Table II. Statistical Analysis of Factorization

no. of factors	eigenvalue,[a] λ	cumulative % variance[b]
1	51.132	94.69
2	2.811	99.90
3	0.051	99.99
4	0.005	~100.00

[a] The remaining factors have vanishingly small eigenvalues. [b] Percentage of total variance in the data set accounted for by the reduction. The variance accounted for by each factor is given by: $\lambda_i/\Sigma_{i=1}{}^n\lambda_i$, where λ_i is the eigenvalue of factor i and the sum is over all factors needed to exactly reproduce the data. Cumulative percent variance is analogous to r^2 (× 100) for a regression curve.

properties of the hydrogen-bonded HX molecules. The a_1 and a_2 factors do not seem to account for properties which are dependent on specific (non-orientation-averaged) intermolecular interaction, but they do serve to correlate virtually all physical and spectroscopic properties of liquid and/or gas phase halides. These observations strongly suggest that the success of the correlation is due in large measure to the dominant role of polarizability in determining *changes* in the intermolecular attractive forces between halogen-containing molecules. The C–X bond dipoles are reasonably constant for the halide series (1.74 ± 0.12 D)[38] and, to a first approximation, properties dependent upon averaged intermolecular association (i.e., boiling point, $\Delta H^\circ_{\text{vap}}$, van der Waals terms, T_c, surface tension, etc.) should vary linearly with the polarizability, which, in turn, is related in an approximately linear way (items 1 and 2, Table I) to both a_2 and the integers 1–4.

The monotonic increase in halogen polarizability from F through I, when considered together with the fairly constant magnitude of the C–X bond dipole, provides a qualitatively reasonable (albeit incomplete) rationale for the success of the factor analysis. Most of the physical and spectroscopic (e.g., ^{13}C shifts, IR, and Raman vibrations via their relationship to the stretching force constants (item 7), photoelectron spectra, etc.) properties of halogen-containing molecules could be qualitatively attributed to the dominant role of the "freeness" or "deformability" of electrons associated with halogen. Unfortunately, as noted elsewhere,[3] we are unaware of any theory which can successfully relate all of the properties of such molecules much less account for the apparent linearity of the correlations. Despite the lack of a firm theoretical model, the unifying relationship presented above should prove useful for a variety of empirical investigations.

Acknowledgment. At the University of Connecticut this investigation was supported in part by a grant from the Humphrey Chemical Company, North Haven, CT, and in part by the donors of the Petroleum Research Fund (9456-G4), administered by the American Chemical Society. At Yale this investigation was supported by Grant CHE78-24880 from the National Science Foundation.

Registry No. Methyl fluoride, 593-53-3; methyl chloride, 74-87-3; methyl bromide, 74-83-9; methyl iodide, 74-88-4; ethyl fluoride, 353-36-6; ethyl chloride, 75-00-3; ethyl bromide, 74-96-4; ethyl iodide, 75-03-6; phenyl fluoride, 462-06-6; phenyl chloride, 108-90-7; phenyl bromide, 108-86-1; phenyl iodide, 591-50-4.

Supplementary Material Available: Table III, the b_1 and b_2 property cofactors from the two-factor analysis (3 pages). Ordering information is given on any current masthead page.

[38] The dipole moments of the methyl halides in the gas phase are as follows: CH_3F, 1.85 D; CH_3Cl, 1.87 D; CH_3Br, 1.81 D; CH_3I, 1.62 D. Cf. Cumper, C. W. N. *Tetrahedron* **1969**, *25*, 3131.

Thiosulfonium Ions by Gas-Phase Methylation and Thiomethylation of Sulfur Nucleophiles. 1. Methoxymethyl Cations

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Generation of gaseous thiosulfonium ions $(CH_3SSCH_3)R^+$, R = H, alkyl, and dithiosulfonium ions, R = alkylthio, has been achieved by ion cyclotron resonance techniques. Hitherto, dithiosulfonium ions have been inferred as transient intermediates in solution-phase reactions. It is here reported that these ions can be formed in the gas phase by displacement of methanethiol from protonated methyl disulfide with neutral disulfide. Related ions $(CH_3S)_2CH_3{}^+$ can also be formed in the gas phase by the methylation of methyl disulfide with $CH_3OCH_2{}^+$ derived from methyl ethers on electron impact. Gaseous thio- and dithiosulfonium ions have been shown to thiolate neutral sulfides and selected alkenes, as they do in condensed phase. The ion/molecule chemistry of methyl 1-phenylethyl sulfide has been studied and has been found to lead to thiosulfonium ions $(CH_3S)_2R^+$, R = 1-phenylethyl, by methylthiolation of the neutral sulfide by the molecular ion. A degenerative rearrangement of $(CH_3S)_2R^+$ which has been documented in solution was not evident in the behavior of the gaseous ion. The implication of this observation is discussed. Heats of formation of trimethylsulfonium and several thiosulfonium ions have been estimated.

Thiosulfonium ions having the general structure RSS^+R_2 are highly reactive ions and have been isolated as stable salts in relatively few instances.[1,2] The best characterized ion is dimethyl(methylthio)sulfonium, **1** (R = CH_3), which forms stable salts with nonnucleophilic counterions. However, in the presence of neutral or anionic nucleophiles, the ion readily dissociates by S–S$^+$ and C–S$^+$

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[1] (a) G. K. Helmkamp, H. N. Cassey, B. A. Olsen, and D. J. Pettitt, *J. Org. Chem.*, **30**, 933 (1965); (b) D. J. Pettitt and G. K. Helmkamp, *ibid.*, **28**, 2932 (1963); *ibid.*, **29**, 2702 (1964); (c) N. E. Hesler, G. K. Helmkamp, and G. L. Alford, *Int, J. Sulfur Chem., Part A*, 1, 65 (1971).

