(*Z*)-2-[1-Fluoro-2-(3-tolylthio)ethenyl]-3-(3-tolylthio)benzo[*b*]thiophene 1,1-dioxide (58): mp 120–1 °C. Anal. Calcd for $C_{24}H_{19}FO_2S_3$: C, 63.41; H, 4.21. Found: C, 64.15; H, 4.52.

(*Z*)-2-[1-Fluoro-2-[(4-chlorophenyl)thio]ethenyl]-3-[(4-chlorophenyl)thio]benzo[*b*]thiophene 1,1-dioxide (60): mp 150 °C. Anal. Calcd for $C_{22}H_{13}Cl_2FO_2S_3$: C, 53.34; H, 2.64. Found: C, 53.43; H, 2.80.

(*Z*)-2-[1-Fluoro-2-[(2-chlorophenyl)thio]ethenyl]-3-[(2-chlorophenyl)thio]benzo[*b*]thiophene 1,1-dioxide (61): mp 171 °C. Anal. Calcd for $C_{22}H_{13}Cl_2FO_2S_3$: C, 53.34; H, 2.64. Found: C, 53.21; H, 2.89.

(*Z*)-2-[1-Fluoro-2-[(3,4-dichlorophenyl)thio]ethenyl]-3-[(3,4-dichlorophenyl)thio]benzo[*b*]thiophene 1,1-dioxide (62): mp 168–70 °C. Anal. Calcd for $C_{22}H_{11}Cl_4FO_2S_3$: C, 46.82; H, 1.96. Found: C, 47.07; H, 1.95.

Diethylamino Substitution of 3-Alkylthio Substrates. (*Z*)-2-[2-(Diethylamino)-1-fluoroethenyl]-3-(2-propylthio)benzo[*b*]thiophene 1,1-Dioxide (64). To 1.0 g (0.0032 mol) of **53** in 20 mL of DMF was added 0.5 g (0.01 mol) of anhydrous diethylamine at room temperature. The product was stirred overnight and poured into ice water containing dilute HCl. The product was filtered and air-dried to give 1.0 g (88%) of **64**: mp 75–9 °C; ^{1}H NMR (60 MHz) 1.28 ppm (m, 12 H), 3.36 (m, 5 H), 6.60 (d, 1 H, J = 34.5 Hz), 7.30 (m, 1 H), 7.50–7.72 (m, 3 H). Anal. Calcd for $C_{17}H_{22}FNO_2S_2$: C, 57.44; H, 6.29; N, 3.94. Found: C, 57.67; H, 6.22; N, 3.82.

The diethylamino substitution products (Table VII) were prepared similarly.

(*Z*)-2-[2-(Diethylamino)-1-fluoroethenyl]-3-(*tert*-butylthio)benzo[*b*]thiophene 1,1-dioxide (65): mp 110–11 °C. Anal. Calcd for $C_{18}H_{24}FNO_2S_2$: C, 58.51; H, 6.55; N, 3.79. Found: C, 58.71; H, 6.80; N, 3.89.

(*Z*)-2-[2-(Diethylamino)-1-fluoroethenyl]-3-(1-propylthio)benzo[*b*]thiophene 1,1-dioxide (66): oil. Anal. Calcd for $C_{17}H_{22}FNO_2S_2$: C, 57.44; H, 6.24; N, 3.94. Found: C, 57.69; H, 6.17; N, 3.75.

(*Z*)-2-[2-(Diethylamino)-1-fluoroethenyl]-3-(ethylthio)benzo[*b*]thiophene 1,1-dioxide (67): mp 88 °C. Anal. Calcd for $C_{16}H_{20}FNO_2S_2$: C, 56.28; H, 5.90; N, 4.10. Found: C, 56.51; H, 6.02; N, 4.05.

(*Z*)-2-[2-(Diethylamino)-1-fluoroethenyl]-3-(methylthio)benzo[*b*]thiophene 1,1-dioxide (68): mp 119–120 °C. Anal. Calcd for $C_{15}H_{18}FNO_2S_2$: C, 55.02; H, 5.54; N, 4.28. Found: C, 54.93; H, 5.60; N, 4.15.

