neutral component was studied separately prior to being studied as a mixture in order to identify multicomponent reaction sequences. Deuterium-labeled methyl disulfide and methyl 1-phenylethyl sulfide were prepared as described previously.[7b,15]

Acknowledgment. We gratefully acknowledge the support of this work in part by Grant GM 27319 awarded by the National Institute of General Medical Sciences, DHEW, and in part by Grant CHE 7807993 awarded by the National Science Foundation.

Registry No. 5 (R = $C_6H_5CHCH_3$), 78624-45-0; 2-methoxypropene, 116-11-0; cyclopentene, 142-29-0; 1,2-dimethyl-2-methoxythiiranium, 78624-46-1; CH_3SSCH_3, 624-92-0; CH_3SCH_3, 75-18-3; CH_3OCH_3, 115-10-6; CH_3OH, 67-56-1; $C_6H_5CH(CH_3)SCH_3$, 13125-70-7; H_2S, 7783-06-4; CH_3SH, 74-93-1; H_3S^+, 18155-21-0; $CH_3SH_2^+$, 18683-23-3; $(CH_3)_2SH^+$, 18683-32-4; $CH_3SSCH_3H^+$, 78624-47-2; $(CH_3)_3S^+$, 676-84-6; $(CH_3)_2SSCH_3^+$, 44209-79-2; $(CH_3S)_2SCH_3^+$, 56648-68-1; $CH_3OCH_2^+$, 23653-97-6.

Methoxymethyl Cations. 2. Reactions with Allylic Ethers and Sulfides in the Gas Phase

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Reactions of allylic compounds 3-methoxy-1-propene and 3-(methylthio)-1-propene with gaseous methoxymethyl cations generated from methyl ethers on electron impact have been investigated by ion cyclotron resonance techniques. Three modes of reaction have been identified for the allylic sulfide with $CH_3OCH_2^+$ that correspond to the elimination of the elements of $CH_2{=}O$, CH_3OH, and CH_3SH. The allylic ether and $CH_3OCH_2^+$ reacted to eliminate CH_3OH predominantly. Pathways for these reactions were studied by using isotopic labels. The results are interpreted in terms of attack of the reactant ion at the terminal carbon of the allyl group followed by hydride and/or proton transfers and elimination of CH_2O, CH_3OH, or CH_3SH. Oxygen lost as the neutral arose predominantly but not exclusively by cleavage of the methylene–oxygen bond of the reactant ion. Methylthiolation of 3-(methylthio)-1-propene also was achieved by reaction with $CH_3OCH_2^+$ in the presence of methyl disulfide. The source of a small amount of label scrambling in deuterium-labeled reactant ions is discussed.

The carcinogenic properties of certain electrophilic compounds are generally associated with their ability to alkylate nucleophilic sites of biomolecules.[1] In particular, the alkylation behavior and, by implication, the toxicity of the chemical carcinogen chloromethyl methyl ether[2a] may be attributed to the facility with which it dissociates to give methoxymethyl cations, $CH_3OCH_2^+$ (1).[2b] For this reason, the reactions of these ions with various nucleophiles are directly relevant to an understanding of the chemistry of carcinogenesis. Accordingly, we have investigated the reactions of methoxymethyl cations with neutral nucleophiles in the gas phase by ion cyclotron resonance (ICR) techniques.[3] The gas-phase study has the advantage that the ions can be generated safely from relatively nontoxic precursors (methyl alkyl ethers) by electron impact. Also, the intervention of solvolysis, which often dominates and obscures the chemistry of these ions in solution, can be avoided.

It is important to point out that the stability of ions of structure $CH_3OCH_2^+$ relative to isomeric forms of $C_2H_5O^+$ ions in the gas phase has been established by Beauchamp and Dunbar[8a] and by McLafferty and associates[8b] in classic studies of ion structure by ICR and collisional activation mass spectrometry, respectively. Therefore, we are confident that the reactant ions generated by electron-impact cleavage of methyl ethers are indeed methoxymethyl cations which do not rearrange to isomeric structures under the experimental conditions.

The reactions of particular interest in the present paper are those of $CH_3OCH_2^+$ with sulfur and oxygen nucleophiles, namely, with 3-(methylthio)-1-propene (2) and 3-methoxy-1-propene (3).[4] Although some of the chemistry observed in this study was anticipated, much of it was not. Nevertheless, the reactions observed have some parallel to those reported in previous studies of the gaseous ion,[5–7] and they clearly demonstrate the electrophilicity of the ion.

Results and Discussion

Ion Chemistry of 3-(Methylthio)-1-propene with $ROCH_2^+$. The ion chemistry of 3-(methylthio)-1-propene (2) is not in itself very interesting. Of the primary ions (see Table I) the molecular ion *m/z* 88 is the most intense. The major product ions are the protonated parent MH^+ ion *m/z* 89 and the $(M - 1)^+$ ion *m/z* 87. The reaction to produce *m/z* 87 is evidently one of hydride abstraction from the allyl group by the allyl cation *m/z* 41 (eq 1a) because no $(M - 2)^+$ ion is formed from the methyl-labeled neutral, $CD_3SCH_2CH{=}CH_2$. However, there is some abstraction from *both* methylene groups judging from the appearance of $(M - 1)^+$ and $(M - 2)^+$ ions from both

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[1] (a) See P. D. Lawley in "Chemical Carcinogenesis", C. A. Searle, Ed., American Chemical Society, Washington, DC, ACS Monograph 173, p 83; (b) E. C. Miller and J. A. Miller, *ibid.*, p 737; J. A. Miller and E. C. Miller in "The Molecular Biology of Cancer", H. Busch, Ed., Academic Press, New York, 1974; (c) L. N. Ferguson, *Chem. Soc. Rev.*, 4, 289 (1975).

[2] (a) B. L. Van Duuren, A. Sivak, B. M. Goldschmidt, C. Katz, and S. Melchionne, *J. Natl. Cancer Inst.*, 43, 481 (1969); (b) G. A. Olah, S. Yu, G. Liang, G. D. Matscescu, M. R. Bruce, D. J. Donovan, and M. Arvanaghi, *J. Org. Chem.*, 46, 571 (1981).

[3] See "Ion Cyclotron Resonance Spectrometry", by T. A. Lehman and M. M. Bursey, Wiley, New York, 1976.

[4] For part 1, see previous paper in this issue.

[5] R. van Doorn and N. M. M. Nibbering, *Org. Mass. Spectrom.*, 13, 527 (1978).

[6] J. K. Pau, J. K. Kim, and M. C. Caserio, *J. Am. Chem. Soc.*, 100, 3838 (1978).

