Mechanisms of Hydrolysis and Related Nucleophilic Displacement Reactions of Alkanesulfonyl Chlorides: pH Dependence and the Mechanism of Hydration of Sulfenes[1]

J. F. King,* J. Y. L. Lam, and S. Skonieczny

Contribution from the Department of Chemistry, University of Western Ontario, London, Ontario, Canada N6A 5B7. *Received August 26, 1991*

Abstract: pH-rate profiles, primary kinetic isotope effects, deuterium substitution patterns, and pH-product ratios in the presence of added nucleophiles provide evidence for the following overlapping set of mechanisms for the hydrolysis of methanesulfonyl chloride (**1**) (in 0.1 M KCl at 25 °C): (a) pH ≤ 1-6.7, reaction with water by direct nucleophilic attack on the sulfonyl chloride; (b) pH ≥ 6.7-11.8, rate-determining attack by hydroxide anion to form sulfene (**2**), which is then trapped by water in a fast step; and (c) pH ≥ 11.8, sulfene formation and sulfene trapping by hydroxide anion; careful inspection showed no sign of sulfene formation in the reaction with water or of direct displacement by hydroxide anion. This pattern, with appropriate variations in the values of pH_i (the pH at which two competing mechanisms have the same rate), is apparently general for simple alkanesulfonyl chlorides having at least one hydrogen on the carbon bearing the sulfonyl group. Azide and acetate anions react with **1** below pH_i for **1** (6.7) by direct nucleophilic substitution at the sulfur, but above pH_i by trapping of the sulfene. 2-Chlorophenoxide anion reacts with **1** below pH 6.7 by *both* (a) direct displacement to form the ester and (b) elimination to form the sulfene. Above pH 6.7, sulfene is formed from the sulfonyl chloride by reaction with either 2-chlorophenoxide or hydroxide ion; this is followed by trapping of the sulfene with 2-chlorophenoxide, water, or hydroxide. The possibility of the 2-chlorophenoxide anion acting as a general base promoting the reaction of water with either **1** and **2** was examined, but no sign of either process was detected.

Nucleophilic substitution reactions of sulfonyl chlorides are well-known for making sulfonamides, sulfonic acid esters, and other sulfonic acid derivatives. Some of these products, notably those sulfonamides known as sulfa drugs, are important in themselves, while others are useful intermediates. Certain sulfonamides, for example, are used to make sulfonylureas such as tolbutamide and tolazamide, which are widely used by non-insulin-dependent diabetics. Sulfonic acid esters, because of their high reactivity in bimolecular substitution reactions, are much applied in organic synthesis for the conversion of the hydroxyl function into a wide array of other groups. It might be expected that the mechanisms of such familiar transformations would be well-understood, but although this is largely true of the reactions of arenesulfonyl chlorides and related compounds, it is by no means so with their alkanesulfonyl analogues, which are both less extensively studied and more complex in their chemistry.[2] The hydrolysis of these compounds, for example, though looked at as long ago as 1940,[3] was at the outset of our study only partly understood in general terms, with the different mechanisms only vaguely defined in scope.

About 30 years ago Hall[4] and Foon and Hambly[5] suggested that the hydrolysis of methanesulfonyl chloride and other simple alkanesulfonyl halides was an S_N2 reaction in which water attacked the sulfonyl sulfur atom and displaced the halide ion. This proposal was based in part on the parallels between their work and observations of the hydrolysis of arenesulfonyl chlorides[6,7] and of the ethanolysis of alkanesulfonyl chlorides,[8] in which S_N2 processes had been adduced on the basis of a combination of solvent, substituent, and steric effects. In 1965, in a paper from this laboratory[9] dealing primarily with reactions in organic media, it was reported that the hydrolysis of $PhCD_2SO_2Cl$ in aqueous dioxane (1:1) proceeded (as expected from the S_N2 mechanism) without hydrogen-deuterium exchange to give $PhCD_2SO_3H$ but, by contrast, that of $PhCH_2SO_2Cl$ in NaOD in D_2O-dioxane (1:5) yielded the monodeuterated product, $PhCHDSO_3^-$; it was proposed[9] that the hydroxide reaction went via an elimination-addition process going by way of the intermediate sulfene, $PhCH{=}SO_2$. We made no attempt at that point to define either (a) the threshhold hydroxide concentration at which the sulfene reaction becomes the major process with $PhCH_2SO_2Cl$ or any other sulfonyl chlorides or (b) the nature of the hydration of the sulfene to form the sulfonate anion.

Subsequent papers by others have described (a) α-deuterium exchange in the reaction of 2-propanesulfonyl chloride with NaOD in D_2O;[10] (b) lack of hydrogen exchange in the hydrolysis of methanesulfonyl or chloromethanesulfonyl chlorides in D_2O but, surprisingly, exchange of the hydrogen by deuterium in both unreacted dichloromethanesulfonyl chloride and its hydrolysis product, dichloromethanesulfonic acid, as a result of standing in D_2O;[11] and (c) rate constants for the reaction of hydroxide with some alkanesulfonyl chlorides in certain aqueous-organic media.[12-14]

In the course of other studies in the chemistry of sulfonyl derivatives, we found that we needed a clearer understanding of the mechanisms of hydrolysis of alkanesulfonyl chlorides, and as the first step to attain this we determined the pH-rate profiles for the reactions of methanesulfonyl chloride and a series of related compounds in water. We have also carried out the same measurements with methanesulfonyl-d_3 chloride and some related α-perdeuterated substrates. In addition, we have examined either (a) the extent of hydrogen incorporation in the products of the reactions of the α-perdeuterated compounds in H_2O or, alternatively, (b) the amount of deuterium uptake in the reaction of undeuterated substrates in D_2O. Finally, we have looked at the effect of certain added nucleophiles on pH-rate and pH-product ratio profiles. The results of these experiments, which are reported herein, enable us to develop a much clearer picture of the mechanisms of the hydrolysis and some related reactions of simple

(1) Organic Sulfur Mechanisms. 35. Part 34: King, J. F.; Khemani, K. C. *Can. J. Chem.* **1989**, *67*, 2162-2172.
(2) Reviews: (a) Kice, J. L. *Adv. Phys. Org. Chem.* **1980**, *17*, 65-181. (b) Gordon, I. M.; Maskill, H.; Ruasse, M.-F. *Chem. Soc. Rev.* **1989**, 123-151.
(3) Hedlund, I. *Ark. Kemi Min. Geol.* **1940**, *14A*, 1-17.
(4) Hall, H. K. *J. Am. Chem. Soc.* **1956**, *78*, 1450-1454.
(5) Foon, R.; Hambly, A. N. *Aust. J. Chem.* **1962**, 668-683, 684-695.
(6) Tommila, E.; Hirsjärvi, P. *Acta Chem. Scand.* **1951**, *5*, 659-664.
(7) Jenkins, F. E.; Hambly, A. N. *Aust. J. Chem.* **1961**, *14*, 190-204.
(8) Scott, R. B.; Lutz, R. E. *J. Org. Chem.* **1954**, *19*, 830-839. Scott, R. B.; Gayle, J. B. *J. Org. Chem.* **1956**, *21*, 391-393 and earlier papers cited.
(9) King, J. F.; Durst, T. *J. Am. Chem. Soc.* **1965**, *87*, 5684-5692.
(10) Günther, G.; Hampel, M.; Höbold, W.; Hübner, H.; Just, G.; Müller-Hagen, G.; Pritzkow, W.; Rolle, W.; Wahren, M.; Winter, H. *J. Prakt. Chem.* **1969**, *311*, 596-603.
(11) Seifert, R.; Zbirovský, M.; Sauer, M. *Coll. Czech. Chem. Commun.* **1973**, *38*, 2477-2483.
(12) Hampel, M.; Just, G.; Krebes, W.; Pritzkow, W. *J. Prakt. Chem.* **1980**, *322*, 987-990.
(13) Beck, H.; Doerffel, K. *J. Prakt. Chem.* **1983**, *325*, 36-40.
(14) Farng, L. O.; Kice, J. L. *J. Am. Chem. Soc.* **1981**, *103*, 1137-45.