(*Z*)-2-[2-[(2-Chlorophenyl)thio]-1-fluoroethenyl]-3-[(4-methoxyphenyl)thio]benzo[*b*]thiophene 1,1-dioxide (63): mp 137–8 °C. Anal. Calcd for $C_{23}H_{16}ClFO_3S_3$: C, 56.26; H, 3.28. Found: C, 56.24; H, 3.23.

X-ray Crystallography of Compound 30. Compound **30** crystallized in the space group $P2_1/n$, with four molecules in a unit cell having the dimensions a = 12.798 (4) Å, b = 10.158 (2) Å, c = 9.722 (3) Å, β = 91.81 (2)°, and a calculated density of 1.51 g cm^{-3}. A total of 1597 unique reflections with 2θ less than 116.0° were measured on an automated four-circle diffractometer using monochromatic copper radiation. The structure was solved using the direct methods routine SOLV of the SHELXTL program library[29] and was refined by the least-squares method with anisotropic temperature factors for all atoms except hydrogen. All hydrogen atoms were included with isotropic temperature factors at calculated positions. The final R factor was 0.088 for 1723 observed reflections. Figure 1 shows an ORTEP plot of the molecule and Tables IX–XIV in the supplementary material give the atomic coordinates, bond lengths, bond angles, and anisotropic temperature factors.

Acknowledgment. We wish to acknowledge G. E. Babbitt and associates for NMR spectral data.

Supplementary Material Available: Tables of atom coordinates, bond lengths, bond angles, anisotropic temperature factors, hydrogen coordinates, and nonbonded distances for **30** (7 pages). Ordering information is given on any current masthead page.

(29) Sheldrick, G. M. *Shelxtl*, rev 4, 1983, from Nicolet Instrument Corp.

Solvolysis of 2-Propyl 4-Nitrobenzenesulfonate in 1,1,1,3,3,3-Hexafluoro-2-propanol

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Received January 31, 1989

The reaction of the halide nucleophiles and of 1,1,1,3,3,3-hexafluoro-2-propanol (HFIP) with methyl 4-nitrobenzenesulfonate (methyl nosylate) and 2-propyl nosylate was examined in the solvent 1,1,1,3,3,3-hexafluoro-2-propanol. A plot of the logarithm of the second-order rate constant, k_{nuc}, for reaction of the halides and solvent with 2-propyl nosylate against log k_{nuc} for reaction with methyl nosylate is linear and has a slope of 0.34. The point corresponding to the reaction with HFIP falls on the same line as the halide nucleophiles. On the basis of these results, it is suggested that the solvolysis in HFIP of the simple secondary compound 2-propyl nosylate may be occurring by a concerted S_N2 mechanism and may not involve an ion-pair intermediate.

Secondary carbon compounds are known to solvolyze in the borderline region[1] and show characteristics of both the S_N1 and S_N2 mechanisms.[2] It is often suggested that the solvolysis of simple secondary carbon compounds occurs through the formation of an intermediate,[2–9] such as an ion-pair intermediate.[2,5–7,9] However, there is no conclusive evidence for the existence of an intermediate carbocation during the solvolysis of a simple secondary substrate in solvents of moderate nucleophilicity.[10,11] Most of the

