration data indicate that a minimum of 36–49% of the ion pairs formed undergo return, it seems likely that the fraction of ion pairs returning is even greater than this because the favored position of the originally bonded oxygen for return is not accounted for in these observations.[3,17d]

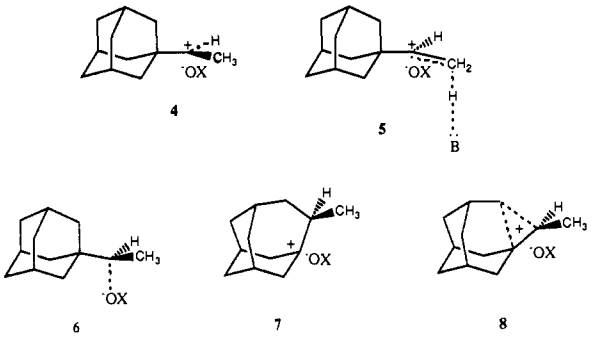
Table VI. Fractionation Factors Used in Steady-State Calculations

transition-state structure	RDS[a]	fractionation factor relative to initial state		fractionation factor relative to unrearranged ion pair	
		α-d_1	β-d_3	α-d_1	β-d_3
4	k_2	1.23	1.46	1.00	1.00
5	k_{5e}	1.23	3.65	1.00	2.50
6	k_1, k_{5s}	1.155	1.20	0.94	0.82
7	$k_{2'}$	1.07	1.00	0.87	0.68
8	k_r	1.20	1.24	0.97	0.85

[a] Rate constant for the rate-determining step as labeled in Scheme I.

Since the reaction involves significant proportions of internal return, then the overall rate-determining step would be a composite of the various proportions of each of the remaining reactions competing at the ion-pair stage. As is apparent from the product and stereochemical results the relative rates of the competing reactions at this stage depend on solvent basicity, nucleophilicity and ionizing ability, and since each step has associated with it a distinct transition state it is obvious that solvent influences on this mixture of rate-determining steps will also influence the overall observed isotope effects. However, without further modifications this mechanism does not suffice to explain the magnitudes of the isotope effects.

In the EtOH/water solvents the deuterium isotope effects are similar to those of the pinacolyl sulfonate esters but in the more ionizing, fluorinated alcohol solvents they are smaller. In Table VI are listed H/D fractionation factors relative to the initial state which earlier studies indicate should obtain for secondary ion-pair intermediates and transition states for the reactions involving them. H/D fractionation factors relative to the initial state result from changes occurring in the environment of the α-d and β-d labels.[13,20] Reactions which involve rate-determining solvent separation of the ion pair (**4**) or rate-determining elimination from the ion pair (**5**) will show α-d effects of about 1.23[1,21] while the β-d_3 effects for these reactions are 1.46[22] and 2.2–3.0, respectively.[21] For reactions which involve rate-determining nucleophilic attack by solvent on the ion pair (**6**), an α-d effect of 1.15 and a β-d_3 effect of 1.20 are expected.[1,5c,21] In the solvolysis of 2,2-dimethylcyclopentyl brosylate where the rate-determining step was shown to involve rearrangement after reversible formation of the tight ion pair (the analogous transition state here is **8**), an α-d effect of 1.19–1.20 and a β-d_2 effect of 1.24 were observed.[5c] Since



any combination of these four reactions of the ion pair in the rate-determining step will show α-d effects intermediate between 1.15 and 1.23 and β-d_3 effects greater than 1.20, a modification of the mechanism outlined above is required. The fact that in the fluorinated alcohol solvents, where the abnormally low isotope effects are observed, we find the greatest proportion of rearranged substitution suggests that some step other than rearrangement from the reversibly formed secondary ion pair must be rate-limiting

(17) (a) Goering, H. L. *Rec. Chem. Prog.* **1960**, *21*, 109–127. (b) Goering, H. L.; Thies, R. W. *J. Am. Chem. Soc.* **1968**, *90*, 2967; 2968. (c) Goering, H. L.; Jones, B. E. *J. Am. Chem. Soc.* **1980**, *102*, 1628–1633. (d) Diaz, A. F.; Lazdins, I.; Winstein, S. *J. Am. Chem. Soc.* **1968**, *90*, 1904–1905.

(18) (a) Jencks, W. P. *Chem. Soc. Rev.* **1981**, *10*, 345–375. (b) Dietze, P. E.; Jencks, W. P. *J. Am. Chem. Soc.* **1986**, *108*, 4549–4555. (c) Dietze, P. E.; Jencks, W. P. *J. Am. Chem. Soc.* **1987**, *109*, 2057–2062. (d) Dietze, P. E.; Hariri, R.; Khattak, J. *J. Am. Chem. Soc.* **1989**, *54*, 3317–3320.

(19) A similar slope (m = 0.80) is observed for 2-adamantyl brosylate at 25 °C from the plot of the ^{18}O equilibration rates in 80E (1.8×10^{-7} s^{-1}) and 97T (4.8×10^{-6} s^{-1}).[39]

(20) (a) Buddenbaum, W. E.; Shiner, V. J., Jr. In *Isotope Effects in Enzyme Catalyzed Reactions*; Cleland, W. W., O'Leary, M. H., Northrup, D. B., Eds.; University Park Press: Baltimore, MD, 1977; Chapter 1. (b) Shiner, V. J., Jr.; Neumann, T. E. *Z. Naturforsch.* **1989**, *44a*, 337–354.

(21) Shiner, V. J., Jr.; Nollen, D. A.; Humski, K. *J. Org. Chem.* **1979**, *44*, 2108–2115.

(22) Streitwieser, A., Jr.; Dafforn, G. A. *Tetrahedron Lett.* **1969**, 1263.

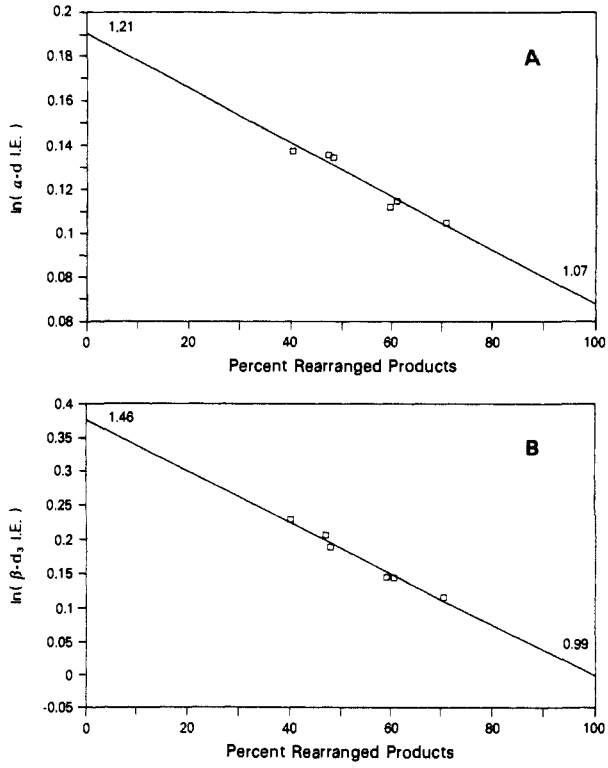


Figure 2. Correlation of the isotope effects on solvolysis rates of 1-(1-adamantyl)ethyl brosylate vs product yields: (A) α-*d* isotope effect; (B) β-d_3 isotope effect.

and must have a transition state responsible for the overall lowering of the α-*d* effects below 1.15 and the β-d_3 effects below 1.20. While the magnitudes of the isotope effects in these solvents are similar to those obtained for neopentyl sulfonate esters which solvolyze with participation by a neighboring methyl group during irreversible ionization,[5a,b] such a mechanism can not be operative here for it would require all of the ester to solvolyze by this route and, therefore, would not accommodate the evidence already given supporting the existence of the secondary ion-pair intermediate.

The only possibility that seems feasible to us to explain the lowering of the isotope effects is that the rearranged tertiary ion pair (**7**) is also an intermediate and *that it is at least partly involved in the rate-determining step.* When the α-*d*-substituted secondary ion pair rearranges, the deuterium becomes situated at the β position relative to the new carbonium ion center and a carbon–carbon single bond replaces the original carbon–oxygen bond at the α-carbon. The fractionation factor of the original α-deuterium in this rearranged structure relative to the initial state can be approximated from fractionation factors calculated for small molecules to be about 1.07.[23] For the β-d_3-substituted secondary ester, which after rearrangement would give deuterium situated in the γ-position relative to the tertiary cationic center, the expected H/D fractionation factor is 1.0 because β-substituents have been shown to have little effect on α-H/D fractionation factors if the β-carbon does not have a vacant p orbital.[13,20]

(23) It is known that the effect on the H/D fractionation factor of a given change for a group attached at the α-carbon atom, in this case a C–C bond for C–O bond, is roughly independent of the other groups attached at that atom.[13,20] Thus, the fractionation factor calculated for methyl alcohol relative to ethane would adequately model the change in environment of the α-*d*-substituted ester when it rearranges to the tertiary ion pair. When the calculated fractionation factor for methanol (relative to acetylene) is divided by the fractionation factor for ethane (relative to acetylene) the calculated H/D fractionation factor is CH_2DOH/CH_2DCH_3 = 1.446/1.361 = 1.07. The same result is predicted by the following considerations. It has been shown that replacing an α-chlorine by carbon has a very little effect on the H/D fractionation factor (e.g., CH_3CHDCl/CH_3CHDCH_3 = 1.00).[20] In solvolysis it has been determined that the maximum α-*d* isotope effect for a chlorine leaving group is about 1.15 while the maximum for a sulfonate leaving group is 1.23;[1] it follows that the effect on an initial-state fractionation factor caused by replacing α-oxygen by α-carbon is about 1.23/1.15 = 1.07.