[2] (a) H. Meerwein, K. F. Zenner, and R. Gipp, *Justus Liebigs Ann. Chem.*, **688**, 67 (1965); (b) R. A. Goodrich and F. M. Treichel, *J. Am. Chem. Soc.*, **88**, 3509 (1966).

0022-3263/81/1946-4230$01.25/0

cleavage.[3-8] The existence of higher homologues has been inferred from kinetic and NMR data. For example, the temperature dependence and the concentration dependence of the NMR spectra of salts of 1 with sulfides and disulfides suggest that the equilibria of eq 1 and 2 are rapidly established.[6b,7a,8] Nevertheless, attempts to isolate

$$\underset{\mathbf{1}}{(CH_3)_2S^+SCH_3} + R_2S \rightleftarrows R_2S^+SCH_3 + (CH_3)_2S \quad (1)$$

$$(CH_3)_2S^+SCH_3 + (RS)_2 \rightleftarrows \underset{\mathbf{2}}{(R^+S)_2SCH_3} + (CH_3)_2S \quad (2)$$

thiosulfonium ions and dithiosulfonium ions **2** by direct methylthiolation of sulfides and disulfides have been unsuccessful,[1a] largely because of the intervention of alkylthiolation reactions that result in disulfide interchange (eq 3)[7a] and alkylation reactions that lead to sulfonium salts (eq 4).[7b]

$$(RS^+)_2SCH_3 + (CH_3)_2S \rightleftarrows RSSCH_3 + (CH_3)_2S^+SR \quad (3)$$

$$R_2S^+SCH_3 + (CH_3)_2S \rightarrow RSSCH_3 + (CH_3)_2S^+R \quad (4)$$

In order to generate and detect thiosulfonium ions by direct means, we sought to prepare them in the gas phase by ion cyclotron resonance (ICR) techniques.[9] The absence of solvent and counterions, as well as the low sample pressures inherent in the ICR experiment, makes the technique ideally suited for the observation of reactive ions that appear as transient intermediates in condensed phase. Accordingly, we report here the results of an ICR study on the generation of gaseous thio- and dithiosulfonium ions and their subsequent reactions with sulfur nucleophiles. The work is part of an on-going project concerned with the effect of alkylating agents and other electrophiles on compounds with S–S and S–N bonds. In this regard, the alkylation behavior of the methoxymethyl cation, $CH_3OCH_2^+$, is of special interest because certain neutral precursors to this ion are proven or potential carcinogens. Safety regulations prohibit the use of carcinogens such as CH_3OCH_2Cl as a source of $CH_3OCH_2^+$ in concentrations sufficient for standard laboratory manipulations. Therefore, in order to generate methoxymethyl cations safely, and to study their reactions, we have resorted to ICR techniques whereby the gaseous ions can be formed from relatively nontoxic neutral precursors, CH_3OCH_2R, by electron impact. This paper represents the first of several reports on the diverse behavior of gaseous methoxymethyl cations. In the present report, we describe the reactions of this ion with methyl sulfide and disulfide.

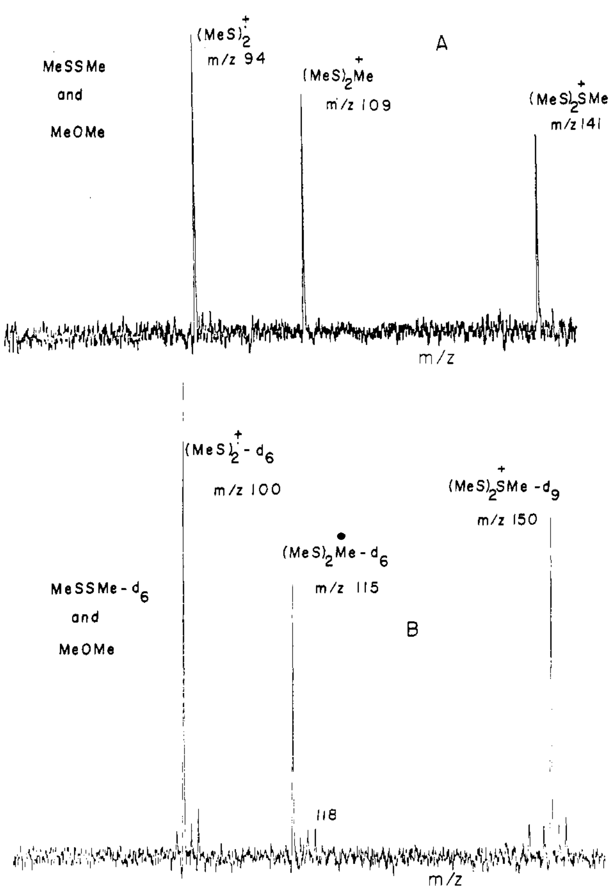
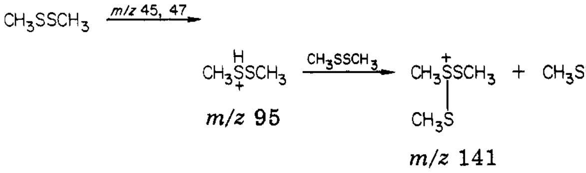


Figure 1. (A) ICR mass spectrum at 300 ms in the reaction of methyl disulfide (1×10^{-6} torr) with methyl ether (2×10^{-6} torr). (B) As in A but with CD_3SSCD_3 and methyl ether.