(1) Jencks, W. P. *Chem. Soc. Rev.* **1981**, *10*, 345–375.
(2) For reviews on solvolysis, see: (a) Harris, J. M. *Prog. Phys. Org. Chem.* **1974**, *11*, 89–173. (b) Bentley, T. W.; Schleyer, P. v. R. *Adv. Phys. Org. Chem.* **1977**, *14*, 1–67.
(3) Bentley, T. W.; Schleyer, P. v. R. *J. Am. Chem. Soc.* **1976**, *98*, 7658–7666.
(4) Schadt, F. L.; Bentley, T. W.; Schleyer, P. v. R. *J. Am. Chem. Soc.* **1976**, *98*, 7667–7674.
(5) Shiner, V. J., Jr.; Dowd, W.; Fisher, R. D.; Hartshorn, S. R.; Kessick, M. A.; Milakofsky, L.; Rapp, M. W. *J. Am. Chem. Soc.* **1969**, *91*, 4838–4843.
(6) Shiner, V. J., Jr.; Nollen, D. A.; Humski, K. *J. Org. Chem.* **1979**, *44*, 2108–2115.
(7) Doering, W. E.; Zeiss, H. H. *J. Am. Chem. Soc.* **1953**, *75*, 4733–4738.
(8) Bentley, T. W.; Bowen, C. T.; Morten, D. H.; Schleyer, P. v. R. *J. Am. Chem. Soc.* **1981**, *103*, 5466–5475.
(9) Paradisi, C.; Bunnett, J. F. *J. Am. Chem. Soc.* **1985**, *107*, 8223–8333.

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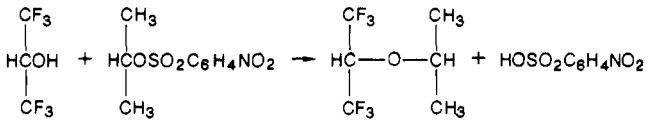
Scheme I



evidence for the existence of an intermediate comes from characterizing the transition state; however, characterizing the transition state does not prove the existence of an intermediate. Dietze and Jencks have suggested that the solvolysis of simple secondary carbon compounds can best be described as occurring by a one-step concerted S_N2 (A_ND_N) mechanism.[10,11] The concerted mechanism is thought to involve only a small amount of bond formation to the attacking nucleophile but a large amount of bond breaking to the leaving group, and the transition state may be described as an "exploded" transition state. Specifically, the solvolysis of the secondary compound 1-(4-nitrophenyl)-2-propyl tosylate in 50% aqueous trifluoroethanol does not show the behavior expected for a stepwise mechanism involving a carbocation intermediate and appears to be concerted.[10] It was expected that the points corresponding to the reaction of the solvent components with 1-(4-nitrophenyl)-2-propyl tosylate would show a positive deviation on a Swain–Scott correlation defined by stronger nucleophiles that react by a concerted mechanism, if the solvent reaction was occurring by a stepwise mechanism involving an intermediate. The observation that the points corresponding to the solvent reaction fell on the Swain–Scott correlation was suggestive that the reaction of the solvent components was also concerted. A positive deviation of the point corresponding to the reaction of the solvent on a Swain–Scott plot has been observed for the reaction of nucleophiles and solvent with 1-(4-nitrophenyl)ethyl chloride and tosylate and has been attributed to a change in mechanism for the reaction with solvent.[12] We report here that the solvolysis of 2-propyl 4-nitrobenzenesulfonate (2-propyl nosylate) in 1,1,1,3,3,3-hexafluoro-2-propanol (HFIP), a solvent that is more polar and less nucleophilic than 50% aqueous trifluoroethanol,[13] also shows no indication of the behavior that would be expected for a stepwise mechanism involving a carbocation intermediate but is consistent with a concerted mechanism involving a single transition state (Scheme I).

The second-order rate constants, k_{nuc}, for the reaction of methyl nosylate and 2-propyl nosylate in HFIP with the halide nucleophiles and with solvent at 50 °C and ionic strength 0.50 M are reported in Table I. The reaction of 2-propyl nosylate in HFIP produces propene and the hexafluoroisopropyl ether in a ratio of 75:25, the same product ratio as that observed for solvolysis of isopropyl β-naphthalenesulfonate in 97% HFIP.[14] Since the solvolysis of 2-propyl nosylate was carried out in the presence of 2,6-lutidine, as described in the Experimental Section, the propene formed does not undergo readdition of 4-nitrobenzenesulfonic acid[14] and is stable under the reaction conditions.[15] The rate constant for nucleophilic reaction

Table I. Second-Order Rate Constants for the Reaction of Halide Nucleophiles and Solvent with Methyl Nosylate and 2-Propyl Nosylate[a]

nucleophile	$10^6\ k_{nuc}$, $M^{-1}\ s^{-1}$ methyl nosylate	2-propyl nosylate
I^-	3900	1800
Br^-	450	660
Cl^-	110	600[b]
F^-	5[c]	110[c,d]
$(CF_3)_2CHOH$	0.005[e]	14[f]