Table VII. Percent Product Yields[a] and Percent Net Chiral Purity[b] from Solvolysis of 4-Methyl-3-homoadamantyl Heptafluorobutyrate (OHFB) (**3a**) 25 °C

solvent[c]	rearranged OHFB ester (**2f**)	rearranged alcohol (**2c**)	rearranged ether (**2d,e**)	unrearranged alcohol (**3b**)	unrearranged ether (**3c,d**)
97T	48	13		39	
	(100)	(95)		(96)	
60E	50	12		38	
80E	52	12		36	
	(99)	(96)	(97)	(97)	(98)

[a] Expressed as a percentage of total product mixture. [b] The values in parentheses are the enantiomeric excesses (ee) of each product expressed as a percentage of the ee of the starting ester (40% ee). [c] Solvents are as described in Table I.

Thus, if a significant proportion of the reaction involves rate-determining reaction of the rearranged tertiary ion pair (**7**) the observed lower isotope effects in the fluorinated solvents can be explained. Since the observed α-*d* and β-d_3 effects are not as low as 1.07 and 1.0, respectively, a significant proportion of the reaction must also proceed through the secondary ion pair. Support for this interpretation is afforded by the correlations observed for both the α-*d* and β-d_3 isotope effects with product yields (Figure 2). Both plots are fairly linear, and the extrapolated isotope effects at the extremes are mechanistically informative. This plot suggests that if the reaction proceeded with 100% rearranged products the projected values for the β-d_1 and γ-d_3 isotope effects for the rearranged ion are 1.07 and 0.99, values which are the same as the H/D fractionation factors predicted for the rearranged tertiary ion pair. At the other extreme, the extrapolated α-*d* and β-d_3 effects for the situation yielding 100% unrearranged products are 1.21 and 1.46, respectively. These values are similar to the H/D fractionation factors observed in several secondary sulfonate ester solvolyses for the reversible formation of the secondary tight ion pair followed by rate-determining solvent separation.[1,21]

If the rearranged tertiary ion pair is partly involved in the rate-determining step, as the analysis of the observed isotope effects requires, then the reverse rearrangement to the secondary ion pair must be occurring at a rate competitive with further reaction of the tertiary ion pair. In order to confirm that the reverse rearrangement of the tertiary ion is important and that it undergoes internal return, we investigated the solvolysis of an ester of the alcohol having the Wagner–Meerwein-rearranged structure. Since the tertiary ester is some 10^6 times more reactive than the secondary ester a direct comparison of the reactions of the same sulfonate esters of the two alcohols is operationally difficult. To overcome this problem the slower heptafluorobutyrate (OHFB) leaving group was used. Farcasiu[24] has shown that OHFB is a convenient leaving group to use in mechanistic studies of tertiary reactants because its reactivity is comparable to that of the chloride leaving group. In addition, from ^{18}O labeling studies he has shown that the solvolysis of these tertiary esters is not complicated by the occurrence of acyl–oxygen cleavage.

In Table VII are shown the products and stereochemical results from the solvolysis of chiral (40% ee 4-**R**) 4-methyl-3-homoadamantyl heptafluorobutyrate (**3a**) in three different solvents. The chiral alcohol from which the ester was prepared was that formed stereospecifically from the solvolysis of chirally enriched **2a** in 90H.[25] In each solvent it is apparent that the rearrangement of the tertiary structure is important for the major product is 1-(1-adamantyl)ethyl heptafluorobutyrate (**2f**) resulting from cationic rearrangement and internal return capture by the OHFB anion. Since the secondary ester is some 10^6 times less reactive than the starting tertiary ester it remains inert under the reaction

(24) Farcasiu, D.; Jahme, J.; Ruchardt, C. *J. Am. Chem. Soc.* **1985**, *107*, 5717–5722.

(25) The assignment of the tertiary alcohol as having the predominant *R* configuration at the 4-position is based upon the absolute configuration assigned to the α-carbon of the secondary alcohol (ee *R*)[32] from which **2a** is prepared and the assumption that rearrangement of the secondary ion pair occurs with inversion of configuration.

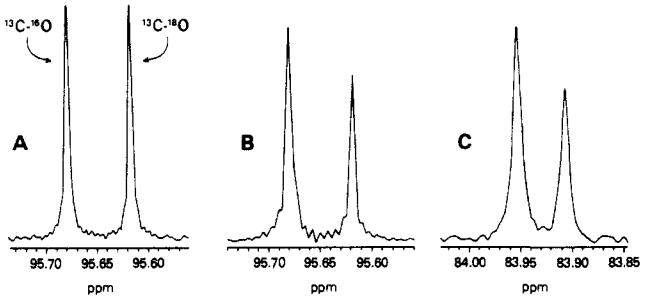


Figure 3. The ^{13}C–O resonances of the α-carbon in the natural abundance ^{13}C NMR spectra at 125 MHz of (A) the ester **3a** before solvolysis in 80E (% ^{18}O is 50.7), (B) the isolated unreacted ester **3a** after 80E solvolysis for 1 half-life (% ^{18}O is 43.7), (C) the isolated product ester **2f** from 80E solvolysis of **3a** for 1 half-life (% ^{18}O is 41.6).

conditions. In addition, significant proportions of the unrearranged tertiary substitution products as well as small yields of rearranged secondary substitution products are also found. Within the limits of ^1H NMR detection no elimination product was observed. In each solvent the products are formed stereospecifically; the secondary ester and the secondary substitution products have the same chiral purity as that of the starting ester with each being formed with complete inversion at the secondary carbon center giving an enantiomeric excess of the *R* configuration. The tertiary substitution products are formed with retention of configuration and no detectable loss of chiral purity. In contrast to the solvolysis of 1-(1-adamantyl)ethyl brosylate, where the product yields varied with solvent polarity, nucleophilicity and basicity, the product yields from solvolysis of the tertiary ester are, within experimental error, the same in all three solvents. Thus it seems that the tertiary solvolysis must involve a branch to yield the products in which the rates of the irreversible competing reactions do not differ significantly in their demands on these solvent properties. This solvent invariant behavior as well as the stereochemical results can be adequately explained by a mechanism involving the reversibly formed tertiary tight ion pair as an intermediate which undergoes both rate-determining dissociation to the solvent separated tertiary ion pair and rate-determining rearrangement to the secondary tight ion pair. From Hammond's postulate[26] it is expected that the transition state for both steps would closely resemble the tertiary ion pair in structure and the role of solvent in favoring one reaction over the other would be minimal. The secondary cation formed after rearrangement in the ion pair is exclusively trapped at the backside of the chiral center by combination with the OHFB anion to give the secondary ester with complete inversion at the α-carbon. Solvent nucleophilic attack on the secondary ion pair (as occurs in part in the solvolysis of **2a**, especially in 80E, Table III) appears not to be important in this case; it would give product with overall retention of configuration at the chiral center and a loss of net chiral purity. No such loss of chirality in the secondary products is observed. Thus it seems probable that the small yield of secondary substitution product is formed after solvent separation and rearrangement of the tertiary ion pair. Rearrangement within the tight ion pair must lead to dominant capture by the counter ion and the formation of rearranged secondary ester.

If the solvolysis of the tertiary ester involves the tertiary tight ion pair as an intermediate then internal return might also be involved. In order to confirm this we investigated the extent of ^{18}O equilibration accompanying solvolysis of ether ^{18}O labeled tertiary ester. The OHFB ester was prepared from 4-methyl-3-homoadamantanol enriched to the extent of 50.7% with ^{18}O. After solvolysis in buffered 80E for 1 half-life the unreacted tertiary ester, the rearranged secondary ester and the solvolysis products were isolated and the ^{13}C–O resonances in the ^{13}C NMR spectra were inspected to determine the amount of ^{18}O present.

