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Communications to the Editor

Dynamics for Reaction of an Ion Pair in Aqueous Solution: The Rate Constant for Ion Pair Reorganization

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The characterization of the dynamics of the reactions of ion pair intermediates by classical studies of the rates and products of aliphatic nucleophilic substitution reactions has played a critical role in the development of our understanding of the mechanism of these reactions.[2] More recently ion pair dynamics have been probed by fast kinetic methods,[3,4] but a significant unknown remains the rate constant (k_r) for *reorganization* of ion pairs within an aqueous solvation shell.[5] We report here that reorganization of the ion pair intermediates **X-1**$^+$•$^-$**O(S)CPh** of the stepwise reactions of ring-substituted 1-phenylethyl thionobenzoates **X-1-O(S)CPh**, which exchanges the position of the O and S atoms of the leaving group (k_r, Scheme 1), is 6-fold faster than diffusional separation to free ions (k_{-d}). Our best estimate, $k_{-d} = 1.6 \times 10^{10}$ s^{-1},[6] gives $k_r = 1 \times 10^{11}$ s^{-1} for ion pair reorganization in water.

Rate constant ratios for partitioning of ion pair intermediates between reorganization (k_r) and competing reactions that lead to formation of nucleophile adducts (k_s' and k_{-d}, Scheme 1) may be determined from the ratios of the yields of the corresponding reaction products, provided the *reorganized* ion pair collapses to form a quantitative yield of the isomerization product ($k_{-1}' > k_{-d} + k_{-r}$, where $k_{-r} \approx k_r$, Scheme 1). If the values of k_s' and k_{-d} are known, the product rate constant ratio $k_r/(k_s' + k_{-d})$ will then provide a value for k_r. Ring-substituted 1-phenylethyl derivatives are ideal substrates for these studies because values of $k_{-d} = 1.6 \times 10^{10}$ s^{-1} and $k_s' \approx k_s$ (s^{-1}) for the partitioning of 1-phenylethyl carbocation−anion pairs in water have been reported in earlier work.[6−8] The reactions of the ion pair intermediate of solvolysis of enantiomerically pure **MeO-1-(4-nitrobenzoate)** labeled with ^{18}O in the bridging position have been examined;[9] however, the rate constant for addition of the 4-nitrobenzoate anion to **MeO-1**$^+$ should be well below the diffusion limit ($k_{-1}' < k_{-d}$).[10] By contrast, we have determined that addition of PhCOS$^-$ to **MeS-1**$^+$ to give **MeS-1-S(O)CPh** is diffusion-limited with $k_{TB} = 7 \times 10^9$ M^{-1} s^{-1},[11] so that nearly every encounter of this nucleophile with **MeS-1**$^+$ gives **MeS-1-S(O)CPh** and $k_{-1}' > k_{-d}$ (Scheme 1). *This establishes that every reorganization of the ion pair intermediate of the reaction of* ***MeS-1-O(S)CPh*** *(k_r, Scheme 1) that moves sulfur into position to form a covalent bond will give a near quantitative yield of* ***MeS-1-S(O)CPh****.*

Scheme 1

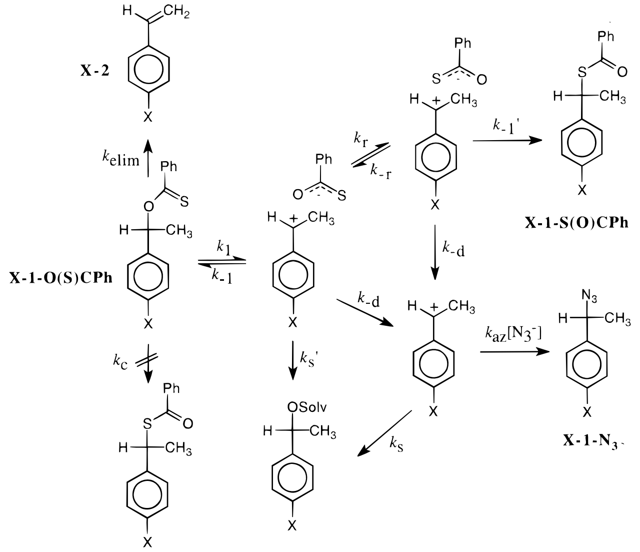

Table 1 gives values of k_{obsd} (s^{-1}) for the disappearance of **X-1-O(S)CPh** in 50:50 (v/v) TFE/H$_2$O (TFE = trifluoroethanol) at 25 °C and $I = 0.50$ (NaClO$_4$) and the yields of the products of these reactions.[12a,b] While O→S isomerization of thionobenzoates to give thiolbenzoates has been observed in earlier work,[13] the very high yields of 64−86% isomerization products from the reactions of **X-1-O(S)CPh** is remarkable for a reaction in water, where fast diffusional separation results in very short lifetimes of ion pair interemdiates.[6] The following experimental results provide strong evidence that **X-1-O(S)CPh** react by the mechanism shown in Scheme 1, in which reorganization of the ion pair intermediate (k_r) is essentially irreversible ($k_{-1}' > k_{-r}$) and results in formation of the isomerization product **X-1-S(O)CPh**.