[a] In HFIP at 50 °C and ionic strength 0.50 M (tetramethylammonium perchlorate). [b] Determined from NMR product studies that gave a ratio of 2-propyl chloride to hexafluoroisopropyl ether of 2.1 ± 0.4. [c] Determined at a single fluoride concentration of 1.0 M. [d] Determined from NMR product studies that gave a ratio of 2-propyl fluoride to hexafluoroisopropyl ether of 0.8 ± 0.1. [e] Determined by measuring the initial rate of appearance of 4-nitrobenzenesulfonic acid. [f] Obtained from the rate constant for solvolysis of $5.5 \times 10^{-4}\ s^{-1}$ and NMR product studies that gave a ratio of propene to hexafluoroisopropyl ether of 75:25 with a range of 70:30 to 78:22.

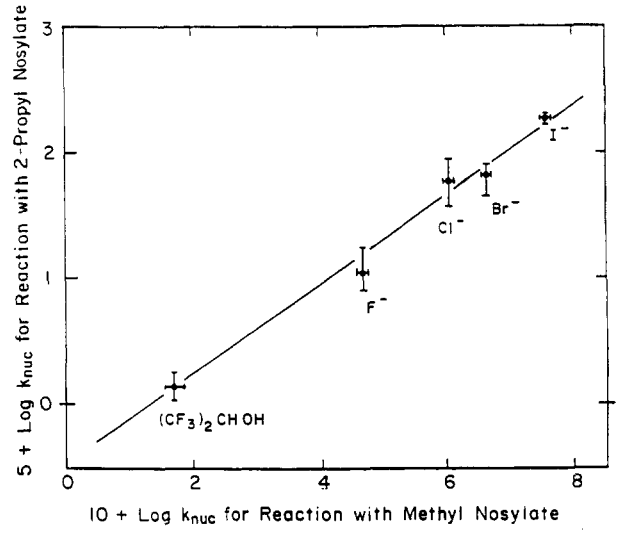


Figure 1. Comparison of nucleophilicity of the halide nucleophiles and solvent toward 2-propyl nosylate and methyl nosylate for reaction in 1,1,1,3,3,3-hexafluoro-2-propanol at 50 °C and ionic strength 0.5 M (tetramethylammonium perchlorate).

of HFIP with 2-propyl nosylate was obtained from the observed product ratios and the rate constant for solvolysis, k_{sol}, of $5.5 \times 10^{-4}\ s^{-1}$. The rate constant for solvolysis of 2-propyl nosylate in the presence of 0.50 M potassium nosylate and 0.50 M 18-crown-6 is $2.5 \times 10^{-4}\ s^{-1}$. We do not attribute this 45% decrease in rate to a common-ion effect, since the same decrease is observed in the presence of 0.50 M acetanilide and 0.50 M 18-crown-6. Rather, these observed rate decreases can be attributed to a medium effect of the nonpolar group. The absence of a common-ion rate depression suggests that a diffusionally free carbocation does not exist during solvolysis. However, a mechanism involving a carbocation intermediate as an ion pair cannot be ruled out by this result since it would not be expected to show a common-ion rate depression.

Figure 1 shows a plot of log k_{nuc} for the reaction of the halide nucleophiles and solvent with 2-propyl nosylate against log k_{nuc} for the reaction with methyl nosylate. The sizes of the boxes indicate the estimated errors in each rate