In Figure 3 are shown the recorded 125-MHz spectra of the ^{13}C–O resonances of the starting tertiary ester and the isolated tertiary and secondary esters after solvolysis for 1 half-life. In the ^{13}C NMR spectra of the tertiary and secondary substitution products no ^{13}C–^{18}O resonances were detected for the α-carbon and so it can be concluded that acyl–oxygen cleavage of the ester did not occur. In the isolated, unreacted tertiary ester we observed that the percentage ^{18}O attached at the α-carbon decreases from 50.7% to 43.7%. Since complete equilibration would result in 25.3% ^{18}O at the α-carbon the proportion of unreacted ester that becomes equilibrated is 27.6%. A kinetic analysis of the data (see Experimental Section) gives the ratio of the oxygen equilibration rate to the solvolysis rate (k_{eq}/k_t) of 0.50 and the estimated minimum fraction of internal return is 0.33. Here again it must be recognized that k_{eq} does not correspond to total return if the oxygen atoms are not equivalent in the ion-pair intermediate. If ionic recombination with the originally linked oxygen is faster than with the original carbonyl oxygen then a significant amount of hidden return remains undetected.

Goering and Humski[27] observed that a significant amount of hidden return occurs in the solvolysis of 1,2-dimethyl-*exo*-2-norbornyl *p*-nitrobenzoate. Being able to estimate independently a lower limit of the magnitude of internal return from the rate of racemization and the chirality of the products, they concluded that the observed ^{18}O equilibration rate accounted for only 20% of the total estimate of internal return.[28] While there is no doubt that a significant amount of hidden return occurs during solvolysis, some of the details of the ^{18}O equilibration remain unresolved because the extent of ^{18}O scrambling within each enantiomer was not determined. For example, the ratio of the rate of ^{18}O equilibration to the rate of racemization ($k_{eq}/k_{rac} = 0.5$) can be explained by the possibility that return from the inverted ion pair formed after the Wagner–Meerwein rearrangement occurs equally with both oxygens of the anion of the ion pair. That is, the oxygens in the anion of the ion pair after rearrangement are equivalent. However, this would also require that essentially all of the internal return of the ion pair of the starting enantiomer occur with the originally linked oxygen while the opposite enantiomer of the reactant is formed with oxygen labels completely scrambled. Alternatively, there is the possibility that ^{18}O equilibration occurs for both ion pairs with hidden return being important for both but not necessarily of equal magnitude.

In our case the results appear to support the latter explanation because the recovered tertiary OHFB ester, which is incapable of racemizing, shows extensive ^{18}O equilibration. However, in order to confirm that hidden return occurs, the determination of the extent of ^{18}O equilibration in the recovered secondary OHFB ester is important. The secondary ester, just as the inverted isomer of the norbornyl ester mentioned above, is also formed after a Wagner–Meerwein rearrangement from an ion pair intermediate, but, unlike the former example, it is a stable product in the reaction. We observe that the ^{18}O content at the α-carbon of the secondary ester is 41.6% which indicates that the ester is only 36% scrambled. Since the scrambling is incomplete it is apparent that the oxygens in the OHFB anion are not equilibrated. In fact an analysis of the data using integrated rate equations for a scheme which takes into account that the secondary ester is formed both from unscrambled starting ester and from ester that has been scrambled during the course of the reaction (see Experimental Section), indicates that the return of the original alkyl-linked oxygen is favored over the carbonyl oxygen attachment by a factor

(26) Hammond, G. S. *J. Am. Chem. Soc.* **1955**, *77*, 334–339.

(27) Goering, H. L.; Humski, K. *J. Org. Chem.* **1975**, *40*, 920–922.

(28) A more accurate estimate of the amount of return can be obtained by use of the steady state equations of Vogel[29] for a model solvolysis system involving an optically active ion pair intermediate which can return, racemize or solvolyze. Using the integrated rate equations derived from the steady state approximation we calculate that the rate of total return in the solvolysis of their norbornyl derivative is 8 times faster than the observed rate of ^{18}O equilibration and 4 times faster than the observed rate of racemization. Or, to put it another way, for every 16 ion pairs that undergo internal return 15 return with the originally bonded oxygen while one returns with the carbonyl oxygen and for every 16 ion pairs undergoing return 14 combine with the original carbon center while two return with inversion after the Wagner–Meerwein rearrangement to the opposite enantiomeric carbon.

(29) Vogel, P. C. *Can. J. Chem.* **1974**, *52*, 1937–1941.

Table VIII. Solvolysis Rates[a] and Deuterium Isotope Effects[b] for 4-Methyl-3-homoadamantyl Heptafluorobutyrate (OHFB) (**3a**) at 25 °C

solvent[c]	k_H	$k_H/k_{\beta d1}$	$k_H/k_{\gamma d3}$	k/k_{tBu}[d]
97T	~235			~56
60E	12.55	1.042	1.010	11.9
80E	1.910	1.045	1.011	9.54

[a] First-order rate constants in units 10^{-5} s^{-1}. [b] The reproducibility of the isotope effects is 0.005 or less. [c] Solvents are as noted in Table I. [d] Rate ratios relative to *tert*-butyl heptafluorobutyrate.

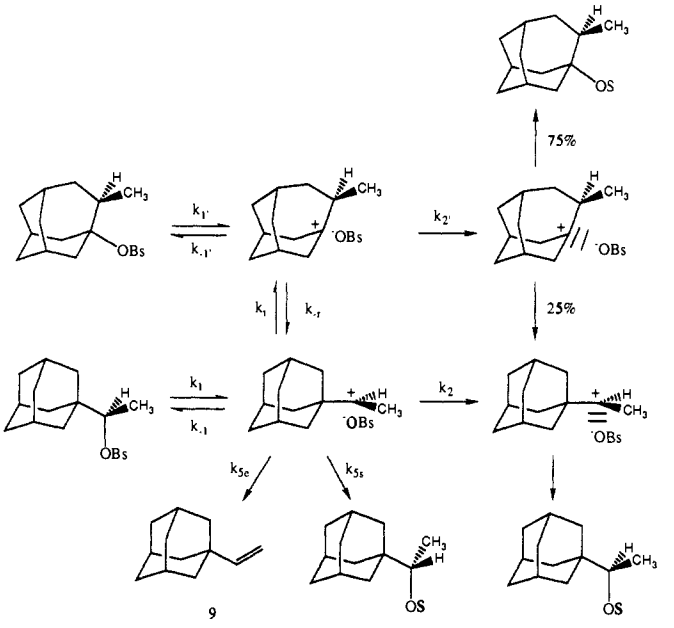
of 6.6:1. Clearly, if original oxygen return of this magnitude is observed for the ion pair formed after Wagner–Meerwein rearrangement then it must be concluded that at least the same factor of hidden return must be occurring at the tertiary ion-pair stage since recombination involves ions more tightly associated. Thus, we conclude that the tertiary OHFB ester solvolyzes with extensive internal return and therefore that ionization cannot be the rate-determining step.

In Table VIII are listed β-d_1 and γ-d_3 isotope rate effects for solvolysis of the tertiary ester as well as rates of solvolysis relative to *tert*-butyl heptafluorobutyrate. The rates were measured conductometrically and found to be first-order. For the tertiary ester in each solvent the difference between the concentration of the starting ester and the final concentration of heptafluorobutyric acid agreed reasonably well with the yield of rearranged secondary ester found in the product analyses mentioned above. In 60E and 80E, where the isotope effects could be measured accurately, the β-d_1 and γ-d_3 isotope effects were both small and invariant with solvent change. This solvent invariance of the isotope effects suggests that the rate-determining step does not change with solvent. This is consistent with the constancy of product yields already mentioned. However as shown in Table VIII the solvolytic *rates* are very much dependent on solvent polarity; the plot of the logarithm of the solvolysis rates of the tertiary ester vs those of the *tert*-butyl ester in the ETOH/water solvents yields a slope m of 1.12. In addition, the rate of the tertiary ester relative to the *tert*-butyl ester is of the magnitude to be expected from the inductive effect of the additional carbon atom substituents. These observations and the extensive ^{18}O equilibration observed in 80E are consistent with a mechanism involving reversible formation of the tertiary tight ion pair with the rate-determining steps involving further reaction of the ion pair. The small magnitudes of both the β-d_1 and γ-d_3 isotope effects indicate that the rate-determining transition state has very little of the secondary cation characteristics, i.e., the secondary ion pair is not a reversibly formed intermediate. If the transition state had the secondary carbocation structure than the β-d_1 isotope effect would be 1.15 and the γ-d_3 effect would be 1.46. On the other hand if the transition state involved solely the tertiary cation structure both effects would be near unity or a little less (β-d_1 ~0.99 and γ-d_3 ~0.95).

Thus we believe that the rate-determining steps are two which compete about equally at the tertiary tight ion-pair stage, one involving solvent separation of the tertiary cation and the other rearrangement to the secondary cation ion-pair structure. In the rearrangement step we estimate that the β-d_1 and γ-d_3 isotope effects would be around 1.08 and 1.20, respectively, although there is not a well-established precedent for this estimation and bridged-transition-state structures may well have much smaller isotope effects than those predicted from their cationic character. All of the secondary ion pair that is formed after rate-determining rearrangement is rapidly captured by combination with the OHFB anion to give the secondary ester. The tertiary solvent-separated ion pair gives the tertiary solvolysis products and a small proportion of rearrangement producing the secondary solvolysis products.