Results and Discussion

Ion Chemistry of Methyl Disulfide. The gas-phase ion chemistry of methyl disulfide is relatively straightforward.[10] The molecular ion is the most abundant ion produced on electron impact by 19-eV electrons. It is slow to react further and remains the most abundant ion during 200-ms reaction time. The most interesting product ions have *m/z* 95 and 141. The former is the protonated parent ion formed by proton transfer to methyl disulfide by acidic fragment ions (see Table I), but it is not a major product ion as it reacts further with methyl disulfide to produce *m/z* 141. The sequence is described by eq 5, which formulates *m/z* 95 as a thiosulfonium ion that transfers CH_3S^+ to the neutral disulfide. The product ion *m/z* 141 corresponds to a dithiosulfonium ion **2** (R = CH_3).



$$CH_3SSCH_3 \xrightarrow{m/z\ 45,\ 47} \underset{m/z\ 95}{CH_3\overset{H}{\underset{+}{S}}SCH_3} \xrightarrow{CH_3SSCH_3} \underset{m/z\ 141}{CH_3\overset{+}{\underset{CH_3S}{S}}SCH_3} + CH_3SH \quad (5)$$

The solution-phase analogue of *m/z* 141 was first proposed as a transient product of the equilibrium in eq 2 to account for the NMR spectra of mixtures of 1 and methyl disulfide.[7a] Subsequent low-temperature NMR experiments have detected analogues of 2,[11a] and their sulfenating properties have been demonstrated, even though salts of

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[3] E. Campaigne, R. L. White, and B. G. Heaton, *Int. J. Sulfur Chem., Part A*, 1, 39 (1971).

[4] (a) M. Kobayashi, H. Minato, J. Fukui, and N. Kamigata, *Bull. Chem. Soc. Jpn.*, **48**, 729 (1975); (b) M. Oki and K. Kobayashi, *ibid.*, **43**, 1223, 1229, 1234 (1970); (c) M. Kobayashi, H. Minato, and K. Shimada, *Int. J. Sulfur Chem., Part A*, 1, 105 (1971).

[5] B. Miller and C-H. Han, *J. Org. Chem.*, **36**, 1513 (1971).

[6] (a) J. L. Kice, *Acc. Chem. Res.*, 1, 58 (1968), and references therein; (b) J. L. Kice and N. A. Favstritsky, *J. Am. Chem. Soc.*, **91**, 1751 (1969).

[7] (a) S. H. Smallcombe and M. C. Caserio, *J. Am. Chem. Soc.*, **93**, 5826 (1971); (b) J. K. Kim and M. C. Caserio, *ibid.*, **96**, 1930 (1974); (c) J. K. Kim, M. L. Kline, and M. C. Caserio, *ibid.*, **100**, 6243 (1978); (d) S. A. Anderson, J. K. Kim, and M. C. Caserio, *J. Org. Chem.*, **43**, 4822 (1978); (e) J. K. Kim, J. K. Pau, and M. C. Caserio, *ibid.*, **44**, 1544 (1979).

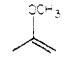
[8] H. Minato, T. Miur, F. Takagi, and M. Kobayashi, *Chem. Lett.*, 211 (1975).

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

[10] No report on the gas-phase ion chemistry of disulfides has appeared, to our knowledge. However, see M. Bonifačic, K. Schäfer, H. Möckel, and K.-D. Asmus, *J. Phys. Chem.*, **79**, 1496 (1975).

[11] (a) G. Capozzi, V. Lucchini, G. Modena, and F. Rivetti, *J. Chem. Soc., Perkin Trans. 2*, 900 (1975); (b) G. Capozzi, O. DeLucchi, V. Lucchini, and G. Modena, *Tetrahedron Lett.*, 2603 (1975); (c) G. Capozzi, O. DeLucchi, V. Lucchini, and G. Modena, *J. Chem. Soc., Chem. Commun.*, 248 (1975).

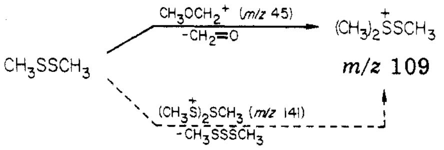
Table I. Summary of Ion Chemistry of Methyl Disulfide and Related Compounds