(10) Dietze, P. E.; Jencks, W. P. *J. Am. Chem. Soc.* **1986**, *108*, 4549–4555.
(11) Dietze, P. E.; Jencks, W. P. *J. Am. Chem. Soc.* **1987**, *109*, 2057–2062.
(12) Richard, J. P.; Jencks, W. P. *J. Am. Chem. Soc.* **1984**, *106*, 1383–1396.
(13) A comparison of *Y* values and *N* values for trifluoroethanol and HFIP taken from ref 4 and 5 indicate that HFIP has a higher ionizing power and is less nucleophilic than 50% aqueous trifluoroethanol.
(14) Yamataka, H.; Tamura, S.; Hanafusa, T.; Ando, T. *J. Am. Chem. Soc.* **1985**, *107*, 5429–5434.
(15) The observation that the solvolysis of *n*-propyl triflate yields some isopropyl products (Dafforn, G. A.; Streitwieser, A., Jr. *Tetrahedron. Lett.* **1970**, 3159–3162) may be due to the formation of propene followed by readdition of triflic acid. These reactions were not run in the presence of an equivalent of a base to trap any acid generated during solvolysis.

constant. A straight line of slope 0.34 is drawn through all the points including the point for reaction with solvent. The slope of 0.34 indicates that the 2-propyl substrate is less sensitive to the nucleophilicity of the attacking reagent than the corresponding methyl compound and is similar to other secondary benzenesulfonate esters in its sensitivity toward nucleophiles. The slope of this plot is similar to that observed when other secondary benzenesulfonate esters are compared to a methyl system. The Swain–Scott s value for reaction of 1-(4-nitrophenyl)-2-propyl tosylate with nucleophilic reagents in 50% aqueous trifluoroethanol is 0.27.[10] This correlation is based on n values for reaction of methyl iodide in methanol.[16] A plot of log k_{nuc} for reaction of 1-(4-nitrophenyl)-2-propyl tosylate with the halides Cl^-, Br^-, and I^- in 50% aqueous trifluoroethanol[10] against log k_{nuc} for reaction of methyl benzenesulfonate with the same halides in water[17] has a slope of 0.34 (plot not shown).

The reaction of the halide nucleophiles with 2-propyl nosylate is a concerted reaction that shows an increase in rate with increasing nucleophile concentration. A Sneen type mechanism[18] that involves formation of an ion-pair intermediate followed by diffusional encounter and reaction with a nucleophile is excluded. If the reaction occurred by a Sneen type mechanism it is expected that the reaction would show no sensitivity toward the nucleophilicity of the attacking reagent and the slope of a plot such as that shown in Figure 1 would be 0.[10] This is because all the nucleophiles studied are more nucleophilic than the nosylate leaving group so the reaction will occur at a diffusion-controlled rate.[10,19] If the reaction of solvent with 2-propyl nosylate were to occur by a mechanism different from the bimolecular mechanism followed for the halide nucleophiles, it is anticipated that the point corresponding to the solvent reaction would show a positive deviation from the correlation in Figure 1 due to the additional mechanism. The observation that the point corresponding to the solvent reaction falls on the line suggests that the solvent reaction can be accounted for by the same concerted mechanism that is followed for the more nucleophilic halides.

Although it is possible to draw a straight line through the points for the halide nucleophiles having a steeper slope than shown in Figure 1, which will lead to a positive deviation in the point corresponding to the reaction with solvent, such a line is unreasonable. A least-squares line based on the points for reaction of the halide nucleophiles has a slope of 0.42 and does show a small positive deviation for the point corresponding to the reaction with solvent. However, a slope greater than 0.34 would indicate that the reaction of a secondary nosylate in HFIP is more sensitive to the nucleophilic reagent than the reaction of a secondary tosylate in the less polar solvent 50% aqueous trifluoroethanol. This is opposite to what is predicted from a consideration of "Hammond" and "anti-Hammond" effects on transition-state structure. The reaction can be described empirically by a More–O'Ferrall–Jencks energy contour diagram[20] where the x and y axes represent bond breaking to the leaving group and bond forming to the nucleophile. Changing to a better leaving group such as from a tosylate to a nosylate lowers the right side of the diagram. The position of the transition state then is expected to move in the direction along the reaction coordinate to a position of higher energy (a Hammond effect) and to move perpendicular to the reaction coordinate to a position of lower energy (an anti-Hammond effect). The overall effect is less bond formation to the nucleophile in the transition state for the better leaving group, which is observed as a smaller sensitivity to the nucleophile. Similarly, changing to a more polar solvent will lower the lower right hand corner of the diagram, and the transition state will move perpendicular to the reaction coordinate to a position of lower energy; the new transition state will have less bond formation to the nucleophile. Since it is predicted that changing to better leaving group and to a more polar solvent will result in less sensitivity toward the nucleophilic reagent, it is expected that the slope in Figure 1 should not be larger than the value of 0.34 obtained when log k_{nuc} for the reaction of halide nucleophiles with a secondary tosylate in 50% aqueous trifluoroethanol is compared to the log k_{nuc} for the same halides reacting with methyl benzenesulfonate. Therefore, a line having a slope steeper than the indicated value of 0.34 is improbable.