In Scheme I is shown our proposed mechanism for the solvolysis of 1-(1-adamantyl)ethyl sulfonates which we think is adequately supported by the observed isotope effects, product and stereochemical studies, and oxygen-18 equilibration results. The secondary sulfonate ester ionizes (via k_1) without neighboring carbon or solvent participation to form the secondary tight ion pair which

Scheme I



in competing processes undergoes in order of relative rate: ionic recombination (via k_{-1}), Wagner–Meerwein rearrangement (via k_r), solvent separation (via k_2) to give retained substitution product, solvent nucleophilic attack (via k_{5s}) to give inverted substitution product, and proton abstraction (via k_{5e}) to give alkene. Similarly, the rearranged tertiary tight ion pair also undergoes competing processes and in order of relative rates they are internal return (via $k_{-1'}$), rearrangement (via k_{-r}), and solvent separation (via $k_{2'}$) to give tertiary substitution products. Since rearrangement of both the ion pairs occurs, our calculations below are simplified by the assumption that the two are in equilibrium. The data do not require this but it should not be an unreasonable approximation because (1) the strain energy introduced in forming the rearranged structure is offset by the energy gained in forming the tertiary cation from the secondary cation isomer and (2) the correlation of the observed isotope effects with product yields requires both ion pairs to be involved in the rate-determining step. In addition, we also assume that a small yield of unrearranged solvolysis product is formed after rearrangement from the tertiary solvent-separated ion pair. In the product studies of tertiary OHFB ester a constant ratio (~3:1) of tertiary to secondary solvolysis products was observed in each solvent and in order to explain the configurational result of substitution of the secondary products it was concluded that they are formed after rearrangement of the tertiary structure from the solvent-separated ion pair.

To further test the proposed mechanism, a steady-state analysis, which correlates the overall observed isotope rate effects and solvent independent single step isotope effects with product yields, was carried out with use of the Simplex method of optimization.[30] The theory and operation of the Simplex method and applications to steady-state analysis of solvolysis have been previously described.[21] Steady-state equations for the mechanism were derived which relate the partitioning of intermediates to products and expected isotope effects on the partitioning steps to the overall isotope effects observed on the solvolysis rates.

In each solvent the mechanism for the undeuteriated reactant may be quantitatively specified by five reaction rate ratios which define the partitioning of the two tight ion pairs. The notation for this is indicated in part A.1 of Table IX. The mechanism for the α-d-substituted reactant can be specified for each solvent in terms of the five partitioning ratios for the undeuteriated reactant and five isotope effects on the individual steps, according to the notation given in part A.2a of Table IX. For the β-d_3 reactant the mechanism is specified analogously to the α-d reactant

(30) Spendley, W.; Hext, G. R.; Mimsworth, F. R. *Technometrics*, **1962**, *44*, 441.

Table IX. Notations

A. Mechanistic Parameters[a]

(1) Partitioning factors: one set for each solvent (defined for the undeuterated compound)

$f_{5e} = k_{5e}/(k_2 + k_{2'} + k_{5s} + k_{5e})$
$f_{2'} = k_{2'}/(k_2 + k_{2'} + k_{5s} + k_{5e})$
$f_2 = k_2/(k_2 + k_{2'} + k_{5s} + k_{5e})$
$f_{5s} = 1 - f_{5e} - f_{2'} - f_2$
$f_{-1} = k_{-1}/(k_2 + k_{2'} + k_{5s} + k_{5e})$

(2) Single-step isotope effects (generally assumed to be solvent independent)[b]

(a) α-deuteration

$r_1^\alpha = (k_1^H/k_1^{\alpha d})(k_2^{\alpha d}/k_2^H)$
$r_{-1}^\alpha = (k_{-1}^H/k_{-1}^{\alpha d})(k_2^{\alpha d}/k_2^H)$
$r_{5s}^\alpha = (k_{5s}^H/k_{5s}^{\alpha d})(k_2^{\alpha d}/k_2^H)$
$r_{2'}^\alpha = (k_{2'}^H/k_{2'}^{\alpha d})(k_2^{\alpha d}/k_2^H)$
$r_{5e}^\alpha = (k_{5e}^H/k_{5e}^{\alpha d})(k_2^{\alpha d}/k_2^H)$

(b) β-d_3 deuteration: defined by analogy with those for α-deuteration

r_1^β; r_{-1}^β; r_{5s}^β; $r_{2'}^\beta$; r_{5e}^β

B. Reaction Results (One Set for Each Solvent)

(1) Stereochemical results

F_{Si}^H: the fraction of unrearranged substitution products of the H reactant which is inverted

(2) Product yields

F_e^α, F_e^β: the fractions of elimination for the α-d and β-d_3 reactants

F_{sr}^α, F_{sr}^β: the fractions of rearranged substitution for the α-d and β-d_3 reactants

F_s^α, F_s^β: the fractions of unrearranged substitution for the α-d and β-d_3 reactants

(3) Isotope rate effects

$k_H/k_{\alpha d}$, $k_H/k_{\beta d3}$, k_H/k_{d4}: isotope effects on solvolysis rates

[a] f generally refers to "fraction" in one branch relative to the total forward reaction (note that f_{-1} can be greater than 1); subscripts refer to the reaction step; r indicates isotope effects; and superscripts refer to the position of deuteration in the reactant: α for α-d and β for β-d_3. [b] The effects on the reactions from each of the two ion pairs are only significant relative to one another. Those for the tight ion pair reactions (k_{-1}, $k_{2'}$, k_{5e}, k_{5s}) are defined relative to the effect on k_2.

by using the five single-step isotope effects indicated in A.2b of Table IX. The total number of relevant mechanistic parameters needed to define the mechanism for nine solvents is (5 partitioning ratios) 9 + 10 single-step isotope effects = 55. This number can be reduced to 46 because 9 of the 10 single-step isotope effects can be given fixed values which correspond to the fractionation factors shown in Table VI for the intermediates and transition states (**4**–**7**) involved in this solvolysis. We believe that this does not bias our minimization procedure in fitting the proposed mechanism to the reaction results because these nine isotope effects on the individual mechanistic steps, with the exception of r_{5e}^β, are well established from earlier mechanistic studies on secondary sulfonates or, as in the case of the rearranged structure, can be reliably predicted from isotope rate effect theory (vide supra).

The number of observed reaction results for each solvent include the following: the fraction of inverted, unrearranged, substitution product for the hydrogen reactant; the fractions of elimination, unrearranged substitution and rearranged substitution for both the α-d and β-d_3 compounds; and isotope rate effects for the α-d, β-d_3, and d_4 compounds. Thus, for each solvent there are 10 observable results for a 9-solvent total of 90. Since not all observations that are actually possible were made (see Table XI), the number used is 82. This number is increased by 4 to 86 by assuming that the calculated ionization rate (k_1) of 1-(1-adamantyl)ethyl brosylate has a linear logarithmic dependence on solvent as compared to the reaction rate of 2-adamantyl tosylate at 25 °C in 60E, 70E, 80E, 70T, 80T, and 97T. Thus, the system which requires 46 parametric values to fit 86 experimental observations appears to be adequately over-determined to allow the calculation of the parameters.

In order to determine the values of the parameters 10 equations are needed to calculate the 10 independently observable quantities in each of the nine solvents. For calculating the three isotope effects, we use equations derived from the steady-state assumption[31] (see supplementary material). For calculating yields, we use equations analogous to those of the steady state method, while the solvolysis rate correlation uses the logarithmic relationship of Raber and Harris.[12]

Table X. Reaction Parameter Values Which Give the Best Fit

single-step isotope effects[a]	
$r_1^\alpha = 1.155$	$r_1^\beta = 1.200$
$r_{-1}^\alpha = r_{5s}^\alpha = 0.939$	$r_{-1}^\beta = r_{5s}^\beta = 0.820$
$r_{2'}^\alpha = 0.869$	$r_{2'}^\beta = 0.684$
$r_{5e}^\alpha = 1.000$	$r_{5e}^\beta = 2.500$

	partitioning factors				
solvent	f_{-1}	f_{5e}	f_{5s}	f_2	$f_{2'}$
80E	1.829	0.185	0.106	0.219	0.490
70E	1.604	0.153	0.112	0.184	0.551
60E	1.422	0.124	0.094	0.199	0.583
70T	1.177	0.057	0.035	0.121	0.787
80T	1.198	0.058	0.030	0.125	0.787
97T	1.050	0.037	0.023	0.034	0.906
80H	1.038	0.071	0.020	0.081	0.828
90H	0.876	0.038	0.020	0.060	0.882
98H	2.202	0.037	0.023	0.147	0.793

[a] The single-step isotope effects are solvent independent and are given fixed values. It is assumed that the single step isotope effects on internal return and those on solvent nucleophilic attack on the secondary tight ion pair are the same since similar transition states are involved.