0002-7863/92/1514-1743$03.00/0

Table I. Rate Constants for the Hydrolysis of Alkanesulfonyl Chlorides[a]

sulfonyl chloride	k_w (s^{-1})	k_{OH} (M^{-1} s^{-1})	$(k_{OH})_H/(k_{OH})_D$	pH_i[b]	sulfonyl chloride	k_w (s^{-1})	k_{OH} (M^{-1} s^{-1})	$(k_{OH})_H/(k_{OH})_D$	pH_i[b]
CH_3SO_2Cl	2.10×10^{-4}	4.07×10^3	6.61	6.71	$(CH_3)_2CHSO_2Cl$	3.70×10^{-5}	1.22×10^2	5.87	7.48
CD_3SO_2Cl	2.12×10^{-4}	6.16×10^2		7.54	$(CH_3)_2CDSO_2Cl$	3.7×10^{-5}	2.08×10		8.25
$CH_3CH_2SO_2Cl$	3.21×10^{-4}	5.47×10^2	6.01	7.77	$CH_3CH_2CH(CH_3)SO_2Cl$	3.45×10^{-5}	9.04×10		7.58
$CH_3CD_2SO_2Cl$	3.18×10^{-4}	9.10×10		8.54	$CH_2{=}CHCH_2SO_2Cl$	4.4×10^{-4}	3.4×10^5		5.11
$CH_3(CH_2)_2SO_2Cl$	3.93×10^{-4}	5.10×10^2		7.89	$PhCH_2SO_2Cl$	2.4×10^{-4}	8.4×10^4	9.1	5.45
$CH_3(CH_2)_3SO_2Cl$	3.77×10^{-4}	4.47×10^2		7.93	$PhCD_2SO_2Cl$	2.2×10^{-4}	9.2×10^3		6.38
$C_6H_{11}CH_2SO_2Cl$[c]	3.87×10^{-4}	3.36×10^2		8.06	$CH_3OCH_2CH_2SO_2Cl$[d]	3.3×10^{-4}	3.7×10^4	6.8	5.93
					$CH_3OCH_2CD_2SO_2Cl$[d]	2.5×10^{-4}	5.5×10^3		6.57

[a] 25.0 °C, 0.1 M KCl. [b] pH_i: the pH at which $k_w = k_{OH}[OH^-]$, given by $pH_i = \log(k_w/k_{OH}) + pK_w$. [c] Cyclohexylmethanesulfonyl chloride. [d] $(k_w)_H/(k_w)_D = 1.3$.

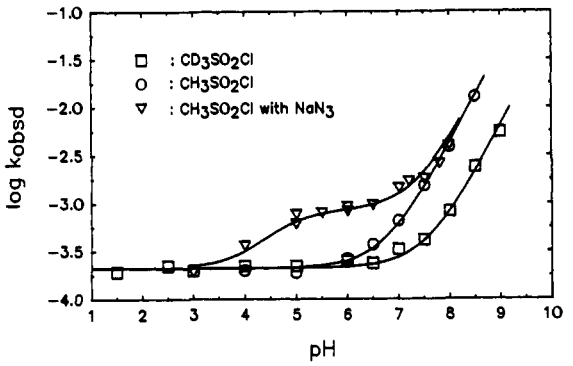


Figure 1. pH–rate profiles (at 25.0 °C) for methanesulfonyl chloride (**1**) (circles), methanesulfonyl-1,1,1-d_3 chloride (squares) (in 0.1 M KCl), and **1** in the presence of sodium azide (0.1 M) (triangles); total added NaN_3 0.01 M (μ = 0.1 M with KCl). The points are experimental; the lines through the circles and squares are from eq 1 with the parameters in Table I. The line through the triangles is given by $k_{obsd} = 2.1 \times 10^{-4} + 4.2 \times 10^3[OH^-] + 6.5 \times 10^{-2}[N_3^-]$, where $[N_3^-] = 0.01K_a/([H^+] + K_a)$ with K_a for hydrazoic acid 2.0×10^{-5} M.

alkanesulfonyl chlorides and, in particular, of the least-known step of these mechanisms, the hydration of sulfenes.[15]

Results and Discussion

Variation of Rates and Mechanism with Changes in pH. The rates of hydrolysis of a series of alkanesulfonyl chlorides were measured by the pH–stat method in 0.1 M KCl at 25.0 °C. Figure 1 shows the pH–rate profiles for the reactions of CH_3SO_2Cl and CD_3SO_2Cl (circles and squares, respectively); those of the other sulfonyl chlorides are qualitatively similar. The pattern in Figure 1 corresponds to a rate law of the form shown by eq 1; the values of k_w, k_{OH}, and pH_i (the pH at which $k_w = k_{OH}[OH^-]$) obtained from similar plots for a range of alkanesulfonyl chlorides are summarized in Table I.

$$k_{obsd} = k_w + k_{OH}[OH^-] \quad (1)$$

One immediately obvious feature of Figure 1 is the sizeable primary kinetic isotope effect (KIE) in the pH-dependent region ($pH \geq pH_i$) and, except for what is evidently a small secondary isotope effect with 2-methoxyethanesulfonyl chloride, its complete absence in the pH-independent zone ($pH \leq pH_i$). With methanesulfonyl chloride, $(k_{OH})_H/(k_{OH})_D = 6.6$; the other KIEs in Table I vary from 5.9 with 2-propanesulfonyl chloride to about 9 for phenylmethanesulfonyl chloride. This result agrees well with the mechanistic picture already described, i.e., an S_N2-S reaction of water for the pH-independent region (k_w term) and a hydroxide-promoted elimination–addition process with a rate-determining formation of the sulfene corresponding to the k_{OH} term.

To refine this picture further, the products of the reaction of CD_3SO_2Cl at low and high pH were carefully examined. At kinetic concentrations (about 10^{-4} M), the pH of a hydrolytic run starting at pH 2.5 finished at pH 2.0; the product of this reaction was $CD_3SO_3^-$ with no sign (i.e., ≤1%, as estimated by ^{13}C NMR) of any of the other isotopomers present. The reaction evidently proceeds, within experimental uncertainty, entirely by way of the S_N2-S process with no indication whatever of sulfene formation.

Reaction of CD_3SO_2Cl at pH 10.0 gave $CHD_2SO_3^-$, estimated to contain <5% of $CD_3SO_3^-$. As the ^{13}C NMR and mass spectrometric measurements used to put a limit on the amount of $CD_3SO_3^-$ in the product are not very accurate and the ^{13}C NMR method is better adapted to discerning small amounts of $CH_3SO_3^-$ in the presence of $CH_2DSO_3^-$, the hydrolyses of CH_3SO_2Cl in D_2O at pD 10.4 ($[OD^-] = 3.2 \times 10^{-5}$ M) and 13.4 ($[OD^-] = 0.032$ M) were investigated; the product in each experiment was estimated to be ≥99% $CH_2DSO_3^-$, i.e., the reaction of methanesulfonyl chloride with deuterioxide (or hydroxide) takes place entirely by way of sulfene with no detectable attack of either water or hydroxide anion directly on the sulfonyl sulfur. The generality of this picture was confirmed by the observation of (a) complete lack of exchange (<1%) in acidic D_2O (pD < 4) and (b) monoexchanged product (>97%) at high pD (i.e. $pD \geq pH_i + 1.5$) with each of the protiated alkanesulfonyl chlorides listed in Table I.

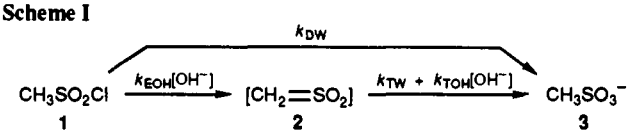
The unimportance of direct attack of hydroxide at sulfur with the alkanesulfonyl chlorides is consistent with what is known of the rate of this reaction relative to direct attack of water with the arene- and 1-alkenesulfonyl analogues.[16,17] For these reactions, the ratio of the rate constants for attack of hydroxide vs water at the sulfur atom varies from 2.0×10^3 to 3.4×10^5 M^{-1}. With even the largest of these ratios the predicted specific rate of attack of hydroxide at the sulfur of methanesulfonyl chloride would be only about 70 M^{-1} s^{-1}; the observed value of k_{OH} (4.07×10^3 M^{-1} s^{-1}) is therefore consistent with the incursion of another, faster pathway. Also consistent with the sulfene mechanism is the formation, in some instances, of byproducts not expected from simple nucleophilic displacement. 2-Propene-1-sulfonyl chloride, $CH_2{=}CHCH_2SO_2Cl$, in D_2O at pD 7.0 gave both $CH_2{=}CHCHDSO_3^-$ (95%) and the rearranged product, $CH_2DCH{=}CHSO_3^-$ (5%), products easily accounted for by respective 1,2- and 1,4-addition to vinylsulfene, $CH_2{=}CHCH{=}SO_2$. 2-Methoxyethanesulfonyl chloride yielded, in addition to $CH_3OCH_2CH_2SO_3^-$, a small amount (5%) of ethenesulfonate anion $CH_2{=}CHSO_3^-$, which by analogy with a related reaction of such 2-substituted ethanesulfonyl chlorides as 2-acetoxy- and 2-(phenylthio)-ethanesulfonyl chlorides[18] may be presumed to arise by loss of methoxide anion during trapping of the sulfene.