Results reported here do not show behavior that would be expected for a reaction occurring by a carbocation intermediate and suggest that the solvolysis of simple secondary carbon substrates, even in solvents as polar and nonnucleophilic as HFIP, may occur by a concerted mechanism involving a single transition state.

Experimental Section

Methods. Melting points were determined on a Thomas-Hoover capillary melting point apparatus and are uncorrected. Proton NMR spectra were recorded on an IBM NR/80 spectrometer. High-pressure liquid chromatography (HPLC) was performed by using a Shimadzu HPLC system equipped with a Model SPC-6A variable-wavelength detector and a Model C-R6A electronic integrator.

Materials. 1,1,1,3,3,3-Hexafluoro-2-propanol (HFIP), 99% from Aldrich, was stored over 4A molecular sieves for several days and distilled before use. Tetramethylammonium salts were commercially available and were recrystallized from anhydrous ethanol and dried in a vacuum desiccator before use. Tetramethylammonium fluoride was purchased as the tetrahydrate and was dried by azeotropic distillation from benzene–ethanol; after azeotropic distillation, the remaining organic solvent was removed under reduced pressure and the tetramethylammonium fluoride was stored in a desiccator. 2,6-Lutidine, 99% from Aldrich, was distilled from aluminum chloride and was stored in an amber bottle. Acetanilide and 18-crown-6 were commercially available and used without further purification.

Methyl 4-nitrobenzenesulfonate (methyl nosylate) was synthesized according to a published procedure[21] [mp 89–90 °C (lit.[21] mp 91.5–92.5 °C)] and was shown to be better than 99% pure by high-pressure liquid chromatography (HPLC).

2-Propyl 4-nitrobenzenesulfonate (2-propyl nosylate) was synthesized according to a published procedure[22] (mp 45–47 °C) and was shown to be better than 98% pure by HPLC analysis.

Potassium 4-nitrobenzenesulfonate was prepared by hydrolysis of the corresponding acid chloride by refluxing for 12 h in water. The aqueous solution of 4-nitrobenzenesulfonic acid was then extracted two times with ethyl ether to remove any traces of the acid chloride. The aqueous acid solution was neutralized to pH

(16) Pearson, R. G.; Sobel, H.; Songstad, J. *J. Am. Chem. Soc.* **1968**, *90*, 319–326.
(17) Koskikallio, J. *Acta Chem. Scand.* **1972**, *26*, 1201–1208.
(18) (a) Sneen, R. A.; Larsen, J. W. *J. Am. Chem. Soc.* **1969**, *91*, 362–366. (b) Sneen, R. A.; Larsen, J. W. *J. Am. Chem. Soc.* **1966**, *88*, 2593–2595. (c) Weiner, H.; Sneen, R. A. *J. Am. Chem. Soc.* **1965**, *87*, 287–296. (d) Weiner, H.; Sneen, R. A. *Tetrahedron Lett.* **1963**, 1309–1316. (e) Sneen, R. A.; Robbins, H. M. *J. Am. Chem. Soc.* **1972**, *94*, 7868–7876. (f) Sneen, R. A. *Acc. Chem. Res.* **1973**, *6*, 46–53.
(19) For criticisms of the Sneen mechanism, see: (a) McLennan, D. J. *J. Chem. Soc., Perkin Trans. 2* **1974**, 481–485. (b) McLennan, D. J. *Acc. Chem. Res.* **1976**, *9*, 281–287. (c) McLennan, D. J. *Tetrahedron Lett.* **1975**, 4689–4692.
(20) Jencks, W. P. *Chem. Rev.* **1985**, *85*, 511–527.
(21) Morgan, M. S.; Cretchen, C. H. *J. Am. Chem. Soc.* **1948**, *70*, 375–377.
(22) Tipson, R. S. *J. Org. Chem.* **1944**, *9*, 235–241.