To optimize the fit of the 46 parameters to the 86 experimental observations we use the sums of the squares of the differences between the observed and calculated values ("residuals") for the reaction results. Since the observed isotope rate effects are usually obtained with a precision of 0.004 or better while the product and stereochemical yields have associated with them errors of approximately 0.02–0.03 we use differential weights for the residuals that takes into account the approximately 5-fold difference in precision. For the observed isotope effects the residuals are squared, multiplied by 5, and added to the grand sum of the squares of the residuals ($\sum R^2$). Additionally, for the k_1(solvent)/k_1(80E) values, the residual (the difference between the logarithm of the calculated and the observed rate ratios) are squared, multiplied by 0.1, and added to the grand sum of the squares of the residuals ($\sum R^2$).

In Table X are listed the values of the reaction parameters which give the best fit of the experimental data to the proposed mechanism. In the calculation all single-step isotope effects, as we have argued above, are solvent independent, and the fixed values given them from reference to earlier work fit the data satisfactorily. It was necessary, however, to adjust the primary β-deuterium isotope effect on elimination from a reversibly formed ion pair, r_{5e}^β, since this isotope effect is not as well established nor is it known with certainty how much its magnitude is affected by factors such as different bases (EtOH vs TFE) being involved in the proton abstraction. In the solvolytic study of cyclopentyl brosylate, where the yields of elimination are substantial with the relative error in their determination being low, an isotope effect of 1.78 was found to best fit the data, and it is thought to be indicative of an early transition state for the carbonium ion elimination.[21] A similar transition state is expected here; however, in the present minimization such a well defined value for r_{5e}^β was not possible due to the fact that the yields of elimination are small and, while the amounts in the EtOH/water solvents are significant, their accuracy is no doubt less certain. We find that values ranging from 2.0 to 3.0 for r_{5e}^β (which includes the primary isotope effect on elimination as well as any secondary effects that may be involved for the other two deuteriums not being eliminated) give similar optimized fits to the overall data and can account for the similar range in values of the observed product isotope effect on

(31) Reference 16, p 172.

Table XI. Reaction Results[a]

	solvent								
	80E	70E	60E	70T	80T	97T	80H	90H	98H
$k_H/k_{\alpha d}$									
obsd	1.147	1.145	1.144	1.122	1.119	1.111	1.120	1.113	1.116
calcd	1.144	1.138	1.137	1.124	1.124	1.117	1.123	1.122	1.115
R	0.003	0.007	0.007	−0.002	−0.005	−0.006	−0.003	−0.009	0.001
$k_H/k_{\beta d3}$									
obsd	1.256	1.225	1.205	1.151	1.153	1.120	1.146	1.135	1.120
calcd	1.255	1.220	1.202	1.143	1.143	1.120	1.143	1.132	1.121
R	0.001	0.005	0.003	0.008	0.010	0.000	0.003	0.003	−0.001
k_H/k_{d4}									
obsd	1.427	1.388	1.363	1.276	1.275	1.252			
calcd	1.417	1.374	1.354	1.280	1.280	1.251	1.280	1.267	1.244
R	0.010	0.014	0.009	−0.004	−0.005	0.001			
F^H_{si}									
obsd	0.245	0.265	0.220	0.100	0.085	0.085			
calcd	0.238	0.257	0.214	0.099	0.082	0.083	0.060	0.061	0.060
R	0.007	0.008	0.006	0.001	0.003	0.002			
F^α_e									
obsd	0.146	0.104	0.093	0.041	0.040	0.032	0.070	0.040	0.040
calcd	0.171	0.141	0.113	0.051	0.052	0.032	0.063	0.034	0.033
R	−0.025	−0.037	−0.020	−0.010	−0.012	0.000	0.007	0.006	0.007
F^α_{sr}									
obsd	0.396	0.466	0.476	0.604	0.590	0.689	0.660	0.700	0.640
calcd	0.391	0.436	0.460	0.606	0.606	0.687	0.635	0.671	0.610
R	0.005	0.030	0.016	−0.002	−0.016	0.002	0.025	0.029	0.030
F^α_s									
obsd	0.457	0.430	0.431	0.355	0.370	0.279	0.270	0.260	0.320
calcd	0.438	0.423	0.427	0.343	0.342	0.281	0.302	0.295	0.356
R	0.019	0.007	0.004	0.012	0.028	−0.002	−0.032	−0.035	−0.036
F^β_e									
obsd	0.051	0.042	0.033	0.025	0.020	0.030	0.030	0.030	0.030
calcd	0.065	0.052	0.041	0.017	0.017	0.011	0.021	0.011	0.011
R	−0.014	−0.010	−0.008	0.008	0.003	0.019	0.009	0.019	0.019
F^β_{sr}									
obsd	0.490	0.510	0.530	0.650	0.670		0.640	0.650	0.600
calcd	0.472	0.509	0.526	0.646	0.647	0.709	0.676	0.697	0.644
R	0.018	0.001	0.004	0.004	0.023		−0.036	−0.047	−0.044
F^β_s									
obsd	0.459	0.448	0.437	0.325	0.310		0.300	0.320	0.370
calcd	0.463	0.439	0.433	0.337	0.336	0.281	0.303	0.292	0.345
R	−0.004	0.009	0.004	−0.012	−0.026		0.027	0.028	0.025

[a] Values calculated with use of parameter values from Table X. See Table IX for notations. Blanks indicate where experimental values were not observed.

elimination for the α-*d* and β-d_3 reactants in the EtOH/water solvents. The results shown below were calculated by using 2.5 for r^β_{se}. With these selected values for the single-step isotope effects the five partitioning factors of the two ion pairs in each solvent were optimized and their final values shown in Table X.

Table XI compares the observed reaction results with those calculated with use of the optimized partitioning fractions and single-step isotope effects of Table X. Of these calculated results, 51 agree within less than 0.01 of the observed values while 13 are within 0.01–0.02, 11 within 0.02–0.03, and 7 are greater than 0.03. The agreement of the predicted isotope effects on solvolysis rates is remarkably good with 23 of the 24 predicted values agreeing within 1% of the observed values giving an average fit of 0.005 to the observed values. Similarly, the calculated product yields agree generally well within the error of the NMR product analysis with an overall average fit to the observed values being 0.016. The fact that a satisfactory quantitative fit has been achieved indicates that within the limits of experimental error our assumptions made concerning the solvent independence and the magnitudes of the single-step isotope effects are justified. Particularly gratifying is how well the theoretically predicted H/D fractionation factors for the rearranged tertiary ion pair accommodates the smaller observed isotope rate effects in TFE/water solvents. Thus, it appears that the proposed mechanism provides an adequate quantitative accounting of all our results for 1-(1-adamantyl)ethyl sulfonates.

In Table X, column 2, are shown the return factor values, f_{-1}, calculated for the reaction in each solvent. These factors represent the ratio of the internal return rate of the secondary tight ion pair (k_{-1}) relative to the combined forward rates for further reaction of the two ion pairs ($k_{5e} + k_{5s} + k_2 + k_{2'}$). Inasmuch as each of the forward rates of the ion pairs is a rate-determining step in the mechanism, the return factor can be viewed as being the ratio of the rate of internal return relative to the overall solvolysis rate (k_{-1}/k_1). Previously we have shown that return factors are not very precisely determined by the isotope effects alone; the isotope effects are not particularly sensitive to the magnitude of the return factors so long as moderate but varying amounts are allowed, especially for a reaction whose observed isotope effects on rate vary with solvent.[21] In order to impose constraints on the magnitude of the various return factors we added as an additional constraint a linear free energy relationship (LFER) of variable slope, *m*, for the ionization rate, k_1 [which is equal to the observed first-order rate constant multiplied by ($f_{-1} + 1$)], relative to the solvolysis rates for 2-adamantyl *p*-toluenesulfonate in 80E, 70E, 60E, 70T, 80T, and 97T. The return factors for the HFIP/water solvents were not included in the LFER constraint because a different leaving group (OPms) was used. The $k_1(f_{-1} + 1)$ values calculated from the return factors of Table X fit the linear free energy relationship with an *m* value of 0.892 and a correlation coefficient of 0.999 (Figure 1). In comparison to the slope of the analogous LFER plot for the observed solvolysis rates ($m = 0.96$; corr coeff = 0.999) the smaller slope for the calculated ionization rates is expected since the transition state for ionization should be less sensitive to solvent ionizing power than are transition states for rate-determining reactions of reversibly formed ion pairs. In additional calculations in which the LFER restraint was not used, we observe that return factors having values smaller than those

shown in Table X result in relatively poorer fits to the observed isotope rate effects, whereas larger return factors give marginally comparable fits. Thus it appears that the added LFER restraint is useful in establishing the magnitudes of the return factors necessary to correlate the observed isotope rate effects with the single step isotope effects and the proportion of reaction going through these steps. The magnitudes for the return factors shown in Table X support the conclusion made from the ^{18}O equilibration evidence that internal return is the most competitive reaction of the secondary tight ion pair. However, the optimized values show a slight trend with solvent change whereby they gradually decrease on going from 80E (1.83) to 97T (1.05). This trend is opposite to that usually expected with changes in solvent ionizing power[21] and is probably related to rearrangement being more competitive in 97T (see f_2, values, Table X).