(1) The reaction of **MeS-1-O(S)CPh** gives an 86% yield of **MeS-1-S(O)CPh** and a 14% yield of total solvent adducts **MeS-1-OSolv** (Table 1). The reaction is zero-order in [N$_3^-$] and Figure 1A shows that formation of **MeS-1-N$_3$** occurs at the expense of **MeS-1-OSolv** but not **MeS-1-S(O)CPh**. Reaction of

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[2] Raber, D. J.; Harris, J. M.; Schleyer, P. v. R. In *Ions and Ion Pairs in Organic Reactions*; Szwarc, M., Ed.; John Wiley & Son: New York, 1974; Vol. 2. Allen, A. D.; Fujio, M.; Tee, O. S.; Tidwell, T. T.; Tsuji, Y.; Tsuno, Y.; Yatsugi, K. *J. Am. Chem. Soc.* **1995**, *117*, 8974−8981.

[3] Bockman, T. M.; Hubig, S. M.; Kochi, J. K. *J. Org. Chem.* **1997**, *62*, 2210−2221.

[4] Lipson, M.; Deniz, A. A.; Peters, K. S. *Chem. Phys. Lett.* **1998**, *288*, 781−784.

[5] Paradisi, C.; Bunnett, J. F. *J. Am. Chem. Soc.* **1985**, *107*, 8223−8233.

[6] Richard, J. P.; Jencks, W. P. *J. Am. Chem. Soc.* **1984**, *106*, 1373−1383.

[7] Richard, J. P.; Rothenberg, M. E.; Jencks, W. P. *J. Am. Chem. Soc.* **1984**, *106*, 1361−1372.

[8] Richard, J. P. *J. Org. Chem.* **1992**, *57*, 625−629. Ritchie, C. D.; Hofelich, T. C. *J. Am. Chem. Soc.* **1980**, *102*, 7039−7044.

[9] Goering, H. L.; Briody, R. G.; Sandrock, G. *J. Am. Chem. Soc.* **1970**, *92*, 7401−7407.

[10] For example, the rate constant for addition of the more basic acetate ion to **MeO-1**$^+$, $k_{AcO} = 7.6 \times 10^7$ M^{-1} s^{-1},[6] is 70-fold smaller than $k_{az} = 5 \times 10^9$ M^{-1} s^{-1} for the diffusion-limited reaction of N$_3^-$ with benzylic carbocations.[14]

[11] The value of k_{TB} was calculated from the following product rate constant ratios determined for the reaction of **MeS-1-(3,5-dinitrobenzoate)** in 50:50 (v/v) TFE/H$_2$O at 25 °C and $I = 0.50$ (NaClO$_4$):[12b] $k_{az}/k_s = 80$ M^{-1} (Figure 1B), $k_{TB}/k_s = 110$ M^{-1}, and $k_{az} = 5 \times 10^9$ M^{-1} s^{-1} for the diffusion-limited reaction of N$_3^-$ with benzylic carbocations.[14]

[12] (a) The reactivity of **Me-1-O(S)CPh** is similar to that of the corresponding pentafluorobenzoate.[6] This is consistent with a low pK_a (ca. 1.4) and nucleophilic reactivity for *oxygen* of the bidentate thionobenzoate leaving group. (b) Procedures for the preparation of **X-1-O(S)CPh** and **X-1-S(O)CPh**, NMR spectral data, and the results of elemental analyses are given in the Supporting Information. Product yields were determined by HPLC analyses following procedures described in earlier work [Richard, J. P. *J. Am. Chem. Soc.* **1989**, *111*, 1455−1465].[6]

[13] Smith, S. G. *J. Am. Chem. Soc.* **1961**, *82*, 4285−4287. Smith, S. G. *Tetrahedron Lett.* **1962**, *21*, 979−982. Smith, S. G.; Petrovich, J. P. *Tetrahedron Lett.* **1964**, *45*, 3363−3365. Smith, S. G.; Petrovich, J. P. *J. Org. Chem.* **1965**, *30*, 2882−2886. Buckson, R. L.; Smith, S. G. *J. Org. Chem.* **1967**, *32*, 634−639. Smith, S. G.; Goon, D. J. W. *J. Org. Chem.* **1969**, *34*, 3127−3131.