neutral reactants	primary ions, *m/z* [a]	product ions, *m/z* [a]	precursor ions, *m/z*
CH_3SSCH_3	**94** $M^{+\cdot}$	**141** $(CH_3S^+)_2SCH_3$	95
	79 CH_3SS^+		
	61[c]	95 MH^+	45, 47
	48 CH_3SH^+		
	47 CH_3S^+		
	46 CH_2S^+		
	45 CHS^+		
CH_3SCH_3	**62** $M^{+\cdot}$	**63** MH^+	46, 47, 61
	61[c] $CH_3SCH_2^+$		
	47 CH_3S^+		
	46 CH_2S^+		
CH_3SSCH_3 + CH_3SCH_3 [b]		**109** $(CH_3)_2{}^+SSCH_3$	141, 95
CD_3SSCD_3 + CH_3SCH_3 [b]		**112** $(CH_3)_2S^+SCD_3$	
CH_3OCH_3	46 $M^{+\cdot}$	61 $(CH_3)_3O^+$	47
	45 $CH_3OCH_2^+$	47 MH^+	
CH_3SSCH_3 + CH_3OCH_3 [b]		**109** $(CH_3S)_2^+CH_3$	45, 141[d]
CD_3SSCD_3 + CH_3OCH_3 [b]		**115** $(CD_3S)_2^+CH_3$	45
CH_3SSCH_3 + CH_3OCH_3 + 		119	141
CH_3SSCH_3 + CH_3OH [e] + 		115	141, 95
$C_6H_5CH(CH_3)SCH_3$	**152** $M^{+\cdot}$	**199** $(CH_3S)_2R^+$	152
	105 $C_6H_5C^+HCH_3$	**153** MH^+	105
	91 $C_7H_7^+$		
	79 $C_6H_7^+$		
	78		
	77		
$C_6H_5CH(CH_3)SCD_3$	**155** $M^{+\cdot}$	**205** $(CD_3S)_2R^+$	155
	105	**156** MH^+	105
	91		
	79		
	78		
	77		
$C_6H_5CH(CH_3)SCH_3$ [b] + CD_3SSCD_3 + CH_3OCH_3 [f]		**202** $(CD_3SSCH_3)R^+$	150, 115
		199 $(CH_3S)_2R^+$	152, 105,[g] 100[g]
$C_6H_5CH(CH_3)SCD_3$ [b] + CH_3SSCH_3 + CH_3OCH_3 [f]		**205** $(CD_3SSCD_3)R^+$	155, 105,[g] 94[g]
		202 $(CD_3SSCH_3)R^+$	141, 109, 95
$C_6H_5CH(CH_3)SCH_3$ [b] + $C_6H_5CH(CH_3)SCD_3$		**205** $(CD_3SSCD_3)R^+$	202, 155
		202 $(CD_3SSCH_3)R^+$	205, 199, 155, 152
		199 $(CH_3SSCH_3)R^+$	202, 152

[a] Major ions are in boldface type. [b] Primary and product ions from separate neutrals are not listed in mixtures. [c] For structures, see B. Van de Graal and F. W. McLafferty, *J. Am. Chem. Soc.*, **99**, 6806 (1977). [d] A weak double-resonance response was observed at 300 ms from *m/z* 141 when this ion is most abundant. With CD_3SSCD_3, the precursor is *m/z* 150, which leads to *m/z* 118 in minor amount at 300 ms. [e] Added to increase abundance of *m/z* 95 and 141. [f] Added to increase abundance of *m/z* 202. [g] Electron transfer.

these ions have not been isolated.[11b,c]

For production of gaseous thiosulfonium ions $(CH_3)_2S^+SCH_3$, mixtures of methyl disulfide and methyl ether were subjected to electron impact under ICR conditions. Thereby, *m/z* 45 $CH_3OCH_2^+$, which is the major fragment ion of methyl ether, was observed to methylate methyl disulfide to produce *m/z* 109 (eq 6a). The only



(6a)

(6b)

ions remaining in significant abundance after 300-ms reaction time were disulfide molecular ions *m/z* 94, thiosulfonium ions *m/z* 109, and dithiosulfonium ions *m/z* 141 (see Figure 1a). Double-resonance experiments and the time dependence of ion abundance confirmed that the exclusive source of *m/z* 109 was *m/z* 45.

The methylating property of methoxymethyl cations was not unexpected because Nibbering and associates have shown previously that the gaseous ion transfers a methyl group to the carbonyl oxygen of acetone in an S_N2-type displacement.[16] We also observed that $CH_3OCH_2^+$ methylates methyl sulfide, and the process is described by eq 7 in which the cluster ion is a methyl cation associated

$$(CH_3)_2S + CH_3OCH_2^+ \rightarrow [(CH_3)_2S\cdots CH_3^+\cdots O{=}CH_2] \rightarrow (CH_3)_3S^+ + O{=}CH_2 \quad (7)$$

with two neutral molecules. Calculations described later indicate that the methylation reactions 6a and 7 are exothermic by 34–37 kcal/mol.

Returning to the ion chemistry of methyl disulfide–methyl ether mixtures, the fact that *m/z* 141 contributed indetectably to *m/z* 109 means that the gaseous dithiosulfonium ion **2** is slow to methylate CH_3SSCH_3 (eq 6b). Also, the observation that *m/z* 109 is *not* a precursor to *m/z* 141 implies that the gaseous thiosulfonium ion **1**, *m/z*

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(12) (a) G. K. Helmkamp, B. A. Olsen, and D. J. Oettitt, *J. Org. Chem.*, **30**, 676 (1975); (b) G. K. Helmkamp, B. A. Olsen, and J. R. Koskinen, *ibid.*, **30**, 1623 (1965).

(13) Methanol provides a good source of acidic fragment ions with which to protonate the disulfide to give *m/z* 95. Abundance of *m/z* 141 is therefore formed from *m/z* 95 and methyl disulfide (eq 5).

(14) R. T. McIver, Jr., *Rev. Sci. Instrumen.*, **49**, 111 (1977).

(15) J. K. Kim, E. Lingman, and M. C. Caserio, *J. Org. Chem.*, **43**, 4545 (1978).

