J. Am. Chem. Soc. **1993,** *115,* 8465–8466

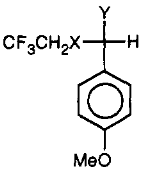
Kinetic and Thermodynamic Stabilities of α-Oxygen- and α-Sulfur-Stabilized Carbocations in Solution

Vandanapu Jagannadham,[1a] Tina L. Amyes, and
John P. Richard*,[1b]

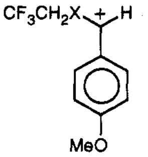
Department of Chemistry
University of Kentucky
Lexington, Kentucky, 40506-0055

Received June 3, 1993

Despite a great deal of experimental and theoretical work, there is still uncertainty about the relative effects of α-oxygen and α-sulfur substituents on carbocation stability. Gas-phase and theoretical studies show that an α-SMe group provides *ca.* 2–3 kcal/mol more stabilization of the methyl cation than does an α-OMe group, relative to the chloride ion adducts.[2a] By contrast, solution studies show that α-O-substituted carbocations generally form more rapidly in solvolysis than the corresponding α-S species, which suggests that an α-oxygen provides somewhat more stabilization of a carbocation than does an α-sulfur.[2b] We report kinetic and thermodynamic data for formation of CF_3CH_2O-**2** and CF_3CH_2S-**2** in trifluoroethanol/water that resolve this apparent contradiction. These data show that the relative thermodynamic barriers to the formation of CF_3CH_2O-**2** and CF_3CH_2S-**2** are similar to those observed in the gas-phase work but that the relative kinetic barriers to formation and reaction of these species do not follow their thermodynamic stabilities.



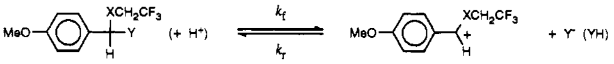
CF_3CH_2X-1-Y



CF_3CH_2X-2

CF_3CH_2O-**1**-N_3 and CF_3CH_2S-**1**-N_3 were synthesized by reaction of N_3-**1**-N_3 with $CF_3CH_2O^-$ and $CF_3CH_2S^-$, respectively.[5] The solvolyses of CF_3CH_2O-**1**-N_3 and CF_3CH_2S-**1**-N_3 in 50:50 (v:v) trifluoroethanol/water are subject to strong azide common ion inhibition, which shows that these substrates react by a stepwise mechanism through the liberated carbocation intermediates CF_3CH_2O-**2** and CF_3CH_2S-**2**, respectively.[6] Analysis of the data for azide common ion inhibition by standard methods[7] gives k_{az}/k_s = 60 and 71 000 M^{-1} respectively for partitioning of CF_3CH_2O-**2** and CF_3CH_2S-**2** between capture by azide ion and by solvent.

Table I. Rate and Equilibrium Constants for Formation and Reaction of α-Oxygen- and α-Sulfur-Stabilized 4-Methoxybenzyl Carbocations in 50:50 (v:v) Trifluoroethanol/Water[a]



rate constant	X = O, Y = N_3	X = S, Y = N_3
k_{solv} (s^{-1})[b]	3.6×10^{-4}	4.2×10^{-4}
k_{az} (M^{-1} s^{-1})[c]	5×10^{9}	5×10^{9}
K_{az} (M)[d]	7.2×10^{-14}	8.4×10^{-14}

rate constant	X = O, Y = OCH_2CF_3	X = S, Y = OCH_2CF_3
k_H (M^{-1} s^{-1})[e]	0.23	5.4×10^{-3}
k_{TFE} (M^{-1} s^{-1})[f]	2.2×10^{5}	2.4×10^{2}
K_{TFE}[g]	1.0×10^{-6}	2.3×10^{-5}

[a] At 25 °C and $I = 0.50$ ($NaClO_4$). [b] Pseudo-first-order rate constant for solvolysis of CF_3CH_2X-**1**-N_3. [c] Diffusional rate constant.[7,9,10] [d] k_{solv}/k_{az}. [e] The slope of a plot of k_{obsd} for C–O bond cleavage against [H^+] for reactions at six different [H^+]. The observed rate constants have not been corrected for trapping of CF_3CH_2X-**2** by trifluoroethanol to regenerate reactant. Product yields from the reaction of CF_3CH_2X-**2**, generated by solvolysis of CF_3CH_2X-**1**-N_3, show that this correction (*ca.* 2%) is smaller than the experimental error of ±5%. [f] Determined from k_{HOH}/k_{TFE} and k_{az}/k_s (M^{-1}) for partitioning of CF_3CH_2X-**2** and $k_{az} = 5 \times 10^9$ M^{-1} s^{-1}, see text. [g] k_H/k_{TFE}.