Inspection of the variation of the rate constants with the structure of the alkyl group shows patterns consistent with the proposed mechanisms. The variation of k_w is small, with about the only effect of consequence being a roughly 5- to 10-fold lowering of k_w with the secondary alkanesulfonyl chlorides, a result ascribable to a steric effect. With the k_{OH}'s the largest effects (250 to 500 times faster than the saturated analogues) are those of the phenyl and vinyl groups, which point to conjugative sta-

(15) Some of these results were reported at the 14th International Symposium on the Organic Chemistry of Sulfur, Lódź, Poland, Sept. 1990: *Phosphorus, Sulfur, Silicon* **1991**, *59*, 177–180.

(16) Rogne, O. *J. Chem. Soc. B* **1968**, 1294–1296; **1970**, 1056–1058.
(17) King, J. F.; Hillhouse, J. H.; Skonieczny, S. *Can. J. Chem.* **1984**, *62*, 1977–1995.
(18) King, J. F.; Hillhouse, J. H.; Lauriston, T. M.; Khemani, K. C. *Can. J. Chem.* **1988**, *66*, 1109–1116.

Scheme I



bilization of the transition state for the elimination. The same effect has been observed by Farng and Kice[14] with alkyl α-disulfones and is well-known in the formation of carbon–carbon double bonds as, for example, in the 80-fold faster rate of elimination from 2-phenylethyl bromide vs ethyl bromide with KOBu^t in Bu^{t}OH at 50 °C.[19] A sizeable effect on k_{OH} is also found with 2-methoxyethanesulfonyl chloride, which shows a 70-fold rate enhancement relative to ethane-, 1-propane-, and 1-butanesulfonyl chlorides. A similar acceleration of sulfene formation by electron-withdrawing groups has been observed with substituted phenylmethanesulfonyl chlorides (reacting with pyridine in DME)[20] and aryl arylmethanesulfonates[21,22] in aqueous media and has been ascribed to the stabilization of a sizeable negative charge on the α-carbon in the transition state; this point is taken up further in the final subsection. The 3- to 10-fold rate reduction accompanying each replacement of a hydrogen in methanesulfonyl chloride by an alkyl group could be due to any or all of the following: (a) increased nonbonding energy in the transition states, (b) destabilization by the alkyl groups of the partial negative charge on the α-carbon in the transition state (see above), and (c) lowering of the population(s) of the conformation(s) with the β-hydrogen antiperiplanar to the chlorine atom.

Sulfene Trapping Reaction. Scheme I provides a basis for further discussion of mechanism and also introduces the acronyms for referring to the various reaction steps and assigning subscripts to their rate constants. In this notation, direct displacement is symbolized by D, elimination by E, and sulfene trapping by T; the reagents are, respectively, water (W) and hydroxide anion (OH). This foregoing subsection may be summarized by stating that alkanesulfonyl chlorides hydrolyze by DW below $pH_i - 1$ and by EOH above $pH_i + 1$ (and by an appropriately changing mixture of both reactions around pH_i) and that two conceivable pathways, DOH and EW, make no detectable contributions (and hence $k_w = k_{DW}$ and $k_{OH} = k_{EOH}$).

Scheme I includes two possible sulfene trapping processes, TW (by water) and TOH (by hydroxide). It was established by earlier work[23] that sulfene formation is the rate-determining step under a wide array of conditions; no information on the nature of sulfene trapping is obtained from rates of disappearance of **1**, but insight into the process may be gained by looking at product ratios in carefully chosen systems.

(**a**) X = 2-Cl
(**b**) X = 3-OCH$_3$

(**a**) X = 2-Cl, R = CH$_3$
(**b**) X = 3-OCH$_3$, R = CH$_3$
(**c**) X = 2-Cl, R = CH$_3$CH$_2$CH$_2$
(**d**) X = 2-Cl, R = (CH$_3$)$_2$CH

Particularly informative among these systems is the reaction of methanesulfonyl chloride (**1**) in the presence of an added nucleophilic sulfene trap (Nu) such as 2-chlorophenol (**5a**) in the pH range 10–13; **5a** has a pK_a of 8.48 and is present in these media more or less entirely as the conjugate base, **6a**, which reacts with sulfene (**2**) as in eq 2.

$$[CH_2{=}SO_2] + 2\text{-}ClC_6H_4O^- + H_2O \xrightarrow{k_{TN}} 2\text{-}ClC_6H_4OSO_2CH_3 + OH^- \quad (2)$$
(**2**) (**6a**) (**7a**)

As may be seen from Figure 2, the product ratio, e.g., [**7a**]/[**3**], is roughly constant from pH 10 to 11 and then drops abruptly with increased pH; this is not simply due to decomposition of the product (**7a**) since a control experiment shows it to be stable to the reaction conditions even at pH 13. These observations are readily explained in terms of Scheme I, which with the addition of eq 2 leads to eq 3 for the variation of the product ratio with reagent concentration (where Nu$^-$ refers to the nucleophilic sulfene trap and CH_3SO_2Nu to the trapping product). In the pH range 10–11, sulfene (**2**) is trapped with either water or Nu$^-$; under the conditions of the experiment these species do not change concentration with pH, and hence the product ratio stays constant. Above pH 11, however, trapping by hydroxide becomes a second route to **3**; this reaction becomes increasingly important, and the plot of log ([**7a**]/[**3**]) drops with a (negative) unit slope, in accord with eq 3. Completely analogous experiments with 3-methoxyphenol (**5b**) to yield 3-methoxyphenyl methanesulfonate (**7b**), and with methanesulfonanilide (**8**) to form the imide **9**, gave results also shown in Figure 2. A method of least squares with these

$$[CH_3SO_2Nu]/[CH_3SO_3^-] = k_{TN}[Nu^-]/(k_{TW} + k_{TOH}[OH^-]) = [Nu^-]k_{TN}/k_{TW}/(1 + [OH^-]k_{TOH}/k_{TW}) \quad (3)$$

CH_3SO_2NHPh (**8**) $(CH_3SO_2)_2NPh$ (**9**)

sets of data gave k_{TOH}/k_{TW} values of 149, 161, and 129 M^{-1},

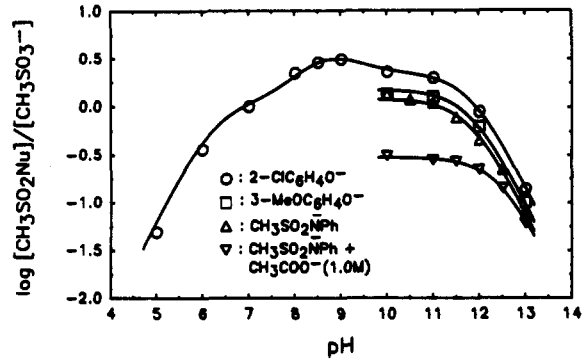


Figure 2. pH–product ratio profiles for the reactions of methanesulfonyl chloride (**1**) with nucleophiles in water: circles, 2-chlorophenol (**5a**) ([**5a**] + [**6a**] = 0.05 M); squares, 3-methoxyphenol (**5b**) ([**6b**] = 0.05 M); triangles, methanesulfonanilide (**8**) ([$CH_3SO_2N^-Ph$] = 0.05 M); inverted triangles, **8** ([$CH_3SO_2N^-Ph$] = 0.05 M) plus potassium acetate (1.0 M). The points are experimental. The line for **6a** is calculated from eq 4 with the parameters in Tables I and II ($k_{DW} = k_w$ and $k_{DOH} = k_{OH}$) plus k_{EN} = 0.85 M^{-1} s^{-1} and k_{DN} = 0.5 M^{-1} s^{-1} (see text). The lines for **5b** and **8** are from eq 3 and the parameters in Table II; the line for **8** with KOAc is obtained similarly except for the addition of a further sulfene trapping term for acetate, given the value k_{TN}/k_{TW} = 3.0 M^{-1}.

Table II. Sulfene Trapping Constants

sulfene	trap (NuH)	k_{TOH}/k_{TW}	pH_i[a]	k_{TN}/k_{TW}
$CH_2{=}SO_2$ (**2**)	**5a**			45
$CH_2{=}SO_2$ (**2**)	**5b**	146[b]	11.8	30
$CH_2{=}SO_2$ (**2**)	**8**			24
$CH_3CH_2CH{=}SO_2$	**5a**	420	11.4	120
$(CH_3)_2C{=}SO_2$	**5a**	850	11.1	110

[a] The pH at which $k_{TW} = k_{TOH}[OH^-]$, calculated from pH_i = log (k_{TW}/k_{TOH}) + pK_w. [b] Average of the values (161, 129, and 149, respectively) from the reactions with **5a**, **5b**, and **8**.