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

Table II. Heats of Formation of Thiosulfonium Ions

M	$\Delta H_f°$(M),[a] kcal/mol	PA(M),[b] kcal/mol	ΔH_f(MH$^+$), kcal/mol	MCA(M),[c] kcal/mol	ΔH_f(MCH$_3^+$), kcal/mol	MSCA(M),[d] kcal/mol	ΔH_f(MS$^+$CH$_3$), kcal/mol
H_2S	−4.9	172.6	188	83	174		
CH_3SH	−5.4	185.7	174	99	158	46	164
CH_3SCH_3	−8.9	198.6	158	115	138	62	145
CH_3SSCH_3	−5.8	195	164	112	145	59	150

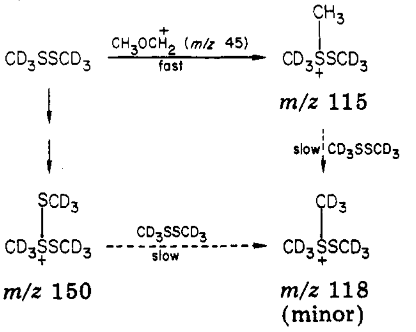
[a] From S. W. Benson, *Chem. Rev.*, **78**, 23 (1978). [b] From J. F. Wolf et al., *J. Am. Chem. Soc.*, **99**, 5417 (1977); PA(M) = $\Delta H_f(M) + \Delta H_f(H^+) - \Delta H_f(MH^+)$. [c] MCA(M) = $\Delta H_f(M) + \Delta H_f(CH_3^+) - \Delta H_f(MCH_3^+)$. [d] MSCA(M) = $\Delta H_f(M) + \Delta H_f(CH_3S^+) - \Delta H_f(MSCH_3^+)$; values of ΔH_f of H$^+$, CH$_3^+$, CH$_3S^+$ of 365.2, 262, and 215 kcal/mol, respectively, were used (H. M. Rosenstock, K. Draxl, B. W. Steiner, and J. T. Herron, *J. Phys. Chem. Ref. Data*, **6**, 1977, Suppl. 1; J. D. Dill and F. W. McLafferty, *J. Am. Chem. Soc.*, **101**, 6526, (1979)).

109, is ineffective in methylthiolating the neutral disulfide. That is to say, the forward reaction in eq 2 is not observed under ICR conditions and, as shown later, is endothermic by about 3 kcal/mol. This result is consistent with solution data on the equilibrium of eq 2 (R = CH_3), which, in nitromethane, lies far to the left, favoring thiosulfonium over dithiosulfonium ions ($\Delta G° = 4.4$ kcal/mol).[7a] For the thermochemistry of gaseous and solution-phase reactions of eq 2 to be qualitatively comparable, the reverse reaction of methylthiolation of methyl sulfide should be rapid. Accordingly, the ion chemistry of mixtures of methyl sulfide and disulfide was studied. As expected, thiosulfonium ion m/z 109 is a major product ion, even though this ion is not formed from either neutral reagent separately. The precursor ion to m/z 109 is m/z 141, initially produced by the sequence in eq 5. The origin of m/z 109 was further confirmed by experiments with mixtures of CD_3SSCD_3 and unlabeled methyl sulfide. The corresponding thio- and dithiosulfonium ions were m/z 112 and 150, respectively, as anticipated (eq 8).

$$\underset{\textstyle}{CD_3SSCD_3} \rightarrow \underset{m/z\ 102}{(CD_3SSCD_3)D^+} \xrightarrow[-CD_3SD]{CD_3SSCD_3}$$

$$\underset{m/z\ 150}{(CD_3S^+)_2SCD_3} \xrightarrow[-(CD_3S)_2]{(CH_3)_2S} \underset{m/z\ 112}{(CH_3)_2S^+SCD_3} \quad (8)$$

Similar experiments with the labeled disulfide CD_3SSCD_3 and unlabeled methyl ether produced ions of m/z 150, corresponding to $(CD_3S^+)_2SCD_3$, and m/z 115, corresponding to $(CD_3S^+)_2CH_3$ (Figure 1b). The very minor amounts of m/z 118 produced in these reactions confirm that methylation of the disulfide by either thio- or dithiosulfonium ions is a slow reaction in the gas phase, as it is in solution, relative to methylthiolation (eq 9).



(6a)

(9)

Overall, the gaseous reactions of thiosulfonium ions are entirely comparable to those in solution. Transfer of CH_3S^+ to a nucleophile by S–S$^+$ cleavage is a more facile reaction than transfer of CH_3^+ by C–S$^+$ cleavage,[7b] and the affinity of CH_3SCH_3 for CH_3S^+ is greater than that of CH_3SSCH_3, which in turn is greater than CH_3SH.

Thermochemistry. The proton affinity (PA) of methyl disulfide is the key value needed in order to make reasonable estimates of the heats of formation of (methylthio)sulfonium ions. Unfortunately, it is not possible to determine the proton affinity of the disulfide by equilibrium ICR studies because the protonated parent ion, m/z 95, reacts rapidly and irreversibly with the parent neutral (eq 5). In fact, the amount of m/z 95 remaining in the ICR cell after 85-ms reaction time at sample pressures of 10^{-6} torr is negligible. However, it is possible to place some limits on the proton affinity by bracketing it between the PA's of other neutral bases. In this manner we have established that the PA of methyl disulfide is less than that of methyl sulfide (198.8 kcal/mol) and greater than that of methyl ether (190.6 kcal/mol). Accordingly, a rough value of 195 ± 3 kcal/mol may be assigned as the PA of the disulfide, which leads to a value of 164 kcal/mol for the heat of formation of $(CH_3S)_2H^+$, m/z 95.[19] This and other pertinent thermochemical data on the heats of formation, proton affinities and methyl cation affinities (MCA) of sulfur compounds are compiled in Table II.

According to the data (Table II), the PA's of H_2S, CH_3SH, and CH_3SCH_3 show an increase of 13 kcal/mol for each methyl substituent. Assuming that the incremental effect of methyl substitution on the methyl cation affinities of H_2S, CH_3SH, and CH_3SCH_3 is similarly additive, the MCA of CH_3SCH_3 and hence the ΔH_f of trimethylsulfonium cations, $(CH_3)_3S^+$, are estimated as 115 and 138 kcal/mol, respectively.