Rate and equilibrium constants for formation of CF_3CH_2X-**2** from the azide ion adducts (α-azido ethers) in 50:50 (v:v) trifluoroethanol/water at 25 °C and $I = 0.50$ ($NaClO_4$) are given in Table I. The rate constants are k_{solv} (s^{-1}) for the stepwise solvolysis reactions of CF_3CH_2X-**1**-N_3 in the absence of azide ion[6,8] and $k_{az} = 5 \times 10^9$ M^{-1} s^{-1} for diffusion-limited trapping of the very reactive carbocations CF_3CH_2X-**2** by N_3^-.[7,9,10] Values for K_{az} were calculated as the ratio of rate constants for carbocation formation and reaction, K_{az} (M) = k_{solv}/k_{az}.

CF_3CH_2O-**1**-OCH_2CF_3 and CF_3CH_2S-**1**-OCH_2CF_3 were synthesized by reaction of $CF_3CH_2O^-$ with N_3-**1**-N_3 (prolonged reaction) and CF_3CH_2S-**1**-N_3, respectively.[11] Rate and equilibrium constants for formation of CF_3CH_2X-**2** from the trifluoroethoxide ion adducts in 50:50 (v:v) trifluoroethanol/water at 25 °C and $I = 0.50$ ($NaClO_4$) are given in Table I. Rate constants k_H (M^{-1} s^{-1}) were determined for the $HClO_4$-catalyzed cleavage of CF_3CH_2X-**1**-OCH_2CF_3.[6] Identical yields (76%) of CF_3CH_2S-**1**-SCH_2CH_2OH are obtained from the reactions of CF_3CH_2S-**1**-N_3 and CF_3CH_2S-**1**-OCH_2CF_3 (at [$HClO_4$] = 0.01 M) in 20% acetonitrile in water that contains 1% $HSCH_2CH_2OH$.[12] This shows that the acid-catalyzed reaction of CF_3CH_2S-**1**-OCH_2CF_3 proceeds by C–O cleavage to give CF_3CH_2S-**2**. A similar cleavage pattern has been reported for

---

(1) (a) V.J. was granted on-duty leave from the Department of Chemistry, Nizam College, Osmania University, Hyderabad-500001, India. (b) Address correspondence to John Richard, Department of Chemistry, University at Buffalo, State University of New York, Buffalo, NY 14214.

(2) (a) References to theoretical and gas-phase studies are summarized in ref 3. (b) Measurements of the relative rate constants for solvolysis through putative α-O- and α-S-substituted carbocation intermediates are summarized in ref 4.

(3) Apeloig, Y.; Karni, M. *J. Chem. Soc., Perkin Trans. 2* **1988,** 625–635.

(4) (a) Jensen, J. L.; Jencks, W. P. *J. Am. Chem. Soc.* **1979,** *101,* 1476–1488. Santry, L. J.; McClelland, R. A. *J. Am. Chem. Soc.* **1983,** *105,* 3167–3172.

(5) CF_3CH_2O-**1**-N_3 was prepared by reaction of 200 mg of diazido-(4-methoxyphenyl)methane [N_3-**1**-N_3: Amyes, T. L.; Richard, J. P. *J. Am. Chem. Soc.* **1991,** *113,* 1867–1869] in 5 mL of trifluoroethanol containing 2 M $NaOCH_2CF_3$ for 90 min at room temperature. Contaminating CF_3CH_2O-**1**-OCH_2CF_3 was removed by chromatography on silica gel, eluting with 1:1 benzene/hexane (40% yield). CF_3CH_2S-**1**-N_3 was prepared by reaction of 100 mg of N_3-**1**-N_3 in 40 mL of 25:15 DMSO/water containing 2 equiv of $NaSCH_2CF_3$ for 1 h at room temperature. Purification by column chromatography on silica gel, eluting with 4.5:4.5:1 hexanes/CH_2Cl_2/EtOAc, gave CF_3CH_2S-**1**-N_3 (70% yield). These compounds were characterized by ^1H NMR and by the strong IR bands at 2110 cm^{-1} for the azido group.

(6) The reactions were followed spectrophotometrically by monitoring the appearance of 4-methoxybenzaldehyde at 272 nm. Pseudo-first-order rate constants (k_{obsd}, s^{-1}) were obtained from the slopes of semilogarithmic plots of reaction progress against time.

(7) Amyes, T. L.; Jencks, W. P. *J. Am. Chem. Soc.* **1989,** *111,* 7888–7900.