(19) Biale, G.; Cook, D.; Lloyd, D. J.; Parker, A. J.; Stevens, I. D. R.; Takahashi, J.; Winstein, S. *J. Am. Chem. Soc.* **1971**, *93*, 4735–4749. See also Farng and Kice[14] and examples quoted in the discussion of sulfene formation from α-disulfones.

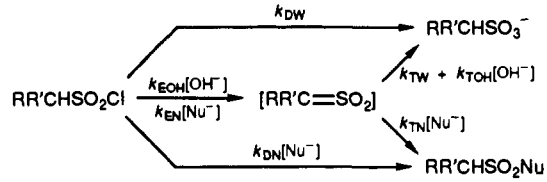
(20) King, J. F.; Lee, T. W. S. *J. Am. Chem. Soc.* **1969**, *91*, 6524–6525.

(21) King, J. F.; Beatson, R. P. *Tetrahedron Lett.* **1975**, 973–976.

(22) (a) Williams, A.; Douglas, K. T.; Loran, J. S. *J. Chem. Soc., Chem. Commun.* **1974**, 689–690. (b) Douglas, K. T.; Steltner, A.; Williams, A. *J. Chem. Soc., Chem. Commun.* **1975**, 353–354. (c) Davy, M. B.; Douglas, A.; Loran, J. S.; Steltner, A.; Williams, A. *J. Am. Chem. Soc.* **1977**, *99*, 1196–1206.

(23) Review: King, J. F.; Rathore, R. In *The Chemistry of Sulphonic Acids, Esters, and Their Derivatives*; Patai, S., Rappoport, Z., Eds.; John Wiley and Sons Ltd.: Chichester, England, 1991; Chapter 17, pp 697–766.

Scheme II



respectively, i.e., the same number within the experimental uncertainty of the method. As may be seen from Figure 2, the lines calculated using the average value (146 ± 16 M^{-1}) and the best fit values of k_{TN}/k_{TW} agree with the experimental points. To check this picture, reactions of **1** with **5a** and **8** were carried out in D_2O at pD > 10 and the products found to be mostly monodeuterated (CH_2DSO_2OAr or $(CH_2DSO_2)(CH_3SO_2)NPh$).

pH–product ratio profiles were also obtained for the reactions of **5a** ([Nu^-] = 0.05 M, 25 °C) with two other alkanesulfonyl chlorides: (a) 1-propanesulfonyl chloride to form a mixture of **7c** and 1-propanesulfonate anion and (b) 2-propanesulfonyl chloride to yield **7d** and 2-propanesulfonate anion. Table II summarizes the k_{TOH}/k_{TW}, k_{TN}/k_{TW}, and pH_i values for the sulfene trapping reactions.

The overall picture may now be summarized: (a) pH ≤ pH_i for the sulfonyl chloride hydrolysis, DW, i.e., direct displacement by water; (b) pH ≥ pH_i for the hydrolysis of the sulfonyl chloride and ≤pH_i for the hydration of the sulfene, EOH + TW, i.e., sulfene formation by hydroxide followed by trapping with water; and (c) pH ≥ pH_i for hydration of the sulfene, EOH + TOH, i.e., both sulfene formation and trapping by hydroxide.

Mechanisms of Reactions of Added Nucleophiles. Rogne had found with benzenesulfonyl chloride that a number of nucleophiles accelerated its disappearance in aqueous medium.[16] The reactions of aniline and imidazole and azide, thiosulfate, and fluoride anions all gave evidence of stable products of nucleophilic displacement. The hydrolyses promoted by pyridine and acetate and nitrite anions are interpreted by Rogne as deriving also from nucleophilic displacement (rather than general-base catalysis); no reaction was detected with thiocyanate, bromide, and iodide anions. The greater complexity of the hydrolysis of alkanesulfonyl chlorides suggests that their reactions with other nucleophiles may also be more complex than those of their arenesulfonyl counterparts. The difference in mode of reaction of alkanesulfonyl chlorides with water and hydroxide ion, in particular, raises the question of whether these other nucleophiles react with alkanesulfonyl chlorides by displacement or elimination or both. Scheme II expands the mechanistic picture to include these other possibilities; examples of all of these processes have, in fact, been observed.

As may be seen from the experimental values shown as triangles in Figure 1, sodium azide in the pH range 4–7.5 leads to an increase in the rate constant for consumption of **1**. The reactive species responsible for this is clearly the azide anion, the concentration of which falls as the pH approaches the pK_a of hydrazoic acid (4.7). At pD 6.4, the product of the reaction of NaN_3 with **1** in D_2O was $CH_3SO_2N_3$, but at pD 8.8 the azide was largely (95%) $CH_2DSO_2N_3$; i.e., depending on the pH the product may be formed principally by either the DN (k_{DN} = 6.5 × 10^{-2} M^{-1} s^{-1}) or the EOH + TN process.

Potassium acetate has an effect qualitatively similar to that of azide on the rate of disappearance of methanesulfonyl chloride (**1**), though the rate constant is lower (k_N = 4.5 × 10^{-3} M^{-1} s^{-1}). The methanesulfonate anion from a reaction in D_2O with 0.1 M KOAc at pD 6.4–5.4, conditions in which more than half of the product would derive from the reaction with acetate, showed no sign of incorporation of deuterium. This clearly excludes significant sulfene formation from **1** with acetate and leaves either (a) direct nucleophilic attack of acetate on **1** to form $CH_3SO_2OCOCH_3$ (**10**) or (b) attack of water on **1** with acetate acting as a general base. The mixed anhydride **10** is rapidly hydrolyzed (to **3** and acetate) under the reaction conditions, but it is possible to detect its formation by trapping experiments. At pH 6.0 the reaction with acetate in the presence of aniline gave, in addition to methanesulfonanilide, a very small amount (0.1% yield) of acetanilide, clearly identifiable in the ^1H and ^{13}C NMR spectra. This is in accord with a DN reaction to form **10** (followed by hydrolysis), but the possibility of some (or most) of the reaction taking place by the general base promoted route is not excluded.

Acetate was also found to play a role at high pH. Figure 2 (inverted triangles) shows the effect of 1 M KOAc at pH 10 on the product ratio, [**9**]/[**3**]. Acetate clearly provides another route to **3**, either by formation of the mixed anhydride (**10**) or by general-base catalysis; the lowering of the curve corresponds to a k_{TN}/k_{TW} term for acetate of 3.0 M^{-1}. Again, a very low yield (0.3%) of acetanilide was observed in the presence of aniline, pointing to the formation of at least some **10** from **2**, but not excluding a measure of general-base reaction as well.

As many be seen from Figure 2, the experiments with 2-chlorophenol (**5a**) below pH 10 point to a number of other processes that change rate with change in pH. At this stage we invoke eq 4, which is derived straightforwardly from Scheme II; note that when the k_{DW} and k_{DN} terms are relatively small eq 4 reduces to eq 3.

$$[CH_3SO_2Nu]/[CH_3SO_3^-] = \{k_{DN}[Nu^-] + cb/(a + c)\}/\{k_{DW} + ab/(a + c)\} \quad (4)$$

where

$$a = 1 + [OH^-]k_{TOH}/k_{TW}$$

$$b = k_{EOH}[OH^-] + k_{EN}[Nu^-]$$

$$c = [Nu^-]k_{TN}/k_{TW}$$

The results in Figure 2, taken with rate measurements which show an acceleration in the consumption of **1** in the presence of **5a** corresponding to k_N = 1.35 M^{-1} s^{-1}, are consistent with the reaction of **6a** by *both* the DN and EN processes, with k_{DN} = 0.85 ± 0.05 and k_{EN} = 0.5 ± 0.05 M^{-1} s^{-1}. The line through the points for the reaction with **5a** in Figure 2 was calculated using these parameters; the agreement with experiment was satisfactory.

In another context we have found evidence for general-base catalysis by phenoxide anion of the hydrolysis of benzenesulfonyl chloride, and we therefore looked at the above results with an eye to seeing if we could detect any general-base catalysis by **6a** in the attack of water on **1**, i.e., a DGB component. In our hands its inclusion only makes the fit to the points in either Figure 2 or the pH–rate profile poorer, and we conclude that any DGB reaction is relatively unimportant (i.e., $k_{DGB} \leq 0.05$ M^{-1} s^{-1}).