It is interesting to compare the return factors from the steady state treatment to the ^{18}O equilibration results for 80E and 97T. Intramolecular ^{18}O equilibration of unreacted ester occurs in both solvents, and, as the LFER plot of the two ^{18}O equilibration rates (Figure 1) indicates, its mechanism is ionic in nature, thus supporting the generally accepted view that ^{18}O equilibration results from internal return of a reversibly formed ion-pair intermediate, in this case the unrearranged secondary tight ion pair. The observed ratios of the equilibration rate relative to the solvolysis rate (k_{eq}/k_t) in these solvents are 0.96 (80E) and 0.55 (97T) whereas the calculated return factors (k_{-1}/k_t) are 1.83 (80E) and 1.05 (97T). While both these results agree in indicating that more internal return is occurring in 80E than 97T, the estimated magnitudes of internal return of these two are significantly different; the fact that the ^{18}O studies give lower estimates than the steady state treatment lends credence to the generally accepted notion that ^{18}O equilibration affords only a *minimum* estimate of the extent of internal return. In the first-order process proceeding to the condition of equilibrium distribution of oxygen labels, k_{eq} is calculated as a measure of the sum of the individual rates for recoordination of the carbocation with the sulfonyl oxygen ($k_{S=O}$) and with the originally bonded ether oxygen (k_{S-O}) assumed to occur in the ratio of 2:1 ($k_{S=O} = 2k_{S-O}$).[3b] If, in the anion of the ion pair, the originally bonded ether oxygen remains closely associated with the carbocation center then there is expected to be a greater probability that internal return will occur with this oxygen than with either one of the other two, resulting in an additional amount of return that is undetected by the measured rate of ^{18}O equilibration. Our results suggest that such hidden return occurs because the ratio of the rate of total internal return relative to the rate of ^{18}O equilibration (k_{-1}/k_{eq}) in both solvents is 1.91. Thus, the amount of hidden return that goes undetected in the two solvents is $0.91k_{eq}$. Since this amount of hidden return is supplemental to the minimal amount of return of the originally bonded oxygen that is inferred to be present in the calculation of k_{eq} ($k_{S-O} = {}^1/_3k_{eq}$), it is apparent that the ratio of the rate of return with this oxygen relative to return with one of the sulfonyl oxygens is $3.7[(0.91k_{eq} + {}^1/_3k_{eq})/{}^1/_3k_{eq}]$. The preferential favoring of return of one oxygen over another is not unexpected since return of the original oxygen involves no atomic reorganization of the ion-pair fragments while return with the sulfonyl oxygen occurs after either carbocation motion or rotation of the C–S bond in the anion has occurred. Since both these processes occur within the solvent shell surrounding the ion-pair intermediate, it is also not unreasonable to expect that the role of solvent to be minimal. The fact that the same ratios are calculated in both solvents lends support to this notion and indicates that the LFER restraint used in the steady-state treatment results in return factors that are of reasonable magnitudes.

Of particular significance to the question concerning the timing of the methyl migration step in the solvolysis of pinacolyl sulfonate esters is the comparison of the solvolysis rates of pinacolyl brosylate to the *ionization* rates for **2a** calculated from the fit of the data to the steady state equations. Since the two reactants are structural analogues, and, for the case of **2a**, the evidence supports the conclusion that ionization occurs without participation (ring expansion), then the solvolysis rate of the pinacolyl ester would be expected to be accelerated relative to the ionization of **2a** if ionization were assisted by participation of the β-CH_3 group. In each solvent the ionization rate of **2a** is greater than the rates for the pinacolyl analogue by the following factors: 2.0 (60E), 2.1 (70E), 2.3 (80E), 7.5 (70T), and 7.7 (97T). These small factors in relative rate can be attributed to the inductive effects of the additional carbon-atom substituents in the adamantyl ring system. Since the hindrance to rearrangement and participation does not slow the rate of ionization of **2a** relative to pinacolyl, the results confirm that pinacolyl esters ionize without methyl participation in the rate-determining step and that methyl migration occurs rapidly after formation of the secondary tight ion pair.

Experimental Section

Boiling points and melting points are uncorrected. NMR spectra were recorded on Varian Associates T60, HR220, and XL-300; Nicolet 360; and Bruker 500 spectrometers, and in all cases the spectra agreed with structural assignments. Chemical shifts are recorded in parts per million (ppm = δ) from tetramethylsilane (TMS) for ^1H spectra and from $CDCl_3$ (δ 77.0) for ^{13}C spectra. Polarimetric readings were obtained on a Perkin-Elmer Model 241 polarimeter. Infrared spectra were recorded on a Perkin-Elmer Model 298 spectrophotometer. Mass spectral data were obtained on a Kratos MS 80 instrument. High-performance liquid chromatography (HPLC) separations were performed on a Rainin HP Rabbit instrument equipped with a silica packed, stainless steel column (1 × 25 cm).

1-(1-Adamantyl)ethanols. The *R*-enriched alcohol was prepared from the commercially available 1-adamantyl methyl ketone (Aldrich) by using the procedure of Hawkins and Sharpless.[32] (*R*)-1-(1-Adamantyl)ethanol, mp 78–79 °C; $[\alpha]^{20}_D = -1.58°$ (c = 0.1, $CHCl_3$). The optical purity of the alcohol was determined by comparison of the intensities of the methyl doublet in the ^1H NMR by using the chiral solvating reagent (*S*)-(+)-2,2,2-trifluoro-1-(9-anthryl)ethanol (TFAE).[10] By use of 50–60 mg of TFAE with 3–5 mg of racemic 1-(1-adamantyl)ethanol in 0.7 mL of $CDCl_3$ the methyl doublet appeared as two doublets separated by 0.01 ppm on a 300-MHz instrument. Assuming that the peak shapes of each enantiomeric doublet are equivalent, the relative abundance was calculated from peak heights. In the racemic sample the relative abundance was nearly 50.2:49.8. In the optically active alcohol the relative abundance was calculated as 70.1:29.9 (40.2% ee). The dominant doublet in the spectrum was the signal at lower field and was therefore assigned to the *R* configuration. ^1H NMR (300 MHz, $CDCl_3$): δ 1.09 (d, 3 H), 1.4–1.75 (m, 12 H), 1.99 (br s, 3 H), 3.28 (q, 1 H). ^{13}C NMR (75 MHz, $CDCl_3$): δ 16.46, 28.36, 36.58, 37.28, 37.74, 75.82.

(*R*)-1-(1-Adamantyl)ethyl, 1-(1-Adamantyl)-1-deuterioethyl, 1-(1-Adamantyl)-2,2,2-trideuterioethyl, and 1-(1-Adamantyl)-1,2,2,2-tetradeuterioethyl Brosylates and Pemsylates. These sulfonate esters were prepared from the corresponding alcohols and either *p*-bromobenzenesulfonyl chloride (brosyl chloride) or pentamethylbenzenesulfonyl chloride[33] (pemsyl chloride) by a modification of the Tipson procedure.[14] The ^1H NMR spectrum of the *R*-enriched brosylate ester in the presence of TFAE showed that the relative abundance of the shifted methyl doublets is the same as that of the starting alcohol (40% ee) and that the dominant doublet corresponding to the *R* configuration also occurs at lower field. ^1H NMR (300 MHz, $CDCl_3$): δ 1.18 (d, 3 H), 1.45–1.75 (m, 12 H), 1.96 (br s, 3 H), 4.28 (q, 1 H), 7.67 (AA′, 2 H), 7.77 (BB′, 2 H). ^{13}C NMR (75 MHz, $CDCl_3$): δ 14.52, 27.97, 36.49, 36.78, 37.63, 88.84, 128.42, 129.19, 132.36, 136.93.

Oxygen-18 Labeled 4-Methyl-3-homoadamantanol. Into a 25-mL round-bottomed flask are placed 0.5 g (28 mmol) of water, 0.55 g (28 mmol) of $H_2{}^{18}O$ (97.4% ^{18}O enriched), 0.28 g of 2,6-lutidine and 9.0 g of HFIP. To the solution was added 1.0 g (*R*)-1-(1-adamantyl)ethyl brosylate, and the solution was magnetically stirred for 3 h. The solvent was removed by vacuum transfer and stored for later use. To the solid residue were added 10 mL of ethyl ether and 1 mL of water and after shaking the two layers were separated. The ethereal solution was dried ($CaSO_4$) and concentrated on a rotary evaporator. The alcohol was separated by HPLC (see Determination of Configuration of Solvolytic Products (2) for details) and 0.28 g of the labeled alcohol was obtained. ^{13}C NMR analysis of the α-carbon showed that the percent ^{18}O enrichment was 50.7%. ^{13}C NMR (300 MHz, CD_2Cl_2): δ 19.21, 28.39, 28.57, 31.77, 36.08, 36.83, 39.47, 39.93, 41.20, 43.43, 50.52, 74.00. The ^1H NMR spectrum of the chiral alcohol in the presence of *S*-TFAE showed

(32) Hawkins, J. M.; Sharpless, K. B. *J. Org. Chem.* **1984**, *49*, 3861–3862.
(33) Paleos, C.; Varveri, F. S.; Gregoriou, G. A. *J. Org. Chem.* **1974**, *39*, 3594–3595.

that the relative abundance of the shifted methyl doublet is the same as that of the starting chiral brosylate (ee 40%, 4-*R*) and that the dominant doublet occurs at lower field.