Further reasonable assumptions lead to estimates of the *methanesulfenyl cation affinities* (MSCA) of methanethiol, methyl sulfide, and methyl disulfide and to heats of formation of thiosulfonium ions. Thus, the CH_3S^+ affinity of CH_3SH (estimated as 46 kcal/mol based on the PA of CH_3SSCH_3 as 195 kcal/mol) suggests a value of 46 + 16 = 62 kcal/mol for the CH_3S^+ affinity of CH_3SSCH_3. This value gives ΔH_f of $(CH_3S)_2CH_3^+$ as 145 kcal/mol and the MCA of CH_3SSCH_3 as 112 kcal/mol. Finally, the difference between the PA's and MCA's of methyl sulfide and disulfide is around 3 kcal in both cases, and, with the assumption that the difference in the MSCA's is also 3 kcal, the MSCA of CH_3SSCH_3 is 59 kcal/mol and ΔH_f of $(CH_3S)_2SCH_3^+$, m/z 141, is 150 kcal/mol.

The values given in Table II for the heats of formation of thiosulfonium ions all derive from the value of 195 kcal/mol for the PA of methyl disulfide and any refinement in PA will similarly refine the ΔH_f values. However, minor changes will not alter the trends shown by the present data.[19] In short, sulfonium ions of the type $(CH_3SH)X^+$, $(CH_3S)_2X^+$, and $(CH_3)_2SX^+$ all show a *decrease* in ΔH_f along the series X = H > SCH_3 > CH_3. The differential is 10–14 kcal on replacing H with SCH_3, and 6 kcal on replacing SCH_3 with CH_3. Using the thermochemical data of Table II, we have calculated the enthalpies of the reactions observed in the present study, as listed in Table III.

Thiosulfonium Ions from 1-Phenylethyl Methyl Sulfide. Previously reported attempts to prepare thiosulfonium ions in solution by methylthiolation of methyl

Table III. Calculated Enthalpies of Methylation and Methylthiolation of Methyl Sulfide and Methyl Disulfide

	reactants		products		
reaction no.	ion	neutral	ion	neutral	ΔH,[a] kcal/mol
2	$(MeS)_2S^+Me$	MeSMe	$(MeS)_2Me^+$	MeSSMe	−3
4	$(MeS)_2Me^+$	MeSMe	Me_3S^+	MeSSMe	−3
	$(MeS)_2S^+Me$	MeSMe	Me_3S^+	MeS_3Me	−3
5	$(MeS)_2H^+$	MeSSMe	$(MeS)_2S^+Me$	MeSH	−13
6b	$(MeS)_2S^+Me$	MeSSMe	$(MeS)_2Me^+$	MeS_3Me	+1
7	$MeOCH_2^+$	MeSMe	Me_3S^+	CH_2O	−38[b]
6a	$MeOCH_2^+$	MeSSMe	$(MeS)_2Me^+$	CH_2O	−34[b]

[a] Calculated from the data of Table II. [b] Calculated by using ΔH_f of CH_2O as −27.7 kcal/mol and $MeOCH_2^+$ as 157 kcal/mol [F. P. Lossing, *J. Am. Chem. Soc.*, **99**, 7526 (1977)].

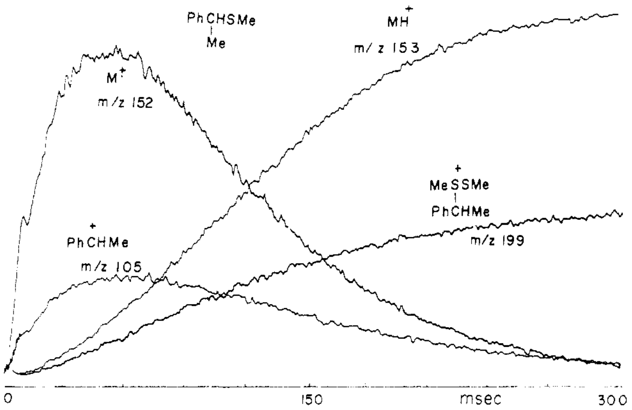
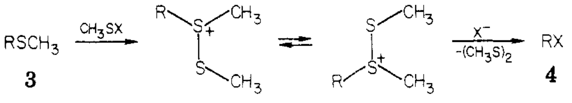


Figure 2. Dependence of ion abundance with time in the ion/molecule chemistry of 1-phenylethyl methyl sulfide at 1.5 × 10^{-6} torr in the time period 1–300 ms.

1-phenylethyl sulfide (**3**) with methanesulfenyl reagents CH_3SX, X = Cl or $^+SMe_2$, led instead to RX, **4**.[7b] Labeling and stereochemical studies established that thiosulfonium ions **5** were formed as intermediates which underwent rapid degenerate 1,2-rearrangement, **5a** ⇄ **5b**, before reacting irreversibly to give the final product **4**. In regard

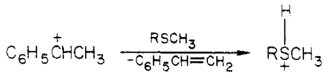


3 4

5a 5b

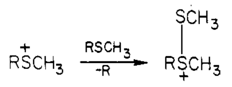
R = $C_6H_5CHCH_3$, X = Cl or $^+S(CH_3)_2$

to the present ICR study, it was of interest to see if thiosulfonium ions **5** could be formed in the gas phase, and if the gaseous ion underwent rearrangement of the type observed in solution. For these reasons, we investigated the gas-phase ion chemistry of methyl 1-phenylethyl sulfide. Although numerous ions are produced from **3** on electron impact (see Table I), the most prominent of these with respect to abundance and reactivity were the molecular ion $M^{+\cdot}$, *m/z* 152, and the 1-phenylethyl cation, *m/z* 105. These ions respectively led to two major product ions, *m/z* 199 and 153. As can be seen from the dependence of ion abundance on the reaction time shown in Figure 2, the product ions *m/z* 199 and 153 increase in abundance at the expense of the primary ions *m/z* 152 and 105, respectively. Formation of *m/z* 153 from *m/z* 105 corresponds to a simple proton transfer reaction (eq 10).