We have also looked at the reactions of alkanesulfonyl chlorides in aqueous medium in the presence of amines and found evidence for both direct displacement (DN) and sulfene formation (EN); the latter appeared to be the principal route in the presence of triethylamine with which sizeable KIEs and monoexchanged products were observed. Triethylamine was also found to influence the trapping of sulfene, perhaps by acting as a general base assisting attack by water (symbolized by TGB). These studies are sufficiently complex as to warrant separate discussion and will be reported more fully at a later date, but the observation of general-base catalysis of the trapping of sulfene by water (TGB) raises the possibility that such a process might be operating in the competition reactions using **5a**, **5b**, and the anion of **8** as sulfene traps. Such a reaction would require expansion of eq 3 to eq 5, which predicts that the product ratio would start to plateau when the concentration of nucleophile is high enough to lead to significant incursion of TGB.

$$[CH_3SO_2Nu]/[CH_3SO_3^-] = k_{TN}[Nu^-]/(k_{TW} + k_{TOH}[OH^-] + k_{TGB}[Nu^-]) \quad (5)$$

It is evident from Figure 3, which shows the variation of the product ratio [**7a**]/[**3**] with the concentration of **6a** at pH 10.0, that there is no sign whatsoever of any plateauing and hence that general-base assistance of water trapping by **6a** is undetectable at concentrations of **6a** up to 0.06 M, at least. The results shown in Figure 3 are in fact in good agreement with conclusions drawn earlier in this paper. Equation 3 predicts a straight line with a

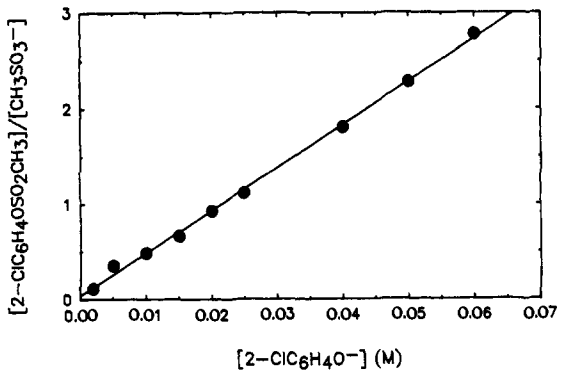


Figure 3. The product ratio [**7a**]/[**3**] as a function of the concentration of 2-chlorophenoxide anion (**6a**) at pH 10.0. The points are experimental; the line is that of the least-squares fit: [**7a**]/[**3**] = 45.7[**6a**] + 0.004.

zero intercept and a slope equal to $(k_{TN}/k_{TW})/(1 + [OH^-]k_{TOH}/k_{TW})$; the least-squares slope (45.7 M^{-1}) compares well with the value of 44.4 M^{-1} calculated from the values derived from the data in Figure 2 (k_{TN}/k_{TW} = 45 and k_{TOH}/k_{TW} = 146 M^{-1}).

Further Comments on the Mechanisms of Sulfene Formation and Trapping. The observation of monoexchanged products and sizeable primary KIEs clearly excludes an $(E1cB)_{rev}$ process, i.e., reversible carbanion generation, as the pathway for sulfene formation. Earlier work with sulfonyl chlorides in DME has been interpreted in terms of an E1cB-like E2 reaction,[20] while extensive study of aryl arylmethanesulfonates in water (containing ≤2% of ethanol)[22] and in aqueous DME (20:80)[21] is in clear accord with a range of E1cB reactions that change from reversible to irreversible and perhaps even to E2[22] as the acidity of the parent phenol increases. Stirling[24] has compared the formation of sulfenes with alkenes (via $(E1cB)_{rev}$ processes involving aryloxides as the leaving groups) and has concluded that cleavage of the leaving group is more advanced in sulfene formation. In the light of this, and in view of the strong case for the E2 reaction of alkyl chlorides to form alkenes,[25] it would seem that sulfene formation from the substrates in this study is most likely an E1cB-like E2 process rather than an $(E1cB)_{irr}$ reaction, but the latter route is not excluded. The effect of substituents on rates noted earlier qualitatively agrees with either pathway. The 70-fold difference between the k_{OH} values of 2-methoxyethanesulfonyl and methanesulfonyl chlorides is rather smaller than the spread of 1200 times in the detritiation of $MeOCH_2CH_2SO_2Ph$ vs $CH_3CH_2SO_2Ph$ (with EtO^- in EtOH at 25 °C) reported by Thomas and Stirling.[26] If the larger effect on the detritiation is not simply due to the difference in solvent, then these results would suggest that the reaction of the sulfonyl chlorides goes by a transition state with a smaller buildup of negative charge than that in a rate-determining carbanion formation (as in the detritiation); i.e., they are in better accord with the E1cB-like E2 process than the $(E1cB)_{irr}$ mechanism.

Sulfene trapping has been but little studied in itself, but the mechanism of at least one such reaction, namely, trapping of phenylsulfene with phenoxide anion in aqueous media, can be confidently assigned from microscopic reversibility. Sulfene formation from $PhCH_2SO_2OPh$ almost certainly proceeds via the carbanion, $PhCH^-SO_2OPh$,[21,22] and hence trapping of $PhCH{=}SO_2$ with PhO^- must go by the same pathway in reverse. By extension, the reaction of **2** with **6a**, **6b**, and the anion of **8** very likely goes the same way. Extending this argument further, attack of hydroxide and water on **2** might be expected to give, respectively, $CH_2^-SO_2OH$ and $CH_2^-SO_2OH_2^+$, but the high acidity of the hydrogens bound to oxygen in the latter would be expected[27] to lead to intervention of general-base assistance by water to give $CH_2^-SO_2OH$; one could even consider the possibility of general-base catalysis to give $CH_2^-SO_3^-$ from both the hydroxide and water reactions. Clear signs of general-base promotion have previously been reported for the trapping of phenylsulfene in aprotic media.[28] Earlier results involving trapping of sulfenes of the type $R_3N^+CH_2CH{=}SO_2$ have also been discussed in terms of addition to the sulfene to yield a negatively charged carbon, in that case a discrete zwitterionic intermediate.[18]

As a final comment, we return to a singular feature of this study pointed to earlier, namely, the totally different reactions of alkanesulfonyl chlorides with water and hydroxide ion (respectively, DW without DOH and EOH without EW). We are not aware of any comparable circumstance in which an alkyl halide, for example, gives exclusively the alcohol in water and entirely the alkene with hydroxide. As is mentioned above, the DOH reaction is well-known with arene- and 1-alkenesulfonyl chlorides[16,17] and might be expected to show rate constants with alkanesulfonyl chlorides about 2–4 orders of magnitude slower than those of the observed EOH reactions; this implies that the EOH reaction is observed, not because the DOH route is slow, but because the EOH reaction is fast. Among the anionic oxygen nucleophiles in this study, the most weakly basic (acetate) reacts only by direct displacement (DN), the most strongly basic (hydroxide) only by the EOH path, and the nucleophile of intermediate basicity (2-chlorophenoxide, pK_a of conjugate acid 8.48) by nearly equal amounts of displacement and elimination. This would point to a greater sensitivity to base strength (e.g., a larger β in a Brönsted plot) in the rates of elimination than in those of displacement; further experimentation is needed to clarify the point.

Experimental Section

General. ^1H NMR spectra were obtained with a Varian XL200 or Gemini-200 spectrometer and ^{13}C NMR spectra with either a Varian XL300 or the Gemini instrument; spectra of $CDCl_3$ solutions were calibrated with Me_4Si and those of D_2O solutions with DSS (sodium (trimethylsilyl)propanesulfonate). Mass spectra were run on a Finnigan MAT 8230 instrument and infrared spectra on a Bruker IFS 32 FTIR spectrometer using NaCl plates for neat liquids or KBr pellets for solid samples. Melting points were determined on a Reichert hot stage and are uncorrected. The pD values were derived from the equation, pD = 0.4 + (pH meter reading).

1,2-Dimethoxyethane (DME) was dried by distillation from CaH_2. Commercially available sulfonyl chlorides were distilled ($MeSO_2Cl$, $EtSO_2Cl$, $PrSO_2Cl$) or recrystallized from hexanes ($PhCH_2SO_2Cl$) before use; $BuSO_2Cl$ was redistilled material prepared by Dr. M. J. McGarrity by aqueous chlorination of 1-butanethiol. Other sulfonyl chlorides (*i*-$PrSO_2Cl$, $C_6H_{11}CH_2SO_2Cl$, $CH_3CH_2CH(CH_3)SO_2Cl$, $CH_2{=}CHCH_2SO_2Cl$, $CH_3OCH_2CH_2SO_2Cl$) were prepared from the corresponding alkyl chloride as follows: (a) reaction with Na_2SO_3 (in 1:1 DME–H_2O) by refluxing for 24 h, followed by removal of solvent and extraction of the sodium salt with ethanol and evaporation; (b) reaction of the salt with $SOCl_2$ plus DMF (1%) and refluxing for 12 h, followed by removal of excess $SOCl_2$, extraction with CH_2Cl_2 (washing with ice water), and evaporation of the solvent; (c) filtration of a benzene solution of the sulfonyl chloride under pressure through Kieselgel 60 GF_{254}, removal of the benzene, and distillation. Unless otherwise noted, other solvents and reagents were reagent grade commercial materials used as supplied. Standard sodium hydroxide solution (0.1 M, Fisher) was used as supplied or diluted appropriately. Solvent evaporation was carried out using a Büchi Rotovap apparatus.