(*R*)-1-(1-Adamantyl)ethyl Heptafluorobutyrate and (4*R*)-4-Methyl-3-homoadamantyl Heptafluorobutyrate (OHFB). These esters were prepared from the corresponding chiral alcohols by the procedure of Farcasiu.[24] The ^1H spectra of the esters in the presence of *S*-TFAE showed that the relative abundance of the shifted methyl doublets is the same as that of the starting alcohols (ee 40%) and that the dominant doublet corresponding to the *R* configuration also occurs at lower field. The secondary ester: ^1H NMR (300 MHz, $CDCl_3$) δ 1.23 (d, 3 H), 1.45–1.80 (m, 12 H), 2.02 (br s, 3 H), 4.75 (q, 1 H). The tertiary ester: ^{13}C NMR (75 MHz, $CDCl_3$) δ 19.00, 27.62, 27.87, 30.81, 35.04, 35.70, 36.16, 39.13, 39.51, 40.15, 44.38, 95.84, 107.5, 107.7, 117.6, 156.7.

Oxygen-18 Labeled *p*-Bromobezenesulfonyl Chloride. A modified procedure adapted from Oae was used.[34] A solution of 20 mL of distilled 1,1,1,3,3,3-hexafluoro-2-propanol (HFIP) and 1.0 g (0.05 mol) of $H_2{}^{18}O$ (90.97% ^{18}O) was placed into a 50-mL three-necked, round-bottomed flask which was fitted with a gas inlet tube and a reflux condenser. Anhydrous conditions were maintained by attaching a $CaSO_4$ drying tube to the condenser. The solution was cooled to 0 °C and while being magnetically stirred a gentle stream of dried HCl gas was bubbled into the solution until saturation was achieved (ca. 1 h). After the solution was warmed to room temperature, 4.73 g (0.025 mol) of *p*-bromobenzenethiol was added to the solution. While the solid suspended solution was magnetically stirred, a slow stream of dried Cl_2 was introduced into the mixture for 2.0–2.5 h. During the addition the reaction mixture turns dark blue and the thiol gradually dissolves. Chlorine addition is stopped when the solution becomes homogeneous and emerald green in color. The solution was heated at 50–55 °C for 2 h during which time the solution turns an amber yellow. The HFIP was removed by distillation, and the yellow solid (6.30 g) was recrystallized with use of 150 mL of hexane to give 4.50 g of brosyl-^{18}O chloride, mp 78–78.5 °C. Concentration of the filtrate to 50 mL afforded an additional 1.25 g (combined yield 90%). 60-MHz ^1H MHz (CCl_4): δ 7.77 (AA'BB', 4 H). IR (CCl_4); 1343 cm^{-1} ($S^{18}O_2$ assymm str), 1138 cm^{-1} ($S^{18}O_2$ symm str). MS (EI): *m/e* (rel intensity) 256 (4.3), 257 (2.7) 258 (33.0), 259 (5.6), 260 (38.3), 261 (3.9), 262 (10.5), 263 (1.7).

Oxygen-18 Labeled 2,6-Lutidinium Brosylate. Sulfonyl ^{18}O labeled isopropyl brosylate was prepared from the alcohol and ^{18}O-enriched (91%) brosyl chloride by the modified Tipson procedure. A solution consisting of 0.20 g (0.71 mmol) of the ester, 0.076 g (0.71 mmol) of 2,6-lutidine, and 15 mL of 50% ETOH/50% H_2O (v/v) was heated at 65 °C for 4 h. After cooling, the solvent, 2-propanol, and isopropyl ethyl ether were removed by distillation under reduced pressure. After drying of the white solid overnight in an oven (110 °C) 0.24 g (98% yield) of 2,6-lutidinium brosylate (60% enriched with ^{18}O) was obtained. ^1H NMR (300 MHz, $CDCl_3$): δ 2.05 (s, 1 H), 2.91 (s, 6 H), 7.48 (d, 2 H), 7.55 (AA' d, 2 H), 7.85 (BB' d, 2 H), 8.14 (t, 1 H).

Solvolytic Product Determinations. 1. 1-(1-Adamantyl)ethyl Brosylate. Product studies of the α-*d* and β-d_3 esters by ^2H NMR spectroscopy were performed in the following manner. A 1.0 mL sample of the reaction mixture (approximately 0.05–0.1 M in deuterium) containing 1.1 equiv of 2,6-lutidine was transferred to an NMR tube, sealed, and allowed to react for 10 half-lives. The ^2H spectra were recorded on a Varian Associates 220-MHz and a Nicolet 360-MHz spectrometers operating at 33 and 55.4 MHz, respectively. The Fourier transform NMR spectra were taken by using between 500 and 1000 scans. Product yields were determined by comparison of peak areas by using either the cut and weigh technique or by using a programmed curve-fitting routine. Estimated errors using these methods is 2–3%. The products and the ranges, in the several solvents, of their δ values relative to external $CDCl_3$ at δ 7.26 are as follows: 1-deuterio-1-(1-adamantyl)ethylene, 5.8–6.0; 2,2-dideutero-1-(1-adamantyl)ethylene, 5.2–5.4; 1-deuterio-1-(1-adamantyl)ethanol and ethers, 3.2–3.5; 2-(trideuteromethyl)-1-(1-adamantyl)ethanol and ethers, 1.3–1.5; 4-deuterio-4-methyl-3-homoadamantanol and ethers, 2.0–2.25; and 4-(trideuteromethyl)-3-homoadamantanol and ethers, 1.0–1.25.

Solvolytic Product Determinations. 2. 4-Methyl-3-homoadamantyl Heptafluorobutyrate. Product studies of this ester by ^1H NMR spectroscopy were performed in the following manner. A 10.0-mL sample of the reaction mixture (0.005 M in ester) containing 1.1 equiv of 2,6-lutidine was allowed to react for 10 half-lives in a stoppered 25-mL round-bottomed flask. The solvent was removed by evaporation under reduced pressure (0.02 mmHg). The resulting solid residue was dissolved in 0.5 mL of $CDCl_3$ and the 300-MHz ^1H NMR spectrum recorded. Product yields were determined by comparison of peak areas of the methyl doublet of each of the products by using the cut and weigh technique. The estimated error using this method is 2–3%. The products and their δ values of the methyl doublet relative to $CHCl_3$ (δ 7.26) are as follows: 1-(1-adamantyl)ethyl heptafluorobutyrate, 1.23; 1-(1-adamantyl)ethanol, 1.10; 1-(1-adamantyl)ethyl 2,2,2-trifluoroethyl ether, 1.08; 1-(1-adamantyl)ethyl ethyl ether, 1.02; 4-methyl-3-homoadamantanol, 1.01; 4-methyl-3-homoadamantyl 2,2,2-trifluoroethyl ether, 0.98; and 4-methyl-3-homoadamantyl ethyl ether, 0.92.

Determination of Configuration of Solvolytic Products. 1. (*R*)-1-(1-Adamantyl)ethyl Brosylate. Into a 100-mL round-bottomed flask were placed 0.20 g (0.5 mmol) of (*R*)-1-(1-adamantyl)ethyl brosylate (ee 40%), 0.059 g (0.55 mmol) 2,6-lutidine, and 100 mL of reaction solvent. The flask was stoppered and kept at 25 °C for at least 2 half-lives. The solvent was removed by evaporation under reduced pressure (0.02 mmHg). To the residue were added 1 mL of water and 10 mL of diethyl ether, and after shaking the two layers were separated. The ethereal layer was dried ($CaSO_4$) and concentrated on a rotary evaporator. The residue was dissolved in a minimal amount of 90% hexane/10% ethyl acetate (v/v) and the mixture was separated by HPLC with use of the same solvent as eluent at a flow speed of 3 mL/min. The following retention times were observed for the products from solvolysis in ETOH solvents: 4.0 min, ethyl ether of 1-(1-adamantyl)ethanol; 4.4 min, ethyl ether of 4-methyl-3-homoadamantanol; 5.9 min, unreacted starting ester; 18.8 min, 1-(1-adamantyl)ethanol; 21.0 min, 4-methyl-3-homoadamantanol. The ^1H NMR spectrum of each product and unreacted ester was recorded in the presence of TFAE by the procedure outlined above in the determination of the optical purity of the chiral secondary alcohol. The results for the measured ee of the products and unreacted ester expressed as a percentage of the ee of the starting ester are listed in Table III. The absolute configuration of the secondary alcohol and secondary ethyl ether (ee *R*) were determined from the comparison of the ^1H NMR spectra of authentic samples taken in the presence of TFAE.