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Table 1. Rate Constants and Product Yields for the Reactions of Ring-Substituted 1-Phenylethyl Thionobenzoates **X-1-O(S)CPh** in 50:50 (v/v) TFE/H_2O at 25 °C and $I = 0.50$ ($NaClO_4$) (Scheme 1)

					product yield (%)		
X	k_{obsd} (s^{-1})[a]	$k_s \approx k_s'$ (s^{-1})[b,c]	k_{-d} [b,d]	k_r [b,e]	**X-1-OSolv**[f,g]	**X-1-S(O)CPh** [f,g]	**X-2**[f,g]
4-MeS	5.5×10^{-4}	6×10^{7} [h]	1.6×10^{10}	1×10^{11}	14 (14)	86 (86)	n. d.
4-Me	2.0×10^{-5}	6×10^{9} [i]	1.6×10^{10}	1×10^{11}	21 (16)	73 (78)	6
4-F	4.1×10^{-7}	2×10^{10} [i]	1.6×10^{10}	1×10^{11}	25 (24)	64 (65)	12

[a] Observed first-order rate constant for the disappearance of **X-1-O(S)CPh**, determined by HPLC analysis.[12b] [b] Rate constant for reaction of the ion pair intermediate **X-1$^+$•$^-$O(S)CPh** (Scheme 1). [c] Rate constant for reaction of **X-1$^+$** with solvent. [d] Rate constant estimated for diffusional separation of the ion pair intermediate taken from ref 6. [e] Rate constant for reorganization of the ion pair intermediate, calculated from the product data for reaction of **MeS-1-O(S)CPh** as described in the text. [f] Product yields determined by HPLC analysis (ref 12). [g] Values in parentheses were calculated from the values of k_s', k_{-d}, and k_r in this table and the fractional yields, f_{alk}, of the alkenes **X-2** using eqs 1 and 2 (see text). [h] Calculated from $k_{az}/k_s = 80$ M^{-1} determined in this work (ref 11) and $k_{az} = 5 \times 10^9$ M^{-1} s^{-1} for the diffusion-limited reaction of azide ion with benzylic carbocations (ref 14). [i] Data from ref 6.

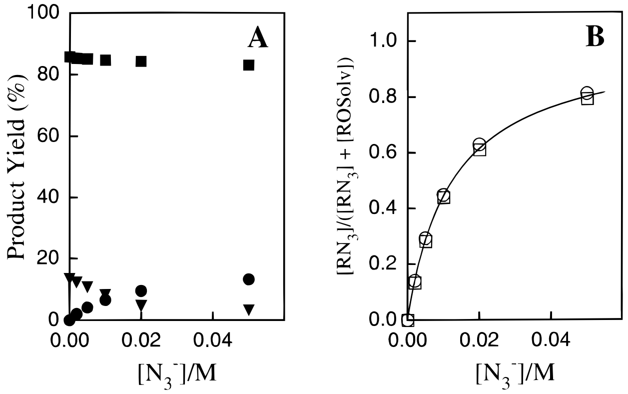

Figure 1. (A) Dependence of the yields of the products from the reaction of **MeS-1-O(S)CPh** on the concentration of added N_3^- in 50:50 (v/v) TFE/H_2O at 25 °C and $I = 0.50$ ($NaClO_4$): (■) **MeS-1-S(O)CPh**; (▼) **MeS-1-OSolv**; and (●) **MeS-1-N_3**. (B) Dependence of the yield of **MeS-1-N_3**, calculated as a fraction of the sum of the yields of **MeS-1-N_3** and **MeS-1-OSolv**, on the concentration of added azide ion in 50:50 (v/v) TFE/H_2O at 25 °C and $I = 0.50$ ($NaClO_4$): (○) data for reaction of **MeS-1-O(S)CPh** and (□) data for reaction of **MeS-1-(3,5-dinitrobenzoate)**. The solid line was calculated using $k_{az}/k_s = 80$ M^{-1}.

MeS-1-(3,5-dinitrobenzoate) under the same conditions gives only **MeS-1-OSolv**.[7] Figure 1B shows that the yields of **MeS-1-N_3**, calculated as a fraction of the sum of the yields of **MeS-1-N_3** and **MeS-1-OSolv**, from the reactions of **MeS-1-O(S)-CPh** and **MeS-1-(3,5-dinitrobenzoate)** are identical. These data show that essentially 100% and 14% respectively of the ion pair intermediates of the reactions of **MeS-1-(3,5-dinitrobenzoate)** and **MeS-1-O(S)CPh** dissociate to give *free* **MeS-1$^+$** which then partitions between addition of N_3^- and solvent. We propose that the primary reaction (86%) of the ion pair formed from **MeS-1-O(S)CPh** is reorganization (k_r) followed by collapse (k_{-1}') of the *new* ion pair to give the rearrangement product **MeS-1-S(O)CPh** (Scheme 1).