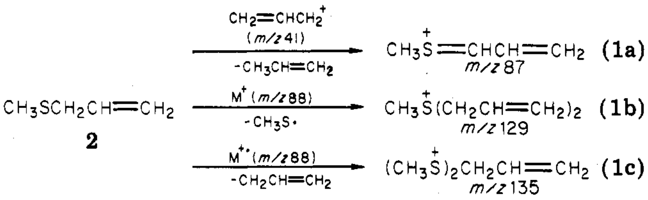
[7] R. C. Dunbar, J. Shen, E. Melby, and G. A. Olah, *J. Am. Chem. Soc.*, 95, 7200 (1973).

Table I. Ion Chemistry of 3-(Methylthio)-1-propene and 3-Methoxy-1-propene

neutral	primary ions,[a] m/z	product ions (precursor ions), m/z
$CH_3SCH_2CH{=}CH_2$	**88** ($M^{+\cdot}$), 73, 61, 41	**89** MH^+ (73),[a] 87 $M^+ - 1$ (41), 129[b] (88), 135[b] (88)
$CD_3SCH_2CH{=}CH_2$	**91** ($M^{+\cdot}$), 73, 64, 41	**92** MH^+ (73),[a] 90 $M^+ - 1$ (41)
$CH_3SCD_2CH{=}CH_2$	**90** ($M^{+\cdot}$), 75, 63, 61, 43	92 MD^+ (75),[a] **91** MH^+ (75), 89[c] $M - 1$ (43) 88[c] $M - 2$ (43), 63), 133[b] (90), 137[b] (90)
$CH_3SCH_2CH{=}CD_2$	**90** ($M^{+\cdot}$), 75, 74, 63, 62, 61, 43	92 MD^+ (75),[a] **91** MH^+ (75), 89[d] $M^+ - 1$ (43), 88[d] $M^+ - 2$, (43)
$CH_3OCH_2CH{=}CH_2$	**72** ($M^{+\cdot}$), 57, 45, 41	**73** MH^+ (57),[a] 71 $M^+ - 1$ (41), 81 (41), 85 (45)
$CD_3OCH_2CH{=}CH_2$	**75** ($M^{+\cdot}$), 58, 57, 48, 41	77 (MD^+),[a] **76** (MH^+), 74 ($M - 1$), 81 (41), 88 (48)
$CH_3OCD_2CH{=}CH_2$	**74** ($M^{+\cdot}$), 59, 58, 47, 43	76 MD^+ (59),[a] **75** MH^+ (59), 73[e] $M^+ - 1$ (43), 72[e] $M - 2$ (43), 89 (47), 88 (47), 85 (43), 84 (43)
$CH_3OCH_2CH{=}CD_2$	**74** ($M^{+\cdot}$), 59, 58, 45, 43	76 (MD^+),[a] **75** (MH^+), 73[f] ($M^+ - 1$), 72[f] ($M^+ - 1$), 87 (45), 85 (43), 84 (43)

[a] Produced at 19 eV, sample pressure 10^{-6} torr. Major ions in boldface type. Additional fragments were formed in the mass range 43–48; most of these reacted rapidly to produce MH^+ such that their abundance as primary fragments is difficult to assess. [b] Minor products (<10% of ion current) after 300 ms. [c] 89/88 ~ 1. [d] 89/88 ~ 3.7. [e] 73/72 ~ 1.7. [f] 73/72 ~ 3.7.

$CH_3SCD_2CH{=}CH_2$ and $CH_3SCH_2CH{=}CD_2$. The molecular ion m/z 88 is unreactive except for the appearance of two minor product ions m/z 129 and 135 at long reaction times (300 ms), according to reactions 1b and 1c.

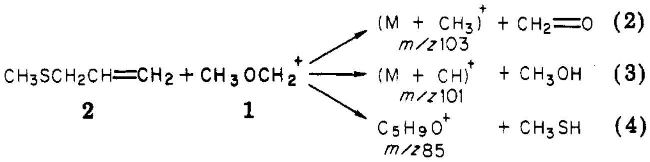


$$\underset{\mathbf{2}}{CH_3SCH_2CH{=}CH_2} \xrightarrow[-CH_3CH{=}CH_2]{CH_2{=}CHCH_2^+\ (m/z\ 41)} \underset{m/z\ 87}{CH_3\overset{+}{S}{=}CHCH{=}CH_2} \quad (1a)$$

$$\xrightarrow[-CH_3S\cdot]{M^+\ (m/z\ 88)} \underset{m/z\ 129}{CH_3\overset{+}{S}(CH_2CH{=}CH_2)_2} \quad (1b)$$

$$\xrightarrow[-CH_2CH{=}CH_2]{M^{+\cdot}\ (m/z\ 88)} \underset{m/z\ 135}{(CH_3\overset{+}{S})_2CH_2CH{=}CH_2} \quad (1c)$$

On adding methyl ether to the allylic sulfide in the ICR cell, the ion chemistry of both neutrals was evident,[8] but *three* new product ions appeared that were not formed from either neutral component alone. These ions had m/z 103, 101, and 85 and were formed in the ratio of 34:48:18 (see Table II). The ratio varied little with electron energy or reaction time. The precursor ion for each of the three product ions was shown by double resonance to be $CH_3OCH_2^+$ m/z 45 derived from electron-impact cleavage of methyl ether. The overall stoichiometry of the three reactions is expressed in eq 2, 3, and 4.



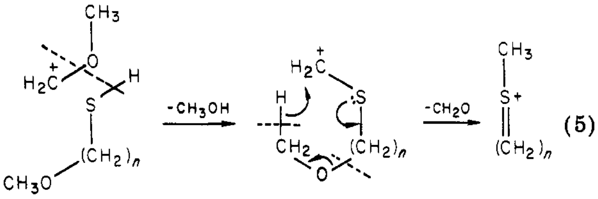
$$\underset{\mathbf{2}}{CH_3SCH_2CH{=}CH_2} + \underset{\mathbf{1}}{CH_3OCH_2^+} \rightarrow \underset{m/z\ 103}{(M + CH_3)^+} + CH_2{=}O \quad (2)$$