α-Perdeuterated Alkanesulfonyl Chlorides. (a) Methanesulfonyl-*1,1,1-d*$_3$ Chloride. CD_3OD was converted to CD_3I (62% yield) with I_2 and red phosphorus.[29] The CD_3I (8.2 g, 36 mmol) was treated with magnesium (1.3 g, 54 mmol) in anhydrous ether (300 mL); the Grignard solution was then cooled in an ice bath and SO_2 bubbled in for 20 min. Evaporation of the ether gave a brown solid, which was dissolved in CH_2Cl_2; the solution was cooled in an ice–salt bath and Cl_2 bubbled in vigorously for 20 min. The orange brown solution was filtered, washed with water and dilute aqueous $NaHSO_3$, dried with $MgSO_4$, and the solvent evaporated. The product was distilled under reduced pressure (0.01 Torr, 70 °C) to give CD_3SO_2Cl as a colorless liquid (28% yield):

(24) Stirling, C. J. M. *Acc. Chem. Res.* **1979**, *12*, 198–203.
(25) Saunders, W. H.; Cockerill, A. F. *Mechanisms of Elimination Reactions*; John Wiley and Sons: New York, 1973.
(26) Thomas, P. J.; Stirling, C. J. M. *J. Chem. Soc., Perkin Trans. 2* **1977**, 1909–1913.
(27) Jencks, W. P. *J. Am. Chem. Soc.* **1972**, *94*, 4731–4732.
(28) King, J. F.; Kang, Y. I. *J. Chem. Soc., Chem. Commun.* **1975**, 52–53.
(29) Shiner, V. J.; Ensinger, M. W.; Rutkowske, R. D. *J. Am. Chem. Soc.* **1987**, *109*, 804–809.

^{13}C NMR δ 51.84 (1:3:6:7:6:3:1 sept, J = 21.7 Hz) with no sign of any protiated isotopomer; exact mass calcd 116.9731, found 116.9726.

(b) Phenylmethanesulfonyl-*1,1-d*$_2$ Chloride. The following exchange procedure was based on a method developed by Dr. M. Aslam. A solution of 4-nitrophenyl phenylmethanesulfonate[22c] (prepared from 3 g of $PhCH_2SO_2Cl$, 3.2 g of 4-nitrophenol, and 4 g of Et_3N in 30 mL of CH_2Cl_2, followed by workup) in DME (100 mL), D_2O (25 mL), and Et_3N (8.0 g, 79 mmol) was stirred at room temperature for 24 h. The residue, after removal of the solvent, was extracted with CH_2Cl_2, and the extract, after evaporation of the CH_2Cl_2, was stirred with NaOD in DME–D_2O (1:1) (pH meter reading 12.0) for an additional 24 h. DCl was added until the yellow green color disappeared, and the mixture was washed with CH_2Cl_2. The aqueous layer was neutralized with dilute NaOD in D_2O, and the solvent was evaporated under reduced pressure, leaving a white crystalline residue of the mixture of sodium and triethylammonium phenylmethanesulfonates and chlorides; this was refluxed with $SOCl_2$ (30 mL), DMF (5 drops), and CH_2Cl_2 (20 mL) for 6 h. Evaporation of the volatile materials left a pale yellow solid, recrystallized from hexanes to give the deuterated sulfonyl chloride as white needles: mp 92–93 °C (0.3 g, 10% from $PhCH_2SO_2Cl$); ^1H NMR showed a small 1:1:1 triplet at 4.87 corresponding to 8% $PhCHDSO_2Cl$.

(c) Ethanesulfonyl-*1,1-d*$_2$ Chloride. Ethanesulfonyl chloride (10.0 g, 78 mmol) was added with stirring to a solution of NaOD in D_2O–DME (1:1) (pH meter reading 11.0), with NaOD solution in D_2O added to maintain constant pH for 1 h, whereupon the mixture was neutralized with aqueous HCl. Removal of the solvent under reduced pressure gave sodium ethanesulfonate-*1-d*, which was converted to ethanesulfonyl-*1-d* chloride with $SOCl_2$–DMF in CH_2Cl_2 as above. After four further such sequences, the product was essentially only the α-dideuterated isotopomer; ^1H NMR showed a 1:2:3:2:1 quintet at 1.62 ppm with no sign of any signal around 3.66 ppm (est >98% $CH_3CD_2SO_2Cl$).

(d) 2-Methoxyethanesulfonyl-*1,1-d*$_2$ Chloride. This was made from $CH_3OCH_2CH_2SO_2Cl$ as $CH_3CD_2SO_2Cl$ was from $CH_3CH_2SO_2Cl$: ^{13}C NMR δ 59.1, 64.3 (1:2:3:2:1 quint, J = 22 Hz, no sign of any of the CHD isotopomer), 65.7.

(e) 2-Propanesulfonyl-*2-d* Chloride. 2-Propanesulfonyl chloride (5.0 g, 35 mmol) was treated with NaOD in D_2O–DME followed by reaction with $SOCl_2$–DMF in CH_2Cl_2 as above (one cycle only) to yield $(CH_3)_2CDSO_2Cl$ (3.5 g, 69%): ^1H NMR δ 1.59 (br s), no sign of any signal around 3.73; ^{13}C NMR δ 17.2, 67.0 (1:1:1 t, J = 22 Hz), with the lowest field arm slightly more intense indicating possibly as much as 2% of $(CH_3)_2CHSO_2Cl$.

Kinetics. The pH–stat apparatus and procedure have been described.[17] Initial concentrations of the sulfonyl chloride varied from 4×10^{-4} to 7×10^{-4} M (added in DME, 60 ± 20 μL) in 50 mL of 0.1 M aqueous KCl (or as otherwise specified) at 25.0 °C, with the reaction followed by titration with 0.1 M NaOH. The k_w values in Table I were obtained from the mean of the k_{obsd} values at pH's below $pH_i - 1.7$, and k_{OH}'s from $k_{OH} = (k_{obsd} - k_w)/[OH^-]$ using k_{obsd} values for pH ≥ pH_i, with occasional small (manual) adjustments to improve the fit of points in the ($pH_i - 1.7$) to pH_i region. For those substrates with $k_{OH} \leq 10^3$ M^{-1} s^{-1}, conformance to eq 1 was as good as or better than that shown in Figure 1. With 2-propene-, phenylmethane-, and 2-methoxyethanesulfonyl chlorides, greater scatter and a slightly flattened curve, possibly arising from mixing effects,[30] resulted in the lower accuracy in k_{obsd} reflected by fewer significant figures in Table I.

Deuterium Substitution Experiments. (a) Without Added Nucleophiles. A solution of CD_3SO_2Cl (0.50 g, 4.3 mmol) in DME (1 mL) was injected into water (1 L) and the mixture stirred for 24 h; the pH after initial mixing was 2.5, and at the end of the reaction, 2.0. Half of the water was removed on the rotary evaporator, the pH was adjusted to 7 with aqueous NaOH, and the rest of the water evaporated. The ^{13}C NMR spectrum of the product (0.5 g) showed the characteristic septet due to $CD_3SO_3^-$ at δ 40.44 (J = 21 Hz). Reaction with PCl_5 (1.0 g) in CH_2Cl_2 (20 mL) under reflux for 24 h, followed by workup and distillation under reduced pressure, gave the sulfonyl chloride (97 mg, 20%): ^{13}C NMR δ 51.86 (sept, J = 22 Hz), est CHD_2SO_3Cl content <1%; the ratio of the peaks at m/z = 81 and 82 indicated at least 97% CD_3SO_2Cl. In water (1 L) at pH 10.0 (kept constant by adding aqueous NaOH), CD_3SO_2Cl (0.8 g) in DME (1 mL) gave a product (1.0 g) shown by ^1H NMR (δ 2.78 1:2:3:2:1 quint, J = 2 Hz) and ^{13}C NMR (quint at δ 40.57, J = 21 Hz) to be essentially entirely $CHD_2SO_3^-$. On conversion to the sulfonyl chloride, the ^{13}C NMR spectrum showed a quintet at δ 52.10 (J = 22 Hz) with no sign (estimated <5%) of the CD_3 isotopomer; the mass spectrum indicated ≥95% CHD_2SO_2Cl.