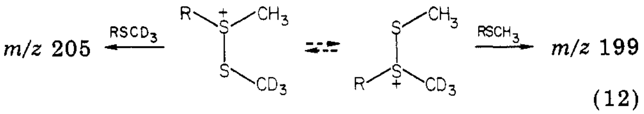
$$\underset{m/z\ 105}{C_6H_5\overset{+}{C}HCH_3} \xrightarrow[-C_6H_5CH=CH_2]{RSCH_3} \underset{m/z\ 153}{R\overset{H}{\underset{+}{S}}CH_3} \tag{10}$$

The reaction of *m/z* 152 to form *m/z* 199 is more interesting because it was unexpected. Thus, the molecular ion *m/z* 152 rapidly transfers a methylthio cation to the neutral sulfide to form the thiosulfonium ion **5**, *m/z* 199 (eq 11).



$$\underset{m/z\ 152}{R\overset{+}{S}CH_3} \xrightarrow[-R]{RSCH_3} \underset{m/z\ 199}{R\overset{SCH_3}{\underset{+}{S}}CH_3} \tag{11}$$

In order to probe for possible rearrangement of *m/z* 199, it was necessary to devise experiments to determine whether or not a d_3-labeled methyl group introduced into **5a** at dicoordinate sulfur remained distinct from the methyl group at tricoordinate, positive sulfur.



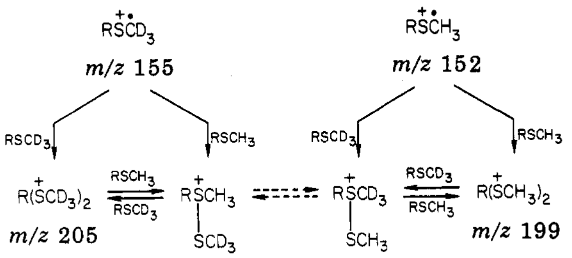
(12)

5a, *m/z* 202 5b, *m/z* 202

On introduction of CD_3SSCD_3 into the ICR cell containing *unlabeled* $RSCH_3$, both unlabeled and d_3-labeled thiosulfonium ions, *m/z* 199 and 202, were formed. Double resonance confirmed that *m/z* 202 was formed from ions of the type $(CD_3S^+)_2R$, R = H, CH_3, and SCD_3, that are able to transfer CD_3S^+ to the neutral. The initial structure of *m/z* 202 is therefore assigned as **5a** (eq 12). In contrast, the major precursor to *m/z* 199 was *m/z* 152, with lesser contributions from *m/z* 100, $CD_3SS^{+\cdot}CD_3$ (Table I). Thus, the two thiosulfonium ions are formed by different routes. The unlabeled ion is formed by methylthiolation of **3** by the molecular ion (eq 11). The labeled ion is formed by methylthiolation of **3** by (methylthio)sulfonium ions. Of critical importance to the question of rearrangement **5a** ⇄ **5b** is whether or not *m/z* 202 is a precursor to *m/z* 199 in the presence of $RSCH_3$ as the reactant neutral (eq 12). In fact, no evidence was obtained from double-resonance experiments that *m/z* 199 was derived even in part from *m/z* 202. Admittedly, reliable double-resonance data is not easily obtained when the reactant and product ions differ by only a few mass units. Nevertheless, we were able to show that double-resonance response was clearly evident when a precursor ion differed in mass by only 3 mass units (see below).

The related set of reactants comprising d_3-labeled sulfide $RSCD_3$ and unlabeled disulfide CH_3SSCH_3 led to d_3- and d_6-labeled thiosulfonium ions *m/z* 202 and 205, respectively. Precursors to *m/z* 202 were ions capable of CH_3S^+ transfer to $RSCD_3$ and, accordingly, *m/z* 202 formed in this manner is assigned structure **5b** (eq 12). Again, if a rapid interconversion of **5a** and **5b** were to occur, followed by methylthio transfer to $RSCD_3$ (eq 12), then *m/z* 202 should be a precursor ion to *m/z* 205. However, double resonance failed to show *m/z* 202 as a precursor to *m/z* 205.

Scheme I

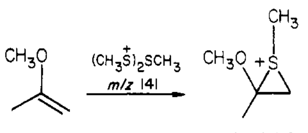


5a, m/z 202 **5b**, m/z 202

Similarly negative results were obtained from mixtures of $RSCH_3$ and $RSCD_3$. The ion chemistry of the mixture led to d_0-, d_3-, and d_6-labeled ions, m/z 199, 202, and 205. Double-resonance experiments showed that the d_3-labeled ion, m/z 202, was produced from both molecular ions $RSCH_3^{+\cdot}$ and $RSCD_3^{+\cdot}$, and from m/z 199 and 205; but m/z 199 came entirely from the unlabeled molecular ion $RSCH_3^{+\cdot}$ and m/z 202; and m/z 205 came entirely from the labeled molecular ion $RSCD_3^{+\cdot}$ and m/z 202. There was no indication that m/z 199 was a source of m/z 205, and vice versa. These results are interpreted by Scheme I wherein isomeric ions **5a** and **5b** are indeed formed by the routes shown, but they do not interconvert on the time scale of the ICR experiment. Had they done so, then m/z 199 would be a precursor to m/z 205, and vice versa.