$$\rightarrow \underset{m/z\ 101}{(M + CH)^+} + CH_3OH \quad (3)$$

$$\rightarrow \underset{m/z\ 85}{C_5H_9O^+} + CH_3SH \quad (4)$$

Concerning reaction 2, it might appear to be a straightforward methylation for which there is ample precedent in the ion chemistry of $CH_3OCH_2^+$.[4,5,8] However, the reaction of **2** with the deuterium-labeled ion $CD_3OCH_2^+$ m/z 48 (derived from $CD_3OCH_2CH_3$) produced $(M + CH_2D)^+$ m/z 104 instead of the expected $(M + CD_3)^+$ m/z 106. Also, $CH_3OCD_2^+$ m/z 47 (derived from $CH_3OCD_2CH_3$) produced $(M + CD_2H)^+$ m/z 105 instead of $(M + CH_3)^+$ m/z 103 (Table II). Very clearly, it is *not* the methyl but the methylene group of the ion that is transferred to the neutral; hence the ion must cleave along the methylene–oxygen bond rather than the methyl–oxygen bond. Furthermore, *one* of the three methyl hydrogens is retained in the product ion. These conclusions are fully confirmed by combinations of labeled sulfides and ethers, as summarized in Table II. In particular, reactant ions $C_2H_5OCH_2^+$, $C_2H_5OCD_2^+$, and $C_2D_5OCH_2^+$ derived from d_0- and d_5-labeled diethyl ether do *not* "ethylate" **2**—rather they transfer the equivalent of a methyl group to the sulfide with elimination of the elements of acetaldehyde.

Although we had every expectation that alkoxymethyl cations would attack sulfur to produce sulfonium ions, the $(M + CH_3)^+$ ion of reaction 2 cannot be understood by this pathway. The only reasonable alternative is that the ion attacks carbon of the allylic double bond, as shown in Scheme I, path A. Should this occur, the intermediate ion **4** is well set up for hydride transfer from the *O*-alkyl group followed by, or concomitant with, displacement of aldehyde RCHO (R = H, or CH_3) to give m/z 103, which is suggested to have the sulfonium ion structure, **5**. There is some precedent for this reaction pathway in that reactions of m/z 45 with methoxyalkanethiols have been shown to proceed by hydride transfer and aldehyde elimination (eq 5).[4] Furthermore, Nibbering and co-workers have established a similar pathway in the reactions of methoxymethyl cations with alkenes.[5]



Turning to reactions 3 and 4, the product ions m/z 101 and 85 are most likely formed by the elimination of methanol and methanethiol, respectively. Labeling data for **2** with $CD_3OCH_2^+$, or with $C_2H_5OCH_2^+$, leave no doubt that the RO group of the reactant ion is lost as ROH, while the CH_3S of the neutral is lost as methanethiol (see entries 2, 5, 10 in Table II). The more difficult question to address is where the proton comes from that is eliminated as the acidic proton in the neutral products. It can be seen from entries 3, 4, 6, 7 in Table II that when the sulfide is labeled with deuterium at either the allylic position (**2a**) or at the terminal position (**2b**), reaction with **1** leads to both m/z 102 and 103 by loss of both CH_3OD and CH_3OH.

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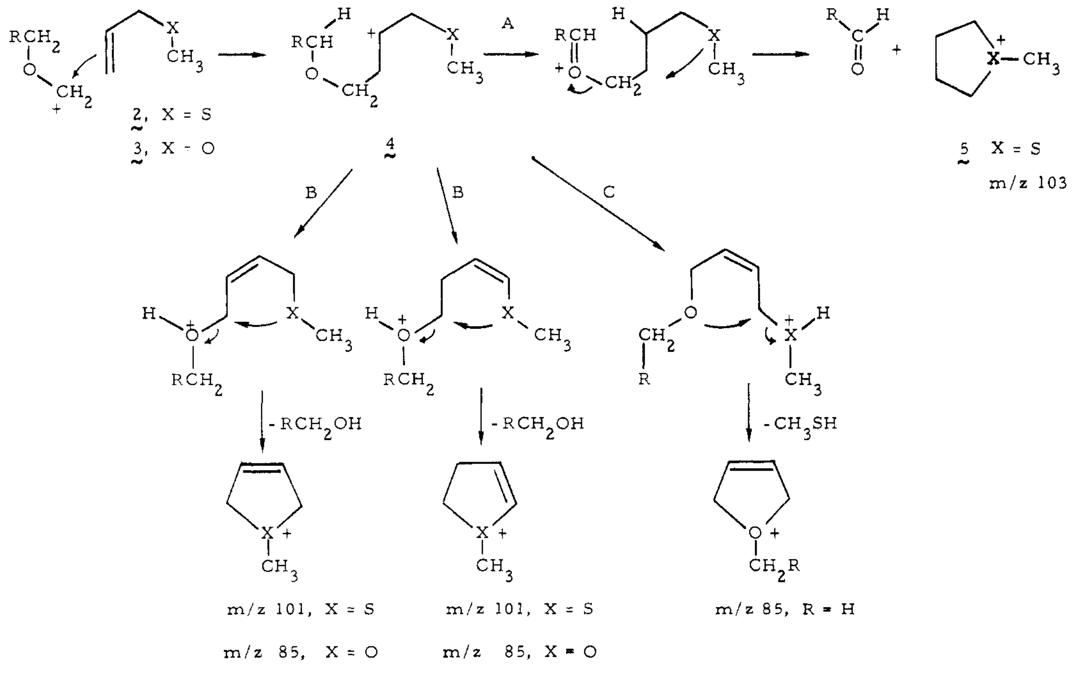
[8] (a) For a report on the ion chemistry of methyl ether under ICR conditions, see J. L. Beauchamp and R. C. Dunbar, *J. Am. Chem. Soc.*, **92**, 1477 (1970). (b) For the structure of $C_2H_5O^+$ ions by CA mass spectrometry, see F. W. McLafferty, R. Kornfeld, W. F. Haddon, K. Levsen, I. Sakai, P. F. Bente III, S-C Tsai, and H. D. R. Schuddemage, *ibid.*, **95**, 3886 (1973).