(8) The large selectivity of CF_3CH_2S-**2** for reaction with azide ion leads to inhibition of the reactions of CF_3CH_2S-**1**-N_3 by the small amount of azide ion that forms as a reaction product. Therefore, k_{solv} for this compound was determined in the presence of a low concentration of $HClO_4$ in order to protonate the azide ion produced. Identical values of k_{solv} were determined at [$HClO_4$] = 0.001 and 0.003 M.

(9) (a) Richard, J. P.; Rothenberg, M. E.; Jencks, W. P. *J. Am. Chem. Soc.* **1984,** *106,* 1361–1372. (b) Richard, J. P. *J. Am. Chem. Soc.* **1989,** *111,* 1455–1465. (c) Amyes, T. L.; Richard, J. P. *J. Chem. Soc., Chem. Commun.* **1991**, 200–202.

(10) McClelland, R. A.; Kanagasabapathy, V. M.; Banait, N. S.; Steenken, S. *J. Am. Chem. Soc.* **1991,** *113,* 1009–1014.

(11) CF_3CH_2O-**1**-OCH_2CF_3 was prepared from N_3-**1**-N_3 as described in ref 5 for the synthesis of CF_3CH_2O-**1**-N_3, except that the reaction was stirred overnight at room temperature. This gave the acetal in an overall purity of 99% which was used directly. CF_3CH_2S-**1**-OCH_2CF_3 was prepared by reaction of 45 mg of CF_3CH_2S-**1**-N_3 in 5 mL of trifluoroethanol containing 0.5 M $NaOCH_2CF_3$ at room temperature overnight. Purification by column chromatography on silica gel, eluting with 1:1 benzene/hexane, gave CF_3CH_2S-**1**-OCH_2CF_3 (89% yield). These compounds were characterized by ^1H NMR.

(12) Product yields were determined by HPLC analysis as described in previous work.[9a,b]

0002-7863/93/1515-8465$04.00/0

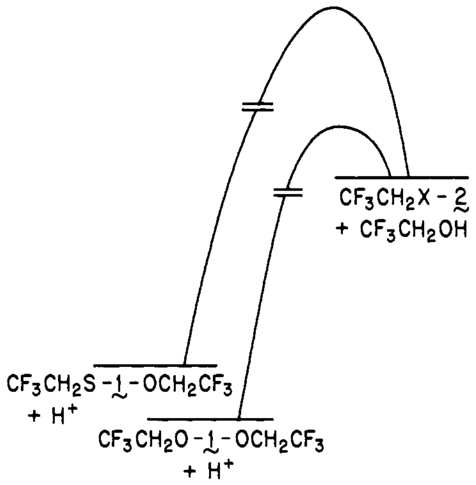


Figure 1. Reaction coordinates for acid-catalyzed formation of CF_3CH_2O-**2** and CF_3CH_2S-**2** from the respective trifluoroethoxide ion adducts constructed using data from Table I. The figure is drawn to show the minimum difference in the ground-state stabilization of CF_3CH_2O-**1**-OCH_2CF_3 and CF_3CH_2S-**1**-OCH_2CF_3 by electronic geminal interactions,[3,13] which was estimated from the difference in the values for K_{az} and K_{TFE} (Table I) to be 1.8 kcal/mol.

the acid-catalyzed reaction of MeO_2CCH_2S-**1**-OEt.[4a] Values of k_{HOH}/k_{TFE} = 13.6 and 10.1, respectively, for partitioning of CF_3CH_2O-**2** and CF_3CH_2S-**2** between capture by water and trifluoroethanol in 50:50 (v:v) trifluoroethanol/water ($I = 0.50$, $NaClO_4$) were determined from product yields in the solvolysis reactions of CF_3CH_2X-**1**-N_3.[12] Absolute rate constants k_{TFE} (M^{-1} s^{-1}) for capture of CF_3CH_2O-**2** and CF_3CH_2S-**2** by trifluoroethanol (Table I) were calculated from the values of k_{HOH}/k_{TFE}, k_{az}/k_s (M^{-1}, see above), and $k_{az} = 5 \times 10^9$ M^{-1} s^{-1}, using eq 1.

$$k_s(s^{-1}) = k_{HOH}[HOH] + k_{TFE}[TFE] \qquad (1)$$

Table I gives the equilibrium constants for formation of CF_3CH_2X-**2** from the corresponding trifluoroethoxide ion adducts, calculated as the ratio of rate constants for carbocation formation and reaction, $K_{TFE} = k_H/k_{TFE}$.

The following conclusions can be drawn from the data in Table I.