7 by using 1 N potassium hydroxide, and the water was removed under reduced pressure to give a yellow orange solid, which was dried overnight in a vacuum desiccator.

Kinetics. Pseudo-first-order rate constants for the reactions of bromide, chloride, and fluoride ion with methyl nosylate in the presence of excess nucleophilic reagent at 50 ± 0.5 °C and ionic strength 0.50 M (adjusted with tetramethylammonium perchlorate) were determined by measuring the decrease in absorbance of the methyl ester at 253 nm using a Gilford response spectrophotometer equipped with a thermostated cell holder. Solutions of the nucleophiles were prepared by combining known volumes of a tetramethylammonium perchlorate solution (0.50 M in HFIP) with a known volume of a tetramethylammonium halide solution (0.50 M in HFIP) to give a final volume of 2.0 mL. After temperature equilibration, 40 μL of a freshly prepared HFIP solution of methyl nosylate (2.5×10^{-2} M) was added and the disappearance of the ester was followed as a function of time. The spectrophotometer was interfaced to a PC's Limited Model 286 computer, and the pseudo-first-order rate constant, k_{obsd}, was obtained by a nonlinear regression analysis of absorbance vs time data. Reactions were generally followed for more than 3 half-lives. The nonlinear regression analysis calculated the best end point. For reactions that could be followed to completion, the observed end points always agreed well with the calculated end points. Second-order rate constants were obtained from the slopes of plots of five pseudo-first-order rate constants against the concentration of the nucleophile which ranged from 0.1 to 0.5 M, except for fluoride ion, which was determined from k_{obsd} obtained at a single fluoride concentration of 1.00 M.

The pseudo-first-order rate constant for the reaction of methyl nosylate with iodide was determined by measuring the disappearance of the methyl nosylate relative to an internal standard using HPLC. A 2.0-mL solution of tetramethylammonium iodide (0.10–0.50 M) with ionic strength 0.50 M (tetramethylammonium perchlorate) was prepared in a 4-mL glass vial as described above for the other halide nucleophiles. The vial was closed tightly with a Teflon-sealed cap and placed in a constant-temperature bath at 50 ± 0.5 °C. After temperature equilibration, the reaction was initiated by addition of 40 μL of a freshly prepared HFIP solution of methyl nosylate (2.5×10^{-2} M) and 4-nitroacetophenone (2.5×10^{-2} M). At various time intervals, a 50-μL aliquot of the reaction mixture was removed by syringe, quenched in 0.5 mL of acetonitrile, and cooled to −78 °C. The acetonitrile solutions were warmed and analyzed by HPLC separation on a 4.6 × 25 cm C-18 column using a mobile phase of 50:50 methanol–water (v/v). The peak area of the methyl nosylate and the 4-nitroacetophenone internal standard were obtained by electronic integration of their UV absorbance at 253 nm. The pseudo-first-order rate constant, k_{obsd}, was obtained from semilogarithmic plots of the methyl nosylate area relative to the internal standard against time.

The pseudo-first-order rate constant for solvolysis of methyl nosylate in HFIP (ionic strength 0.50 M with tetramethylammonium perchlorate) at 50 ± 0.5 °C was determined by measuring the initial rate of appearance of 4-nitrobenzenesulfonic acid relative to an internal standard (4-nitroacetophenone) using HPLC. The reaction was followed at 253 nm as described above except that the mobile phase was 72:18:10 water–acetonitrile–methanol (v/v/v) that was 0.045 M in tetrabutylammonium phosphate (Waters Associates PIC-A reagent). The initial rate was obtained from the slope of a plot of the ratio of 4-nitrobenzenesulfonic acid area at time t to 4-nitrobenzenesulfonic acid area at infinite time against time. The reaction was followed for the first 7% of reaction. The value of 4-nitrobenzenesulfonic acid area at infinite time was obtained by adding 40 μL of the HFIP solution of methyl nosylate and internal standard to 2.0 mL of a 0.5 M tetramethylammonium bromide solution in HFIP at 50 ± 0.5 °C; this quantitatively converted the methyl nosylate to tetramethylammonium 4-nitrobenzenesulfonate, which was analyzed by HPLC. The average of four HPLC injections of this solution was used for the ratio at infinite time.