Table II. Product Distribution in the Reaction of $ROCH_2^+$ with 3-(Methylthio)-1-propene

entry	neutral	reactant ion, m/z	products[a]									
			reaction 2			reaction 3			reaction 4			
			m/z	neutral	I[b]	m/z	neutral	I[b]	m/z	neutral	I[b]	ΣI
1	$CH_3SCH_2CH{=}CH_2$	$CH_3OCH_2^+$, 45	103	$CH_2{=}O$	34	101	CH_3OH	48	85	CH_3SH	18	100
2	$CD_3SCH_2CH{=}CH_2$		106	$CH_2{=}O$	31	104	CH_3OH	49	85	CD_3SH	20	100
3	$CH_3SCD_2CH{=}CH_2$		105	$CH_2{=}O$	32	103 102	CH_3OH CH_3OD	23 20	87	CH_3SH	20	95
4	$CH_3SCH_2CH{=}CD_2$		105	$CH_2{=}O$	32	103 102	CH_3OH CH_3OD	43 9	86 87	CH_3SD CH_3SD	16	100
5	$CH_3SCH_2CH{=}CH_2$	$CD_3OCH_2^+$, 48[g]	104	$CD_2{=}O$	16	101	CD_3OH	42	88	CH_3SH	16	74[c]
6	$CH_3SCD_2CH{=}CH_2$		106	$CD_2{=}O$	18	103 102	CD_3OH CD_3OD	24 18	90	CH_3SH	17	76[d]
7	$CH_3SCH_2CH{=}CD_2$		106	$CD_2{=}O$	26	103 102	CD_3OH CD_3OD	45 10	89	CH_3SD	16	99[e]
8	$CH_3SCH_2CH{=}CH_2$	$CH_3OCD_2^+$, 47[h]	105	$CH_2{=}O$	16	103	CH_3OH	44	87	CH_3SH	22	82[e]
9	$CH_3SCD_2CH{=}CH_2$		107	$CH_2{=}O$	22	105 104	CH_3OH CH_3OD	20 16	89	CH_3SH	23	81[f]
10	$CH_3SCH_2CH{=}CH_2$	$C_2H_5OCH_2^+$, 59[i]	103	$CH_3CH{=}O$	72	101	C_2H_5OH	28				
11		$C_2H_5OCD_2^+$, 61[j]	105	$CH_3CH{=}O$		103	C_2H_5OH					
12		$CH_3CD_2OCH_2^+$, 61[k]	104	$CH_3CD{=}O$	65	101	CH_3CD_2OH	35				
13		$C_2D_5OCH_2^+$, 64[j]	104	$CD_3CD{=}O$		101	C_2D_5OH					
14	$CH_3SCD_2CH{=}CH_2$	$CH_3CD_2OCH_2^+$, 61[k]	106	$CH_3CD{=}O$	70	103	CH_3CD_2OH	30				
15	$CH_3SCH_2CH{=}CD_2$	$C_2H_5OCD_2^+$, 61[j]	107	$CH_3CH{=}O$								

[a] At 19 eV and 85-ms reaction time, 2×10^{-6} torr pressure. [b] Percent ion intensity for product ions of reactions 2-4. [c] Other ions present were m/z 108 (4%), 107 (6%), 105 (7%), 104 (10%). [d] Other ions present were m/z 106 (6%), 105 (4%), 103 (4%), 102 (10%). [e] Other ions present were m/z 104 (7%), 102 (5%), 101 (3%). [f] Other ions present were m/z 106 (6%), 103 (6%), 102 (3%). [g] From $CD_3OCH_2CH_3$. [h] From $CH_3OCD_2CH_3$. [i] From $(C_2H_5)_2O$. [j] From $C_2H_5OC_2D_5$.

Scheme I



Therefore, the methylene protons of the allyl group are implicated as the source of the acidic proton. However, substantially more m/z 103 than 102 is formed from both **2a** and **2b**, which suggests that an isotope effect complicates the ion distribution. Primary H–D isotope effects have been observed in ionic reactions under ICR conditions with k_H/k_D approaching 2.[9,10] Assuming an isotope effect of similar magnitude in the present instance, we conclude that proton removal from the allylic methylene is preferred over the vinylic methylene by a factor of 1.8–2.3. In contrast, methanethiol elimination appears to involve more

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(9) J. L. Beauchamp and M. C. Caserio, *J. Am. Chem. Soc.*, **94**, 2638 (1972).

(10) In unpublished work from this laboratory, a direct measure of k_H/k_D was obtained from an ICR study of $(CH_3S)_2CHD$, dimethylthiomethane-d_1. The major product ions were M – 1 and M – 2, formed respectively by hydride and deuteride abstraction from the parent neutral by the fragment ion CH_3CHD^+. The ratio (M – 1)/(M – 2) was determined as 2.0.

Table III. Product Distribution in the Reactions of $ROCH_2^+$ with 3-Methoxy-1-propene[a]

			products		
entry	neutral	reactant ion, *m/z*	*m/z*	neutral	I^b
1	$CH_3OCH_2CH{=}CH_2$	$CH_3OCH_2^+$, 45	85	CH_3OH	100
2	$CD_3OCH_2CH{=}CH_2$		85	CD_3OH	19
			88	CH_3OH	81
3	$CH_3OCD_2CH{=}CH_2$		86	CH_3OD	39
			87	CH_3OH	61
4	$CH_3OCH_2CH{=}CD_2$		86	CH_3OD	16
			87	CH_3OH	84
5	$CH_3OCH_2CH{=}CH_2$	$CD_3OCH_2^+$, 48	85	CD_3OH	67[c]
			88	CH_3OH	15
6	$CH_3OCD_2CH{=}CH_2$		86	CD_3OD	32[d]
			87	CH_3OD	40
			90	CH_3OH	16
7	$CH_3OCH_2CH{=}CD_2$		87	CD_3OH	82
			89	CH_3OD	18
8	$CH_3OCH_2CH{=}CH_2$	$CH_3OCD_2^+$, 47	87	CH_3OH	82[e]
9	$CH_3OCD_2CH{=}CH_2$		88	CH_3OD	34[f]
			89	CH_3OH	48
10	$CD_3OCH_2CH{=}CH_2$	$CH_3{}^{18}OCH_2^+$, 47	87	CD_3OH	18
			88	$CH_3{}^{18}OH$	82
11	$CH_3OCH_2CH{=}CH_2$	$C_2H_5OCH_2^+$, 59	85	C_2H_5OH	100
12		$C_2H_5OCD_2^+$, 61	87	C_2H_5OH	
13		$CH_3CD_2OCH_2^+$, 61	85	CH_3CD_2OH	
14		$C_2D_5OCH_2^+$, 64	85	C_2D_5OH	
15	$CH_3OCD_2CH{=}CH_2$	$C_2H_5OCH_2^+$, 59	87	C_2H_5OH	50
			86	C_2H_5OD	50

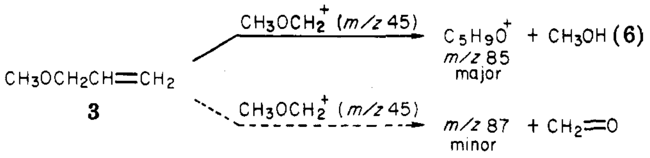
[a] At 19 eV, 85 ms, and 2 × 10^{-6} torr. [b] Percent ion intensity. [c] Other ions formed were *m/z* 86 (11%), 87 (6%). [d] Other ions formed were *m/z* 88 (7%), 89 (5%). [e] Other ions formed were *m/z* 86 (18%). [f] Other ions formed were *m/z* 87 (13%).

proton loss from the vinylic than the allylic methylenes (Table II). Thus, $CH_3SCD_2CH{=}CH_2$ and 1 gave only *m/z* 87 by loss of CH_3SH, whereas $CH_3SCH_2CH{=}CD_2$ and 1 gave both *m/z* 86 and 87 about equally. With the higher homogue, $C_2H_5OCH_2^+$, as the reactant ion, no methanethiol loss was observed.