(2) Rearrangement of **MeS-1-O(S)CPh** by a pathway that is unaffected by N_3^- may represent concerted isomerization of the neutral substrate, which avoids formation of **MeS-1$^+$** (k_c, Scheme 1). Values of $\rho^+_{solv} = -4.9$ and $\rho^+_{isom} = -5.5$ for reactions of **X-1-O(S)CPh** can be calculated from the data in Table 1.[15] The more negative value for ρ^+_{isom} than for ρ^+_{solv} is inconsistent with a concerted isomerization reaction, which would be expected to proceed through a transition state in which cleavage of the C−O bond is accompanied by formation of a C−S bond. This would increase the extent of bonding to the benzylic carbon in the transition state for isomerization compared with solvolysis, and would require $\rho^+_{isom} > \rho^+_{solv}$ which is not observed.

(3) It is unlikely that k_{-1}' is even *partly* rate-determining for formation of **X-1-S(O)CPh** from the ion pair **X-1$^+$•$^-$O(S)CPh** ($k_{-1}' \approx k_{-r}$, Scheme 1). This requires that the yield of the isomerization product *increase* rather than decrease (Table 1) upon destabilization of **X-1$^+$** by a change to a more electron-withdrawing substituent X. This is because destabilization of **X-1$^+$** is expected to lead to an increase in k_{-1}', while k_{-r} for reorganization should be insensitive to **X-1$^+$** stability. The observed results provide evidence that ion pair reorganization is effectively irreversible and rate-determining for formation of **X-1-S(O)CPh** ($k_{-1}' > k_{-r}$, Scheme 1).

(4) The decrease in the yield of **X-1-S(O)CPh** observed on changing to more electron-withdrawing substituents X (Table 1) is consistent with an increase in k_s' ($\approx k_s$)[8] for direct addition of solvent to the carbocation−anion pair, such that k_s' becomes comparable with k_r and k_{-d} (Table 1). Reaction of the ion pair by k_s' provides a significant additional pathway for the formation of **X-1-OSolv** at the expense of **X-1-S(O)CPh**.

Table 1 shows that the yields of products of solvolysis and isomerization of **X-1-O(S)CPh** can be accounted for by the literature values of k_{-d} and k_s' for partitioning of ion pair intermediates in water, and the *derived* value of $k_r = 1 \times 10^{11}$ s^{-1}. The theoretical product yields in Table 1 were calculated from eqs 1 and 2

$$f_{isom} = (1 - f_{alk})\left(\frac{k_r}{k_r + k_{-d} + k_s'}\right) \tag{1}$$

$$f_{solv} = (1 - f_{alk})\left(\frac{k_{-d} + k_s'}{k_r + k_{-d} + k_s'}\right) \tag{2}$$

derived for Scheme 1 and using the following: (a) values of $k_s' = k_s$ (s^{-1}) and $k_{-d} = 1.6 \times 10^{10}$ s^{-1} taken from earlier work;[6,7] (b) a value of $k_r = 1 \times 10^{11}$ s^{-1} for reorganization of the ion pair intermediates **X-1$^+$•$^-$O(S)CPh** [this was calculated from the product rate constant ratio $f_{isom}/f_{solv} = k_r/(k_{-d} + k_s') = 6$ for the reaction of **MeS-1-O(S)CPh** (eqs 1 and 2, $f_{alk} \approx 0$), using $k_s' \approx k_s = 6 \times 10^7$ $s^{-1} \ll k_{-d} = 1.6 \times 10^{10}$ s^{-1}, refs 6−8]; and (c) values of the fractional yields, f_{alk}, of the elimination products **X-2** (Table 1).[16]

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Supporting Information Available: Procedures for the preparation of **X-1-O(S)CPh** and **X-1-S(O)CPh** (X = MeS, Me, and F) (PDF). This material is available free of charge via the Internet at http://pubs.acs.org.

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(14) (a) McClelland, R. A.; Cozens, F. L.; Steenken, S.; Amyes, T. L.; Richard, J. P. *J. Chem. Soc., Perkin Trans. 2* **1993**, 1717−1722. (b) McClelland, R. A.; Kanagasabapathy, V. M.; Banait, N. S.; Steenken, S. *J. Am. Chem. Soc.* **1991**, *113*, 1009−1014.

(15) Individual rate constants k_{solv} (s^{-1}) and k_{isom} (s^{-1}) were calculated from the values of k_{obsd} (s^{-1}) for reaction of **X-1-O(S)CPh** and the fractional product yields f_{isom} and f_{solv} using the relationship $k_X = k_{obsd}f_X$.

(16) Evidence for a concerted mechanism for the alkene-forming elimination reaction [Amyes, T. L.; Richard, J. P. *J. Am. Chem. Soc.* **1991**, *113*, 8960−8961] will be presented in the full report of this work.