(1) The equilibrium constants K_{az} (M) and K_{TFE} for the formation of CF_3CH_2O-**2** and CF_3CH_2S-**2** show that these carbocations have about the same thermodynamic stability relative to the azide ion adducts and that CF_3CH_2S-**2** is *ca.* 1.8 kcal/mol more stable than CF_3CH_2O-**2** relative to the trifluoroethoxide ion adducts. These results are in qualitative agreement with the results of gas-phase and theoretical studies which show that an α-SMe group provides slightly more stabilization of the methyl carbocation than does an α-OMe group relative to the chloride ion adducts.[3]

(2) The larger difference in K_{TFE} for formation of CF_3CH_2O-**2** and CF_3CH_2S-**2** from the trifluoroethoxide ion adducts (20-fold) than in K_{az} (M) for formation of these species from the azide ion adducts (1.2-fold) reflects a relatively large difference between strong ground-state stabilization by oxygen–oxygen geminal interactions in CF_3CH_2O-**1**-OCH_2CF_3 and weaker stabilizing oxygen–sulfur interactions in CF_3CH_2S-**1**-OCH_2CF_3 and a smaller difference in geminal interactions in CF_3CH_2O-**1**-N_3 and CF_3CH_2S-**1**-N_3. The importance of these ground-state effects has been noted in recent work.[3,13]

(3) Figure 1 shows reaction coordinates for formation of CF_3CH_2O-**2** and CF_3CH_2S-**2** from the trifluoroethoxide ion adducts, constructed using the data in Table I. The figure shows that the intrinsic kinetic barrier to the formation and reaction of CF_3CH_2O-**2** is much smaller than that for CF_3CH_2S-**2**. This is reflected by the 40-fold *larger* rate constant k_H (M^{-1} s^{-1}) for formation of the thermodynamically *more unstable* carbocation CF_3CH_2O-**2** in the acid-catalyzed cleavage reactions of CF_3CH_2X-**1**-OCH_2CF_3 and by the very large 900-fold higher reactivity of CF_3CH_2O-**2** than of CF_3CH_2S-**2** toward trifluoroethanol (Table I).[14] *The observation that the thermodynamically less stable α-oxygen-stabilized carbocation is formed more rapidly shows that previous attempts to infer the relative stabilities of α-oxygen- and α-sulfur-stabilized carbocations from the relative rate constants for their formation in solvolyses are invalid.*[2b,15]

We offer two possible explanations for the larger kinetic barrier to the formation and reaction of CF_3CH_2S-**2** than that of CF_3CH_2O-**2**.

(1) Calculations show that the falloff in resonance stabilization at $HSCH_2^+$ is larger than that at $HOCH_2^+$, as rotation about the HX–C bond moves the neighboring π-orbitals from a parallel to an orthogonal alignment.[3,17] By analogy, the instability of the transition state for the formation and reaction of CF_3CH_2S-**2** being greater than that of CF_3CH_2O-**2** may reflect the larger loss in resonance stabilization at the former carbocation as the overlap between π-orbitals is reduced by moving from a planar benzylic carbon at the reactant to a partly pyramidal carbon at the reaction transition state.[7,9a,b,16]

(2) These results might also be explained by the larger stabilizing electronic geminal interactions at CF_3CH_2O-**1**-OCH_2CF_3 than those at CF_3CH_2S-**1**-OCH_2CF_3 if a fraction of these interactions are retained at the transition state for C–O bond cleavage.[13] Theoretical calculations are needed to provide a more detailed rationalization for these results.

Acknowledgment. This work was supported by a grant (GM 39754) from the NIH.

---

[13] Richard, J. P.; Amyes, T. L.; Rice, D. J. *J. Am. Chem. Soc.* **1993**, *115*, 2523–2524. Apeloig, Y.; Biton, R.; Abu-Freih, A. *J. Am. Chem. Soc.* **1993**, *115*, 2522–2523.

[14] Rate data obtained in mixed sulfuric acid/water solutions and extrapolated to 100% water also show that a S for O substitution at the methoxydi-(4-methoxyphenyl)methyl ion causes a large (5000-fold) decrease in k_s for carbocation capture by water [McClelland, R. A.; Ahmad, M. *J. Am. Chem. Soc.* **1978**, *100*, 7031–7036].

[15] The substitution of a pair of sulfur atoms for oxygens at the 2-(4-methoxyphenyl)-1,3-dioxolenium carbocation leads to a similar breakdown in rate equilibrium relationships [Okuyama, T. *Acc. Chem. Res.* **1986**, *19*, 370–376].

[16] Bernasconi, C. F. *Tetrahedron* **1989**, *45*, 4017–4090. Bernasconi, C. F. *Acc. Chem. Res.* **1992**, *25*, 9–16.

[17] Schleyer, P. v. R. *Pure Appl. Chem.* **1987**, *59*, 1647.