The results can be rationalized by the sequence shown in Scheme I, paths B and C. The key intermediate, 4, is thought to be the same for all three reaction channels (eq 2–4) and is formulated to show attack of the reactant ion at the terminal carbon of the neutral. Charge is thereby transferred to the methine carbon which makes the adjacent methylene protons relatively acidic. Hence, proton transfer from the methylenes to oxygen or sulfur followed by elimination of ROH or CH_3SH is a reasonable dissociation pathway for 4. There is no direct evidence bearing on the structures of the product ions, but the conjecture that they are five-membered ring onium ions is reasonable.

The pathways shown in Scheme I for reactions 2–4 are supported in the main by results for reactions of 2 with labeled reactant ions, $CD_3OCH_2^+$ and $CH_3OCD_2^+$, but with the added complexity that some scrambling of the deuterium label evidently occurs. For example, reactions represented by entries 5–9 in Table II gave product ions of mass indicative of from 18% to 25% loss of CD_2HOH, CDH_2OH, and CDHO. The cause of this scrambling is not easily identified. Discussion of this point is given in the next section.

Ion Chemistry of 3-Methoxy-1-propene with $ROCH_2^+$. The unusual chemistry of $CH_3OCH_2^+$ with allylic sulfides prompted a study of related reactions of this ion with the allylic ether 3-methoxy-1-propene (3). As before, the reactant ion was generated from methyl ethers in the presence of the neutral allylic compound. Apart from ions produced from the individual neutral components (see Table I), the only major cross product had *m/z* 85 corresponding to the reaction of $CH_3OCH_2^+$ with 3 (eq 6, Figure 1a). In contrast to the behavior of $CH_3OCH_2^+$ with the allylic sulfide, the ion *m/z* 87 corresponding to elimination of $CH_2{=}O$ was a relatively minor product ion (~5%).



Reaction to give *m/z* 85 in eq 6 amounts to the loss of neutral methanol. The question as to which methyl ether group is eliminated as the neutral and which is retained in the ion was investigated using labeled substrates. Definitive information on this point came from the reaction of the unlabeled ion *m/z* 45 with methyl-d_3 allyl ether. As shown in Table III, entry 2, two ions of *m/z* 85 and 88 were formed in the ratio 19:81, indicating the loss of CD_3OH *and* CH_3OH, respectively. In a separate experiment, reaction of $CH_3{}^{18}OCH_2^+$ *m/z* 47 (derived from ^{18}O-labeled dimethyl ether) with $CD_3OCH_2CH{=}CH_2$ gave ions *m/z* 87 and 88 in the ratio 18:82, corresponding to the loss of CD_3OH and $CH_3{}^{18}OH$, respectively (Figure 1b and entry 10). This means that about 18% of the reaction in eq 6 involves loss of the methoxyl from the neutral and 82% from the reactant ion.[11] The higher homologue, $C_2H_5OCH_2^+$ *m/z* 59, reacted similarly but led to the loss of C_2H_5OH only (Table III, entries 11–15).

For location of the site of proton loss in the elimination of methanol from 1 and 3, deuterium labels were both helpful and confusing. Proton loss from the methyl group of 3 can be excluded because reactions of $CD_3OCH_2CH{=}CH_2$ gave no trace of *m/z* 87 due to CH_3OD elimination (entry 2). When, however, the label was in the allylic portion of the ether, loss of CH_3OD was significant (entries 3, 4). However, the ratio *m/z* 86/*m/z* 87 for the reaction of $CH_3OCD_2CH{=}CH_2$ with 1 is higher than the ratio for

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[11] The estimate of 20% loss of methanol from the neutral is probably a lower limit for the reason that $CD_3OCH_2^+$ *m/z* 48 from EI fragmentation of 2-d_3 also contributes to the formation of *m/z* 88.

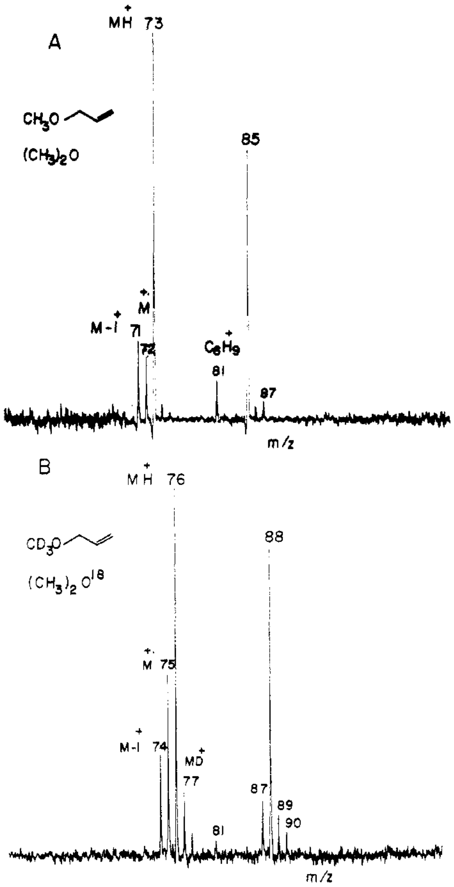
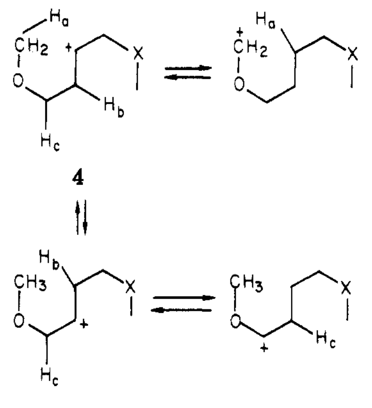


Figure 1. (A) ICR mass spectrum of a mixture of 3-methoxy-1-propene (1×10^{-6} torr) and methyl ether (1.2×10^{-6} torr) after 85-ms reaction time and 19 at eV. (B) ICR mass spectrum of $CD_3OCH_2CH{=}CH_2$ (8×10^{-7} torr and ^{18}O-labeled methyl ether, 98% enriched, (5×10^{-7} torr) after 85-ms reaction time and at 19 eV.