Determination of Configuration of Solvolytic Products. 2. (*R*)-4-Methyl-3-homoadamantyl Heptafluorobutyrate. These studies were performed in 80E and 97T as follows. Into a 100-mL round-bottomed flask were placed 0.15 g (0.4 mmol) of (4*R*)-4-methyl-3-homoadamantyl heptafluorobutyrate (ee 40%), 0.052 g of 2,6-lutidine, and 80 mL of reaction solvent. The flask was stoppered and kept at 25 °C for 10 half-lives. Workup of the product mixture was the same as that described above with the products being separated by HPLC with 90% hexane/10% ethyl acetate (v/v) as eluent at a flow speed of 6 mL/min. The following retention times were observed for the products from 97T solvolysis: 2.4 min, 4-methyl-3-homoadamantyl trifluoroethyl ether; 2.6 min, 1-(1-adamantyl)ethyl heptafluorobutyrate; 2.8 min, 1-(1-adamantyl)ethyl trifluoroethyl ether; 11.6 min, 1-(1-adamantyl)ethanol; 13.0 min, 4-methyl-3-homoadamantanol. The ^1H NMR of each product was recorded in the presence of TFAE by the procedure outlined above in the determination of the optical purity of the chiral secondary alcohol. The results for the measured ee of the products expressed as percentages of the ee of the starting ester are listed in Table VII. On the basis of the comparison of the ^1H NMR spectra of the secondary ester and secondary solvolysis products having a known ee of the *R* configuration, each of these products from the solvolysis of the tertiary ester are formed stereospecifically with inversion at the α carbon resulting in an ee of the *R* configuration.

Oxygen Scrambling Studies. 1. 1-(1-Adamantyl)ethyl Brosylate. The oxygen-18 scrambling studies of this ester were performed in 80E and 97T according to the following procedure. A 5 mM solution of the sulfonyl ^{18}O enriched (91.0% ^{18}O) 1-(1-adamantyl)ethyl brosylate in 97T (50 mg/25 mL) containing a 1.1 equiv of 2,6-lutidine was reacted at 25 °C for 1 half-life. The reaction flask was then placed in a 0 °C bath, and the solvent was removed by evaporation under reduced pressure (0.02 mmHg). The solid residue was stirred with 25 mL of diethyl ether, and the ethereal solution was washed with 10 mL of cold water, dried ($CaSO_4$), and concentrated on a rotary evaporator. The isolated solid was dissolved in 0.7 mL of $CDCl_3$, filtered, and sealed in an NMR tube. The natural abundance 75.4-MHz ^{13}C NMR spectrum was recorded on a Varian XL-300 Fourier transform spectrometer at a sweep width of 7000 Hz with a 1-s acquisition time with a 3-s delay, 36° pulse angle, and a 32K data block zero filled to 64K. Protons were broad-band decoupled and a line-broadening factor applied to the accumulated FID. In the acquired spectrum the ^{13}C-^{16}O signal of the ester occurs at 88.84 ppm and the ^{13}C–^{18}O signal occurs 0.048 ppm upfield. Assuming the peak shapes of both signals are equivalent, the amount of ^{18}O present at the α-carbon was calculated from the relative peak intensities.[35] From the

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observed percent ^{18}O incorporation the scrambling rates were calculated by standard methods[16].

Two control experiments in each solvent were performed in order to show that the observed ^{18}O scrambling is not the result of (1) chemical workup or (2) external ion return. In the first experiment 25 mg of the labeled ester was dissolved in the buffered solvent (25 mL) containing 1 equiv of 2,6-lutidinium brosylate, and the reaction mixture was worked up immediately in the same manner. In the second experiment 50 mg of the unlabeled sulfonate ester was dissolved in the buffered solvent (25 mL) containing 1 equiv of ^{18}O enriched (60.7%) 2,6-lutidinium brosylate and after solvolysis for 1 half-life the solution was worked up in the same manner. In the ^{13}C NMR spectrum of the isolated ester from both experiments, no ^{18}O was observed to be present at the α-carbon.

Oxygen Scrambling Studies. 2. 4-Methyl-3-homoadamantyl Heptafluorobutyrate. A 5.3 mM solution of the ether ^{18}O enriched (50.70%) 4-methyl-3-homoadamantyl heptafluorobutyrate in 80E (100 mg/50 mL) containing a 1.1 equiv of 2,6-lutidine was reacted at 25 °C for 9.51 h. The reaction flask was then placed in a 0 °C bath, and the workup was the same as that used in the ^{18}O studies of **2a**. The composition of the product mixture was analyzed by ^1H NMR (300 MHz) in an analogous fashion to that performed in the product studies of the tertiary ester above. In the spectrum the additional methyl doublet of the unreacted tertiary ester occurs at 0.93 ppm. The percentage ^{18}O incorporation at the α-carbon of the two esters and of the solvolysis products was determined from the natural abundance 125-MHz ^{13}C spectrum recorded on a Bruker 500-MHz Fourier transform spectrometer with the conditions for data acquisition being similar to those in the ^{18}O studies of **2a**. No ^{18}O incorporation was observed at the α-carbon of the alcohol and ether solvolysis products. In the unreacted tertiary ester and the rearranged secondary ester the percent ^{18}O present was 43.68% and 41.56%, respectively, and their recorded spectra are shown in Figure 3. The proportion of unreacted tertiary ester that was equilibrated is 27.7% [(50.7 - 43.68)/23.35 × 100] while that for the secondary ester was 36.0%. The calculation of the rate of ^{18}O equilibration (9.47×10^{-6} s^{-1}) for the tertiary ester as well as the ratio of return of the originally bonded oxygen relative to the carbonyl oxygen (6.6:1) which occurs in the formation of the secondary ester from unscrambled tertiary ester is given in detail in the Supplementary Material.[36]

Solvent Preparation. UV and Conductance Kinetic Procedures. The procedures were the same as those which have been previously reported.[5e-f,37,38]

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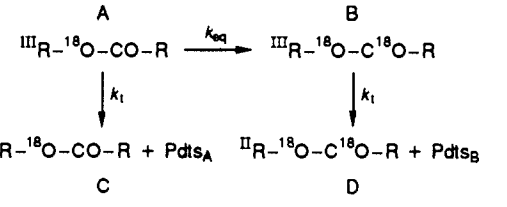
Supplementary Material Available: The details of and the equations used in the Simplex calculation of Scheme I (12 pages). Ordering information is given on any current masthead page.

(36) These calculations were determined from the equations derived by the integration factor method for the following scheme:



which takes into account that the secondary ester (C and D) is formed both from unscrambled starting ester (A) and from ester that has been scrambled (B) durining the course of reaction.

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Addition Reactions of Diarylcarbenium Ions to 2-Methyl-1-pentene: Kinetic Method and Reaction Mechanism‡

Herbert Mayr,* Reinhard Schneider, Christian Schade, Jörg Bartl, and Rainer Bederke§

Contribution from the Institut für Chemie, Medizinische Universität zu Lübeck, Ratzeburger Allee 160, D-2400 Lübeck, Federal Republic of Germany. *Received October 25, 1989*

Abstract: A kinetic method that allows the determination of reactivities of carbenium ions toward alkenes is described: Diarylmethyl chlorides (**1**) are completely ionized by BCl_3 in CH_2Cl_2 to give colored solutions of diarylcarbenium (**2**) tetrachloroborates, which show conductivity. Upon addition of the model alkene **3** (2-methyl-1-pentene) conductance and absorbance disappear due to the formation of the covalent and colorless adducts **5** ($Ar_2CH^+ \cdot BCl_4^- + H_2C{=}C(CH_3)C_3H_7 \rightarrow Ar_2CHCH_2C(CH_3)(C_3H_7)Cl + BCl_3$). The second-order reactions are linear with respect to the concentration of carbenium ions and of the alkene. Free and paired ions exhibit identical reactivity. The attack of the carbenium ions **2** on the alkene **3** is usually rate-determining, but in the case of the highly stabilized **2-OCH$_3$,OCH$_3$**, a small degree of retroaddition can be detected. Variation of the para substituents, X and Y, in the carbenium ions **2** alters $\Delta H^{\ddagger}$ while $\Delta S^{\ddagger}$ remains unaffected. Variation of solvent polarity has a very small effect on the addition rates ($k_{CH_3NO_2}/k_{CHCl_3} = 5$). Kinetic isotope effects ($k_H/k_D \approx 0.8$) and rate equilibrium relationships indicate a late transition state for the reaction of **2** with **3**. In some cases, the rates of ionization of the diarylmethyl chlorides **1** can be measured. Solvolytic studies on the adducts **5** allow the derivation of the energy of the intermediates **4**. Complete energy profiles for the multistep reaction sequence (1) are elaborated.

I. Introduction

The formation of CC bonds via attack of carbon electrophiles at CC double bonds is an important method in synthetic organic[1] and macromolecular chemistry.[2] While extensive mechanistic investigations have been carried out on various electrophilic reactions on alkenes,[3] including halogenations, hydroborations, sulfenylations, oxymercurations, and proton additions, relatively

‡This and the following two articles are dedicated to our teacher P. v. R. Schleyer on the occasion of his 60th birthday.

§Fachhochschule Lübeck.

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