Reactions in D_2O were carried out in acidic and basic media (respectively, in the flat and sloped regions of the pH–rate profiles). For the former the pD was set at ~4.4 (pH meter reading 4.0) with DCl and the reaction allowed to proceed overnight. The mixture was washed with CH_2Cl_2, the aqueous layer was brought to pH 7 with NaOH, and the water was evaporated; the ^1H and ^{13}C NMR spectra showed no sign (i.e., <1%) of any deuterated isotopomer. For the reactions in basic D_2O, the mixture was maintained at the pD specified below with NaOD solution in the pH–stat for 15 min with stirring. The mixture was neutralized (aqueous HCl) and washed with CH_2Cl_2, and the water was evaporated; ^1H and ^{13}C NMR spectra showed the products to be essentially pure α-monodeuterated sulfonate anions: for $MeSO_3^-$ ≥98% $CH_2DSO_3^-$, for phenylmethanesulfonate ≥95% $PhCHDSO_3^-$, and for the others ≥97% of the α-monodeuterated sulfonate. The pD's of these experiments were as follows: $MeSO_2Cl$, 8.9 and 13.4; $EtSO_2Cl$, $PrSO_2Cl$, and $BuSO_2Cl$, 9.4; $MeCH_2CH(Me)SO_2Cl$, 11.0; $PhCH_2SO_2Cl$, 7.4; $CH_2{=}CHCH_2SO_2Cl$, 7.0, $C_6H_{11}CH_2SO_2Cl$ and *i*-$PrSO_2Cl$, 10.0; $CH_3OCH_2CH_2SO_2Cl$, 7.5. The product of the reaction of $CH_2{=}CHCH_2SO_2Cl$ also contained ~5% of the rearranged anion $CH_2DCH{=}CHSO_3^-$, and that of $CH_3OCH_2CH_2SO_2Cl$ 5% of $CH_2{=}CHSO_3^-$, as shown by ^1H NMR.

(b) With Added Nucleophiles. (i) **Azide.** Injection of **1** (0.5 g, 4.4 mmol) into a solution of NaN_3 (0.5 g, 7.8 mmol) in D_2O (10 mL) at pD 6.4 was followed by stirring for 1 h. Workup by extraction with CH_2Cl_2 followed by drying of the extract ($MgSO_4$) and evaporation of the solvent gave $CH_3SO_2N_3$ (0.32 g, 61%): ^1H NMR ($CDCl_3$) δ 3.27; ^{13}C NMR δ 42.7; neither spectrum showed any sign of any deuterated product. A similar reaction of **1** (40 μL, 0.52 mmol) with NaN_3 (30 mg, 0.46 mmol) in D_2O (25 mL) at pD 8.8 for 6 min gave an oily product (47 mg), shown by ^1H NMR to consist of $CH_2DSO_2N_3$ (δ_H 3.23, 1:1:1 t, J = 2 Hz; δ_C 42.6, 1:1:1 t, J = 21 Hz) and $CH_3SO_2N_3$ (δ_H 3.24, s) in the ratio 95:5, plus unreacted CH_3SO_2Cl (8%, δ_H 3.65, δ_C 52.5). In a control experiment, $CH_3SO_2N_3$ (0.1 g) was stirred with NaOD in D_2O (pD 9.4) for 25 min and the mixture worked up; the recovered material (60 mg) was entirely $CH_3SO_2N_3$ (δ_H 3.27, δ_C 42.6), with no sign of deuteration.

(ii) **Acetate.** Into a solution of KOAc (0.1 M) in D_2O (25 mL) at room temperature was injected **1** (40 μL) with stirring. It was allowed to react for 45 min, whereupon the mixture was washed with CH_2Cl_2 and the water evaporated, leaving a dry residue which was triturated with hot ethanol. Evaporation of the ethanol followed by drying in a 60 °C oven gave a white solid (245 mg): ^1H NMR δ 2.81 (s, $CH_3SO_3^-$, no sign of $CH_2DSO_3^-$), 1.91 (s, CH_3COO^-); ^{13}C NMR δ 41.1 (s, $CH_3SO_3^-$), 26.0, 183.9 (CH_3COO^-).

(iii) 2-Chlorophenol (5a). Into a solution of **5a** (0.1 mL, 1.9 mmol) and NaOD in D_2O (10 mL, pD 10.8) was injected **1** (50 μL, 0.65 mmol) with stirring. After 0.65 min, HCl (3 M) was added to give pH 0.2 and the mixture extracted with CH_2Cl_2; the extract was washed with aqueous HCl and dried ($MgSO_4$) and the solvent evaporated to give a pale yellow oil (0.26 g): ^1H NMR δ 3.18 (1:1:1 t, J = 2 Hz, CH_2DSO_2OAr, 72%), 3.19 (s, CH_3SO_2OAr, **7a**, 28%), plus strong signals due to unreacted **5a**; ^{13}C NMR δ 38.26 (1:1:1 t, J = 21 Hz, CH_2DSO_2OAr), 38.46 (s, CH_3SO_2OAr), plus **5a**. At pD 11.8 for 0.3 min, a smaller experiment gave a product with the CH_3 and CH_2D esters in the ratio 22:78. Reactions carried out with longer reaction times and workup by extraction of unreacted **5a** with aqueous NaOH gave ester products with "multiexchange", i.e., a complex mixture of CH_3, CH_2D, CHD_2, and probably CD_3 isotopomers (presumably from random exchange after initial formation and subsequent leaching in workup). In a control experiment, a sample (1 g) of deuterated 2-chlorophenyl methanesulfonate, in which the ^1H NMR integral of the methyl signal was 6% of that calculated for CH_3, was dissolved in CH_2Cl_2 (100 mL) was shaken vigorously in a separatory funnel with 1% aqueous NaOH (100 mL) for 10 min; the organic layer, after separation, drying, and removal of the solvent, gave a residue in which the ^1H NMR integral corresponded to 12% CH_3.

(iv) **Methanesulfonanilide (8).** Into a solution of **8** (0.6 g, 3.5 mmol) and NaOD in D_2O (10 mL, pD 11.4) was injected **1** (0.4 mL, 5.2 mmol) with stirring (pD maintained by pH–stat); a white precipitate appeared instantly. The mixture was extracted with CH_2Cl_2, the extract was washed with 10% NaOH and dried ($MgSO_4$), and the solvent was evaporated, leaving a solid (0.51 g, 58%): ^1H NMR δ 3.37 (1:1:1 t, CH_2DSO_2), 3.39 (s, CH_3SO_2), 7.5 (m); ^{13}C NMR δ 42.4 (1:1:1 t, CH_2DSO_2), 42.7 (CH_3SO_2), 129.7, 130.57, 130.64, 133.5; est from the ^1H NMR integrals, 83% $(CH_2DSO_2)(CH_3SO_2)NPh$ and 17% $(CH_3SO_2)_2NPh$ (**9**). The aqueous portion was acidified to pH 2 with HCl, washed with CH_2Cl_2, and neutralized with NaOH, and the water was evaporated, leaving a white solid which was triturated with hot absolute ethanol. Evaporation of the solvent gave $CH_2DSO_3^-$: ^{13}C NMR (D_2O) δ 40.8 (1:1:1 t).

Reaction of Methanesulfonyl Chloride (1) with Acetate in the Presence of Aniline. To a solution of potassium acetate (20.0 g, 0.2 mol) and aniline (1.0 mL, 0.01 mol) in water (1.0 L) at pH 6.0 was added **1** (0.6 g, 5.2 mmol) with stirring at room temperature for 45 min; the pH dropped to 5.7. The mixture was extracted with CH_2Cl_2, and the extract

(30) Rys, P. *Angew. Chem., Int. Ed. Engl.* **1977**, *16*, 807–817.

was washed with dilute HCl and dried ($MgSO_4$); removal of the solvent gave a crude, pale yellow product (140 mg, 16% based on CH_3SO_2NHPh, **8**): ^1H NMR δ 2.19 (s, $CH_3CONHPh$, 2% of the product, 0.3% overall yield), 3.67 (s, **1**, 1%), 3.02 (s, **8**, 98%); ^{13}C NMR δ 24.0, 120.1, 124.3, 128.9, 169.3 ($CH_3CONHPh$), 52.5 (**1**), 39.0, 120.8, 125.3, 129.6, 136.8 (**8**). To a solution of KOAc (20.0 g) and aniline (9.8 mL, 0.1 mol) in water (1.0 L) at pH 10 was added **1** (1.0 g, 8.7 mmol), and the mixture was stirred at room temperature for 30 min, with dilute aqueous NaOH added to maintain constant pH. Workup as above gave pale yellow crystals (151 mg, 9.3% based on the composition given by ^1H NMR): ^1H NMR δ 7.14–7.5 (m), 2.17 (s, $CH_3CONHPh$, 1.4% of the product, 0.14% overall yield), 3.00 (s, **8**, 75%), 3.41 (s, **9**, 23%); ^{13}C NMR δ 24.4, 120.0, 124.2, 128.8, 169.2 ($CH_3CONHPh$), 39.0, 120.8, 125.3, 129.6, 136.8 (**8**), 42.7, 129.7, 130.5, 130.6, 133.4 (**9**).