$CH_3OCH_2CH{=}CD_2$. As with analogous reactions of the sulfide 2, an isotope effect favoring elimination of CH_3OH is superimposed on a kinetic preference for loss of the allylic proton over the vinylic methylene protons. Related reactions of $C_2H_5OCH_2^+$ with $CH_3OCD_2CH{=}CH_2$ led to *m/z* 86 and 87 in about equal abundance, corresponding to the elimination of EtOD and EtOH (entry 15). In this case it is worth noting that the methylene protons of the reactant ion are not significantly involved because the reaction of 3 with $C_2H_5OCD_2^+$ *m/z* 61 gave loss of EtOH only (entry 12).

The results can be adequately described by the reaction sequence in Scheme I (X = O) with the exception that path A is unimportant. The reactant ion is considered to add to the terminal allylic carbon to give 4, which dissociates by losing methanol by path B (80%) and by path C (20%). When, however, a deuterium label was present in the reactant ion as either $CD_3OCH_2^+$ or $CH_3OCD_2^+$, the label distribution in the product ions was largely but not entirely consistent with Scheme I. Between 10–18% of the product ions can be explained only if some degree of label scrambling occurs.[12] This is evident from Table III, which shows that ions resulting from loss of CD_2HOH and CH_2DOH are formed to a minor extent (entries 6, 8, 9). Rearrangement of the reactant ion must be considered as a possible source of the observed scrambling. Even though rearrangement of methoxymethyl cations to isomeric $C_2H_5O^+$ ions can be ruled out,[8] degenerate rearrangement by 1,3-hydride shifts is conceivable. In fact, complete label scrambling has been observed in $CD_3OCH_2^+$ ions that have sufficient energy to dissociate to methane and formaldehyde.[13] The dissociation process has a high activation energy (83 kcal/mol) and the label scrambling is thought to occur through symmetry-forbidden 1,3-hydride shifts which require an activation energy in the range of 58–83 kcal/mol. However, Nibbering and co-workers have shown that *nondecomposing* methoxymethyl cations generated by electron impact of methyl ethers with 13-eV electrons do *not* rearrange by 1,3-hydride shifts to any significant extent.[5] In the present work, 19-eV electrons were used to generate the reactant ions, yet on lowering the energy of the ionizing beam to 13 eV, the label scrambling was not eliminated. The relative ion intensities of the major product ions varied little with the electron energy, but on reducing the energy from 19 to 13 eV, the ion intensity was lowered to such an extent that it was not possible to measure the intensities of minor ions, and hence the degree of label scrambling, with any accuracy.

It is curious that label scrambling is evident in the reactions of labeled 1 with unsaturated ethers and sulfides but not in the reactions of 1 with other neutral nucleophiles.[4,7] Thus, extensive studies of the reactions of labeled 1 with acyl compounds gave no evidence of rearrangement or label scrambling in the reactant ion.[14] Overall, it appears more likely that the label scrambling observed in the present experiments occurs within the cluster ion formed between the reactant ion and the neutral ether or sulfide, or within the intermediate ion 4. One possibility is that 4 undergoes reversible hydride transfers of the type shown in eq 7 prior to dissociating to products.



(7)

It is important to note that the reactions described are not restricted to allylic compounds. Thus, methoxymethyl cations have been found to react with alkenes and with methyl vinyl ether, and some degree of label-scrambling also was observed.[5] In turn, we have found that the vinylic ether 2-methoxy-1-propene reacts in a similar manner with $CH_3OCH_2^+$. Moreover, 2-methoxy-1-propene with $CD_3OCH_2^+$ leads to the elimination of CD_3OH and CD_2HOH in the ratio of 4:1. The suggestion[5] of hydride transfers in open ion intermediates is the most plausible explanation of the extent of H–D interchange observed.

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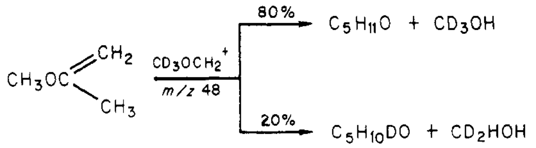
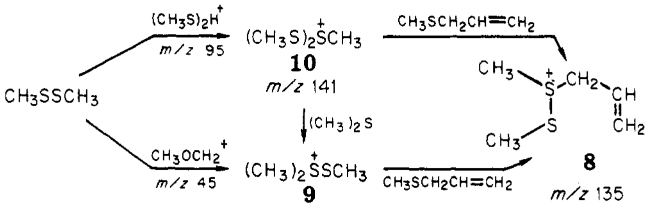
[12] The product distribution is complicated by the fact that the neutral allylic ether also produces methoxymethyl cations on EI fragmentation which contribute to the formation of the product ions of reaction 6. On the basis of the abundance ratio of unlabeled and labeled methoxymethyl cations *m/z* 45/47 or *m/z* 45/48, and on ion-ejection double-resonance experiments, no more than 10% of the ion abundance of *m/z* 85 in reaction 6 comes from *m/z* 45 produced by EI fragmentation of 2 at equal partial pressures of 2 and labeled methyl ether. The product distributions still reflect 10–18% label scrambling even after correction for routes directly from the fragment ions.

[13] G. Hvistendahl and D. H. Williams, *J. Am. Chem. Soc.*, **97**, 3097 (1975).

[14] J. K. Kim and M. C. Caserio, *J. Am. Chem. Soc.*, **103**, 2124 (1981) and unpublished results from these laboratories.

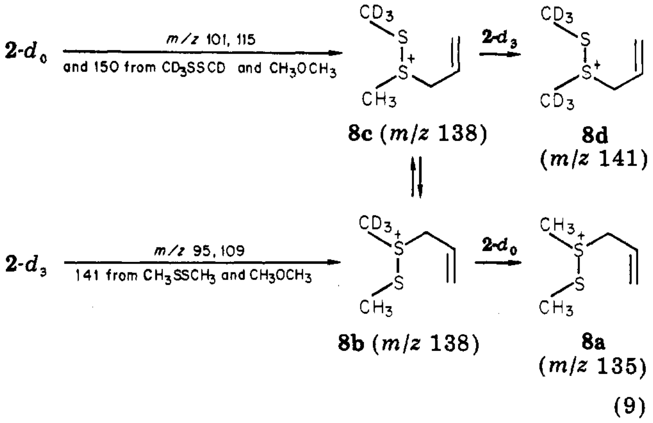


Thiosulfonium Ions. One objective in studying the gas-phase ion chemistry of 3-(methylthio)-1-propene was to generate allylic thiosulfonium ions 8 by the sequential reactions shown in eq 8. We have shown previously that (alkylthio)sulfonium ions such as 9 can be generated in the gas phase by the methylation of disulfides with methoxymethyl ions, and by methylthiolation of alkyl sulfides.[4] It was therefore anticipated that thiosulfonium ion 8 would be generated by methylthiolation of 3-(methylthio)-1-propene. Accordingly, a study was undertaken of the ion chemistry of mixtures of 2 with methyl ether and methyl disulfide. The ether–disulfide combination served to generate the precursors to 8, namely, m/z 109 (9) and m/z 141 (10). As expected, 8 m/z 135 was formed in moderate abundance from the reactions of both m/z 109 and 141 with 2.