The pseudo-first-order rate constants for the reaction of 2-propyl nosylate with halide nucleophiles and HFIP solvent were determined under the same conditions as for the methyl ester except that the reactions were always run in the presence of 1.1 equiv of 2,6-lutidine to prevent readdition of 4-nitrobenzenesulfonic acid, generated during solvolysis, to any propene that forms from elimination.[14] The pseudo-first-order rate constant for solvolysis was determined by using the HPLC (56:44 water–methanol, v/v) or the spectroscopic methods described above. The relative amounts of alkene product and hexafluoroisopropyl ether product formed during solvolysis of 2-propyl nosylate were determined by NMR analysis of the reaction mixture. An HFIP solution of 2-propyl nosylate (1×10^{-2} M) containing 1.1 equiv of 2,6-lutidine was sealed in an NMR tube and allowed to react at 50 ± 0.5 °C for 10 half-lives. The NMR tube also contained a sealed capillary tube containing benzene-d_6 as a lock signal. The methyl hydrogens of 2,6-lutidine were used as a reference (singlet at 2.5 ppm). The amounts of propene and the hexafluoroisopropyl ether were determined from the relative intensities of their methyl signals. The methyl hydrogens of propene occur as a doublet of triplets centered at 1.5 ppm (J = 5, 1.5 Hz); the methyl hydrogens of the hexafluoroisopropyl ether occur as a doublet centered at 1.1 ppm (J = 5 Hz). The relative intensities of the NMR signals obtained after 13 half-lives were the same as obtained after 10 half-lives. The pseudo-first-order rate constant for nucleophilic attack by HFIP on 2-propyl nosylate, k_{HFIP}, can be obtained from the following relationships:

$$k_{sol} = k_{alkene} + k_{HFIP} \quad (1)$$

$$\frac{[\text{propene}]}{[\text{hexafluoroisopropyl ether}]} = \frac{k_{alkene}}{k_{HFIP}} \quad (2)$$

where k_{sol} is the rate constant for solvolysis and k_{alkene} is the rate constant for formation of alkene product.

The second-order rate constant for reaction of 2-propyl nosylate (1.0×10^{-2} M) with chloride ion (0.50 M) was determined by using NMR by measuring the relative intensities of the methyl hydrogens of 2-propyl chloride (doublet centered at 1.25 ppm, J = 5 Hz) relative to the methyl hydrogens of the hexafluoroisopropyl ether. The second-order rate constant k_{nuc} is obtained from the following equation:

$$\frac{[\text{2-propyl chloride}]}{[\text{hexafluoroisopropyl ether}]} = \frac{k_{nuc}[Cl^-]}{k_{HFIP}} \quad (3)$$

The second-order rate constant for reaction of 2-propyl nosylate with fluoride ion was obtained by using NMR as was done with chloride ion except that the solution was 1.0 M in fluoride ion. The methyl hydrogens of 2-propyl fluoride appeared as a doublet of doublets (J_{HH} = 5 Hz, J_{HF} = 24 Hz); the doublets were centered at 0.9 and 1.3 ppm.

The rate constant for reaction of bromide with 2-propyl nosylate was determined by using the UV spectroscopic method described above for the reaction with methyl nosylate. The rate constant for reaction of 2-propyl nosylate with iodide was obtained by using the HPLC method described above except that the mobile phase was 56:44 water–methanol (v/v).

Acknowledgment. This work was funded in part by an institutional DRIF grant from the University of Maryland.