pH–Product Ratio Profiles. Methanesulfonyl chloride (**1**) was injected from a 50-μL syringe into a solution (500 mL) of the nucleophile (either $[Nu^-] = 0.05$ M or $[NuH] + [Nu^-]$ = "total nucleophile concentration" = 0.05 M, as specified; Nu^- = **6a**, **6b**, or $CH_3SO_2N^-Ph$, the anion of **8**) set at the specified pH with NaOH or HCl (initial concentration of **1**, $(1.1 \pm 0.2) \times 10^{-3}$ M). The reaction was allowed to run to completion (times varying from 14 h for pH 5 to 10 min for pH 13), with monitoring of the pH with a Sargent-Welch pH 6000 digital display meter equipped with a Fisher all-range (pH 1 to 14) combination electrode and manual addition of aqueous NaOH to maintain constant pH. The reaction mixture was extracted with CH_2Cl_2, the extract dried ($MgSO_4$), the solvent evaporated, and the product dried to constant weight under vacuum. The weight of this material, after checking its purity by comparison of its ^1H NMR spectrum against that of an authentic specimen, was taken as the yield of the product and that of the methanesulfonate anion was calculated by difference. The results are shown in Figure 2; the experiments with variation in [**6a**] shown in Figure 3, as well as those starting with 1- and 2-propanesulfonyl chlorides ($[Nu^-]$ 0.05 M, pH ranges 9.5–13.0 and 10.0–12.75, respectively), were carried out similarly. In a control experiment, **7a** (64 mg) dissolved in DME (1.0 mL) was injected into an aqueous solution of NaOH (500 mL, pH 13.0), and the mixture was stirred for 5 min and then extracted with CH_2Cl_2 (3 × 50 mL). Evaporation of the extract gave a quantitative recovery of material shown by its ^1H NMR spectrum to be **7a**, with a very small amount (<1%) of DME as the only detectable impurity.

Starting Materials. The phenols **5a** and **5b** were commercial reagent grade distilled before use. Methanesulfonanilide (**8**) was prepared from **1** with aniline and triethylamine (1 equiv each) in CH_2Cl_2 cooled in an ice bath. Conventional workup gave **8** as white crystals (65% yield): mp 102–3 °C (lit. mp[31] 100.5 °C); IR ν_{max} 1329 (vs), 1154 (vs); ^1H NMR ($CDCl_3$) δ 3.0 (s, 3 H), 7.2–7.4 (m, 6 H); ^{13}C NMR ($CDCl_3$) δ 39.2, 120.8, 125.4, 129.7, 136.8.

Products. The esters were prepared by addition of triethylamine (2 equiv) in CH_2Cl_2 (10 mL) to a solution of the alkanesulfonyl chloride (0.5 g) and the phenol (1.2 equiv) in CH_2Cl_2 (10 mL). The mixture was refluxed for 10 min. The cooled mixture was washed with aqueous HCl and then with aqueous NaOH and dried ($MgSO_4$); evaporation of the solvent (Rotovap and vacuum pump) left the ester as a pale yellow oil, which was distilled onto a collecting cold finger under reduced pressure. 2-Chlorophenyl methanesulfonate (**7a**): IR ν_{max} 1372 (vs), 1175 (vs); ^1H NMR ($CDCl_3$) δ 3.2 (s, 3 H), 7.2–7.4 (m, 4 H); ^{13}C NMR ($CDCl_3$) δ 38.9, 125.1, 127.3, 128.76, 128.82, 131.4, 145.8; exact mass calcd for $C_7H_7ClO_3S$ 205.9804, found 205.9801. 3-Methoxyphenyl methanesulfonate (**7b**): IR ν_{max} 1370 (vs), 1184 (vs); ^1H NMR δ 3.11 (s, 3 H), 3.78 (s, 3 H), 6.88 (app d, 3 H), 7.29 (app t, 1 H); ^{13}C NMR δ 37.1, 55.4, 107.9, 113.0, 113.7, 130.2, 150.0, 160.6; exact mass calcd for $C_8H_{10}O_4S$ 202.0300, found 202.0300. 2-Chlorophenyl 1-propanesulfonate: IR ν_{max} 1374 (vs), 1169 (vs); ^1H NMR δ 1.1 (t, 3 H), 2.0 (sext, 2 H), 3.3 (t, 2 H), 7.2–7.5 (m, 4 H); ^{13}C NMR δ 13.1, 17.5, 53.9, 124.9, 127.4, 128.5, 128.6, 131.4, 145.7; exact mass calcd for $C_9H_{11}ClO_3S$ 234.0117, found 234.0124. 2-Chlorophenyl 2-propanesulfonate: IR ν_{max} 1350 (vs), 1156 (vs); ^1H NMR δ 1.6 (d, 6 H), 3.6 (sept, 1 H), 7.2–7.5 (m, 4 H); ^{13}C NMR δ 17.0, 54.5, 124.6, 127.4, 128.2, 128.5, 131.4, 145.6; exact mass calcd for $C_9H_{11}ClO_3S$ 234.0117, found 234.0121. $(MeSO_2)_2NPh$ (**9**) was prepared by adding **1** (0.5 g, 4.4 mmol) to a solution of **8** (1.2 equiv) and Et_3N (2 equiv) in CH_2Cl_2 (20 mL) and refluxing the mixture for 1 h. Upon cooling it was washed with aqueous HCl and 10% aqueous NaOH and dried ($MgSO_4$), and the solvent was evaporated to give crude **9**. This was recrystallized from absolute ethanol, giving white needles: mp 204 °C (lit. mp[32] 201–202 °C); IR ν_{max} 1348 (vs), 1159 (vs); ^1H NMR δ 3.4 (s, 6 H), 7.3–7.5 (m, 5 H); ^{13}C NMR δ 42.7, 129.8, 130.58, 130.64, 133.47; exact mass calcd for $C_8H_{11}NO_4S_2$ 249.0130, found 249.0123.

Acknowledgment. We thank the Natural Sciences and Engineering Research Council of Canada for financial support in the form of operating grants and scholarships, Dr. M. Aslam for valuable preliminary studies, and Dr. M. J. McGarrity for the sample of butanesulfonyl chloride.

Registry No. 2, 917-73-7; **5a**, 95-57-8; **5b**, 150-19-6; **7a**, 17186-79-7; **7b**, 52200-03-0; **7c**, 13659-19-3; **7d**, 138259-45-7; **8**, 1197-22-4; **9**, 1207-62-1; CH_3SO_2Cl, 124-63-0; CD_3SO_2Cl, 35668-13-4; $CH_3CH_2SO_2Cl$, 594-44-5; $CH_3CD_2SO_2Cl$, 138236-00-7; $CH_3(CH_2)_2SO_2Cl$, 10147-36-1; $CH_3(CH_2)_3SO_2Cl$, 2386-60-9; $C_6H_{11}CH_2SO_2Cl$, 4352-30-1; $(CH_3)_2CHSO_2Cl$, 10147-37-2; $(CH_3)_2CDSO_2Cl$, 138236-01-8; $CH_3CH_2CH(CH_3)SO_2Cl$, 4375-72-8; $CH_2{=}CHCH_2SO_2Cl$, 14418-84-9; $PhCH_2SO_2Cl$, 1939-99-7; $PhCD_2SO_2Cl$, 4063-99-4; $CH_3OCH_2CH_2SO_2Cl$, 51517-01-2; $CH_3OCH_2CD_2SO_2Cl$, 138236-02-9; $CH_3CH_2CH{=}SO_2$, 54683-40-8; $(CH_3)_2C{=}SO_2$, 79458-35-8; $(CH_3)_2CHCl$, 75-29-6; $C_6H_{11}CH_2Cl$, 1072-95-3; $CH_3CH_2CH(CH_3)Cl$, 78-86-4; $CH_2{=}CHCH_2Cl$, 107-05-1; CD_3I, 865-50-9; NaN_3, 26628-22-8; $CH_3SO_2N_3$, 1516-70-7; $CH_2DSO_2N_3$, 138236-03-0; KOAc, 127-08-2; $(CH_2DSO_2)(CH_3SO_2)NPh$, 138236-04-1; $CH_2DSO_3^-Na^+$, 138236-05-2; $CH_3CONHPh$, 103-84-4; D_2, 7782-39-0; 4-nitrophenyl phenylmethanesulfonate, 50534-57-1; aniline, 62-53-3.

(31) Marvel, C. S.; Helfrick, M. D.; Belsley, J. P. *J. Am. Chem. Soc.* **1929**, *51*, 1272–1274.

(32) Shriner, R. L.; Goebel, M. T.; Marvel, C. S. *J. Am. Chem. Soc.* **1932**, *54*, 2470–2476.