(8)

If m/z 135 formed in this manner has the allylic thiosulfonium ion structure 8, it may be expected to undergo a [2,3] sigmatropic rearrangement. This degenerate rearrangement has been demonstrated to occur rapidly in condensed phase.[15] We attempted to study the possibility of rearrangement by experiments designed to test for the equilibria of eq 9. Thus, if a rapid rearrangement of 8c and 8b occurs, and if a thermoneutral exchange reaction between 8 and the neutral sulfide is also rapid (as it is in nitromethane solution), then 8c (m/z 138) should lead to 8a in the presence of 2, and 8b should lead to 8d in the presence of 2-d_3. Although m/z 138 was indeed formed from 2 in the presence of CD_3SSCD_3 and methyl ether, we were unable to confirm the rearrangement–exchange sequence 8c → 8b → 8a (m/z 135) because 8a (m/z 135) is also formed to some extent in the ion chemistry of 2 (see eq 1c). Likewise, 8b was formed from 2-d_3 in the presence of CH_3SSCH_3 and methyl ether, but the sequence 8b → 8c → 8d (m/z 141) could not be verified because m/z 141 is also formed in the ion chemistry of methyl disulfide. Weak double-resonance signals indicated that m/z 135 is coming from m/z 138, at least in part, but the evidence is inconclusive.



(9)

Summary

The results described emphasize the reactivity of methoxymethyl cations and related ions toward nucleophiles in the gas phase. The reactions of the ions with unsaturated ethers and sulfides indicate that the ions attack the double bond rather than the nucleophilic oxygen or sulfur. The preferred mode of dissociation of the ionic intermediates results in the cleavage of the methylene–oxygen bond of the reactant ion with expulsion of the elements of aldehyde and/or alcohol. While it is premature to conclude whether comparable reactions would occur in the condensed phase, the potential for such reactions is clearly established.

Experimental Section

Instrumental techniques used in the ICR studies have been described previously.[4,6] Syntheses of deuterium-labeled sulfides $CH_3SCD_2CH{=}CH_2$ and $CD_3SCH_2CH{=}CH_2$ also have been described.[16] **3-(Methylthio)-propene-*1,1*-d_2** was prepared from methyl acrylate as follows. To a methanolic solution of methyl acrylate (17.3 g, 0.2 mol) and methanethiol (10 g, 0.21 mol) at −10 °C was added 0.3 mL of "Triton B" (benzylethylammonium hydroxide). An exothermic reaction ensued. After being stirred at room temperature for 30 min, the mixture was fractionally distilled under reduced pressure and gave methyl 3-(methylthio)propanoate (21 g, 80%) as a colorless liquid [bp 31–33 °C (0.4 mm), lit.[17] bp 80.5 °C (15 mm)]: NMR ($CDCl_3$) δ 2.05 (s, 3 H, SCH_3), 2.6 (m, 4 H, CH_2CH_2), 3.59 (s, 3 H, OCH_3). The ester product (6 g, 44.7 mmol) was reduced with lithium aluminum deuteride (LAD, 1 g, 23.8 mmol) in anhydrous ether to 3-(methylthio)propan-1-ol-*1,1*-d_2 [bp 52–3 °C (2 mm), 4.1 g, 85%)]: NMR ($CDCl_3$) δ 1.80 (t, J = 7 Hz, CH_2CD_2), 2.06 (s, 3 H, SCH_3), 2.56 (t, J = 7 Hz, 2 H, SCH_2), 2.54 (s, 1 H, OH). Dehydration of the alcohol was accomplished by thermal decomposition of the xanthate ester: To 10 mL of warm *tert*-butyl alcohol was added 0.8 g (20 mmol) of potassium metal. After dissolution of the metal, the alcohol $CH_3SCH_2CH_2CD_2OH$ (1.26 g, 11.6 mmol) was added and the mixture was stirred for 30 min. On addition of carbon disulfide (3 g, 40 mmol), the mixture turned to an orange paste. Iodomethane (2.8 g, 20 mmol) was added slowly to the mixture, which was then refluxed for 12 h and filtered, and the filtrate was distilled under vacuum. The product [xanthate ester, bp 74–76 °C (15 mm)] was heated to 220 °C to give a distillate of crude $CH_3SCH_2CH{=}CD_2$ (270 mg, 25%). Further purification was achieved by preparative GC: NMR ($CDCl_3$) δ 1.97 (s, 3 H, SCH_3), 3.02 (d, J = 5 Hz, 2 H, SCH_2), 5.7 (m, 1 H, =CH).

3-Methoxypropan-1-ol-*1,1*-d_2 was obtained in 54% yield by the reduction of methyl 3-methoxypropanoate with LAD [bp 48–49 °C (15 mm), lit.[18] bp 47.8 °C (14 mm)]: NMR ($CDCl_3$) δ 1.79 (t, J = 7 Hz, 2 H, CH_2CD_2), 3.28 (s, 3 H, OCH_3), 3.43 (t, J = 7 Hz, 2 H, OCH_2), 2.90 (br s, 1 H, OH). Dehydration of the alcohol to give **3-methoxypropene-*1,1*-d_2** was achieved by using *o*-nitrophenylselenocyanate.[19] To a solution of the labeled alcohol (1.12 g, 12 mmol) and the seleno cyanate (3.5 g, 15 mmol) in 30 mL of tetrahydrofuran under nitrogen was slowly added tri-*n*-butylphosphine (3 g, 15 mmol). The mixture darkened and a yellow precipitate formed. After being stirred for 3 h, the mixture was cooled to 0 °C and treated with 13.5 mL of 30% hydrogen peroxide over a period of 1 h. Stirring was continued overnight. The absence of residual peroxide was verified and the mixture was then fractionally distilled to give $CH_3OCH_2CH{=}CD_2$ (2.3 g, 77%): NMR ($CDCl_3$) δ 3.27 (s, 3 H, OCH_3), 3.82 (d, J = 5.2 Hz,

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2 H, CH_2), 5.8 (br m, 1 H, $=CH$).

Other labeled ethers, $CD_3OCH_2CH{=}CH_2$, $CH_3OCD_2CH{=}CH_2$, $CD_3OC_2H_5$, and $CH_3OC_2D_5$, were prepared respectively from $CH_2{=}CHCH_2OH$, $CH_2{=}CHCD_2OH$,[16a] C_2H_5OH, and C_2D_5OD (99.5% *d*) by reaction with CD_3I or CH_3I in the presence of silver oxide and dimethylformamide.[6] Yields were in the range of 68–92%. **3-Oxapentane-*1,1,2,2,2-d$_5$*** was prepared in 67% yield from a solution of ethyl-d_5 alcohol-*d* (99.5% *d*, 1.4 g, 27 mmol) and sodium metal (0.13 g, 5.65 mmol) and iodoethane (0.92 g, 5.9 mmol). Methyl ether labeled with ^{18}O was prepared from ^{18}O-labeled methanol by reaction with iodomethane and silver oxide in dimethylformamide. The labeled methanol was obtained by the hydrolysis of tri-*n*-butyl orthoformate with $H_2{}^{18}O$ (99% ^{18}O)[20] followed by reduction of the *n*-butyl formate-^{18}O so formed with LAH in diglyme.[21] This method gave more than 98% isotopically pure ^{18}O-labeled methanol.

Acknowledgment. We gratefully acknowledge support for this work in part by Grant GM 27319 awarded by the National Institute of General Medical Sciences, DHEW, and in part by Grant CHE 7807993 awarded by the National Science Foundation.

Registry No. 1, 23653-97-6; **1a**, 78638-90-1; **1b**, 44652-30-4; **1c**, 78638-91-2; **2**, 10152-76-8; **3**, 627-40-7; $CD_3SCH_2CH{=}CH_2$, 68345-75-5; $CH_3SCD_2CH{=}CH_2$, 41865-20-7; $CH_3SCH_2CH{=}CD_2$, 68388-59-0; $CD_3OCH_2CH{=}CH_2$, 78638-92-3; $CH_3OCD_2CH{=}CH_2$, 78638-93-4; $CH_3OCH_2CH{=}CD_2$, 78656-88-9; $CD_3OCH_2^+$, 78638-94-5; $CH_3OCD_2^+$, 78638-95-6; $CH_3CH_2OCH_2^+$, 43730-63-8; $CH_3CH_2OCD_2^+$, 78638-96-7; $CH_3CD_2OCH_2^+$, 78638-97-8; $CD_3CD_2OCH_2^+$, 78638-98-9.

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Mechanisms of Elimination Reactions. 34. Deuterium and Nitrogen Isotope Effects and Hammett Correlations in the Reaction of (2-Arylethyl)trimethylammonium Ions with Hydroxide Ion in Mixtures of Water and Dimethyl Sulfoxide[1,2]

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When (2-phenylethyl)trimethylammonium and (2-phenylethyl-*2,2-d$_2$*)trimethylammonium bromides are treated with sodium hydroxide in aqueous dimethyl sulfoxide at 60 °C, increasing the dimethyl sulfoxide concentration leads to an increase in the elimination rate (>10^3 between 17.1% and 57.1% Me_2SO). There is also an increase in k_H/k_D from 3.22 at 17.1% Me_2SO to 5.21 at 34.3%, followed by a decrease to 3.83 at 57.1%. The nitrogen isotope effect (k_{14}/k_{15}) decreases initially from ca. 1.009 (estimated from data at 97 °C) in water to 1.007 in 22.8% Me_2SO but thereafter remains essentially constant around 1.006–1.007 up to 57.1% Me_2SO. When substituted (2-phenylethyl)trimethylammonium bromides (substituents *p*-Cl, H, *p*-Me, and *p*-MeO) are used, the rates fit the Hammett equation. The Hammett ρ is +3.11 in 17.1% Me_2SO, but after an initial rise it remains essentially constant (+3.38 ± 0.09) from 30% to 50.6% Me_2SO. Both the nitrogen isotope effects and the Hammett ρ values indicate a transition state that becomes somewhat more reactant-like with increasing dimethyl sulfoxide concentration. The deuterium isotope effects are consistent with this picture but suggest a greater shift in transition-state structure.

2-Phenylethyl derivatives have played a key role in investigations of transition-state structure in bimolecular elimination (E2) reactions[3] and have more recently also figured in the study of tunneling in E2 reactions.[4] In this paper we provide further evidence on the effects of solvent and base on the transition states for E2 reactions of (2-arylethyl)trimethylammonium salts.

Table I. Rate Constants for the Reaction of (2-Arylethyl)trimethylammonium Bromides with Sodium Hydroxide in Aqueous Dimethyl Sulfoxide at 60 °C[a]

Me_2SO, mol %[b]	10^4k_2, s^{-1} M^{-1} for isotope, substituent[c]				
	H, *p*-Cl	H, H	H, *p*-Me	H, *p*-MeO	D, H
17.1	6.87	1.29	0.390	0.189	0.400
22.8		4.03			1.04
30.0	12.1	21.7	5.23	2.23	4.57
34.3	223.0	34.0	11.0	4.17	6.53
37.1	430.0	73.3	23.8	7.73	
40.6	830.0	163.0[d]	46.0	16.1	33.0
44.5	1560.0	282.0	92.3	31.7	58.3
50.6	4700.0	710.0[e,f]	240.0	80.7	160.0
57.1		1660.0			433.0
69.5				930.0[g]	

[a] Substrate ca. 0.004 M, base ca. 0.05 M. Measured as pseudo-first-order rate constants and divided by the base concentration to calculate k_2. [b] Mole fractiom times 100. [c] Each value is the average of at least two runs; reproducibility ±1.5%. [d] 163.0 with KOH as base. [e] 780.0 with KOH as base. [f] 550.0 in the presence of 0.4 M tetrabutylammonium bromide. [g] 1390.0 with KOH as base.

Previous workers have shown that these substances react with ethoxide ion in ethanol with a k_H/k_D of only 3.0[5] at 50 °C, a Hammett ρ of +3.8[6] at 30 °C, and a nitrogen isotope effect, k_{14}/k_{15}, of 1.013[7] at 40 °C. The nitrogen isotope effect is well below the maximum value of 1.040–1.045 from model calculations,[8] which in conjuction with the high ρ value indicates a transition state with a relatively strong C–N bond (at least 70% of normal) and a high degree of carbanion character at the β carbon. The low k_H/k_D could indicate that proton transfer is considerably more than half complete in the transition state, though more recent work[4] suggests that the unsymmetry

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(1) This work was supported by the National Science Foundation.

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