Although the gas-phase results may appear to conflict with the solution behavior of thiosulfonium ions **5**, the results may in fact be illuminating as to the nature of the rearrangement **5a** $\rightleftarrows$ **5b** in condensed phase. The solution data alone leaves some uncertainty as to whether rearrangement is a concerted process or a stepwise dissociative process of the S_N1 type. If rearrangement is a concerted process, there is no reason to expect any difference in the gas-phase and solution-phase behavior of the ions. On the other hand, if rearrangement is a dissociation–recombination (S_N1) process, then it is questionable whether rearrangement would be detected under ICR conditions. If the gaseous ion **5** should dissociate to *free* ions m/z 105 and neutral disulfide, there is little chance that they would recombine. Actually, complete dissociation of **5** is probably endothermic by about 29 kcal/mol[17] and is therefore quite unlikely at thermal ion energies. However, incomplete dissociation of **5** to an ion/molecule complex of m/z 105 with disulfide would be less energetically demanding and would permit rearrangement. The fact that rearrangement was *not* detected implies, however, that the gaseous ion exists as the covalently bonded species **5** that does not reversibly dissociate to an ion/molecule cluster. Also, we conclude that the lack of rearrangement in the gaseous ions is evidence against concerted rearrangement of these ions in condensed phase and supports a dissociative rearrangement for the solvated ions.[7d]

Thiosulfonium Ions with Alkenes. It is generally accepted that sulfenyl compounds in solution add to alkenes and alkynes by way of thiiranium and thiirenium ion intermediates. Thiosulfonium ions have been shown by Helmkamp to function as sulfenyl compounds and to add to alkenes by way of thiiranium intermediates.[11b,c,12] It was of interest to determine whether gaseous thiosulfonium ions exhibit the same reactivity toward carbon–carbon multiple bonds as they do in solution. We therefore studied the ICR ion chemistry of CH_3SSCH_3–CH_3OCH_3 mixtures with various alkenes. The CH_3SSCH_3–CH_3OCH_3 combination served as a source of gaseous thiosulfonium and dithiosulfonium ions, **1** m/z 109 and **2** m/z 141, and we anticipated the formation of adducts corresponding to the transfer of CH_3S^+ to the alkene. Positive evidence for methylthiolation was obtained in the case of 2-methoxypropene. This electron-rich alkene produced an ion m/z 119 in moderate abundance at 300 ms with m/z 141 as the precursor ion. A reasonable course for this reaction is given in eq 13 in which the product ion



(13)

m/z 119

is assumed to have the thiiranium ion structure. There is, however, no evidence apart from elemental composition and mode of formation to support the proposed structure. Comparable reactions of CH_3SSCH_3–CH_3OCH_3 mixtures with *trans*-2-butene, ethene, ethyne, and 3-methoxypropene failed to show product ions of composition alkene + CH_3S^+. These reactions may be marginally feasible energetically, and a rough estimate of the enthalpy of methylthiolation of ethene gave $\Delta H°$ as exothermic by 1 kcal/mol.[18] It is not then surprising that gas-phase methylthiolation of alkenes does not appear to be an efficient ion/molecule reaction.

Summary

Thiosulfonium ions of the type $(RSSR)R^+$ where R is H, alkyl, or alkylthio can be generated in the gas phase under ICR conditions by three routes. In one route, protonated parent disulfide ions $(CH_3SSCH_3)H^+$ transfer a methylthio cation to sulfur of a neutral sulfide or disulfide. In a second route, thiosulfonium ions are formed by the methylation of neutral disulfides with methoxymethyl cations. Lastly, sulfide radical cations $RSCH_3^{+\cdot}$ transfer CH_3S^+ to a neutral sulfide to form thiosulfonium ions.

Gaseous thiosulfonium ions react readily by S–S$^+$ cleavage to methylthiolate sulfur nucleophiles, but they react less readily by C–S$^+$ cleavage to alkylate nucleophiles. Methylthiolation of alkenes is not observed except in the case of 2-methoxypropene. Rearrangement of thiosulfonium ion $(CH_3SSCH_3)R^+$, where R is 1-phenylethyl, is not observable in the gas phase, in contrast to the behavior of this ion in solution. Proton affinities, methyl cation affinities, and CH_3S^+ affinities decrease in the order $CH_3SCH_3 > CH_3SSCH_3 > CH_3SH$.

Experimental Section

The gaseous ion/molecule chemistry described in this paper was investigated by pulsed ICR techniques using a trapped-ion analyzer cell.[14] Sample pressures were maintained within the range 10^{-6} to 5×10^{-6} torr. Ions were generated from the neutrals by impact from 19-eV electrons. The neutral components were held approximately equimolar, and reaction times were extended to 300 ms. All reaction sequences were confirmed by double-resonance and time-abundance plots. The ion chemistry of each

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(17) This number is based on the PA of styrene (200 kcal/mol), ΔH_f of **3** taken as 15 kcal/mol, and pertinent data in Table II, assuming that methyl sulfide and **3** have the same MSCA (62 kcal/mol).

(18) This number is based on ΔH_f of ethylene sulfide and ethene as 19.69 and 12.49 kcal/mol, respectively, and the assumption that the MCA of ethylene sulfide may be equated to that of methyl sulfide (115 kcal/mol; the enthalpy of methylthiolation of ethene may be estimated as −1 kcal/mol.

(19) Since this paper was submitted we have narrowed the limits of the PA of methyl disulfide as follows: methyl ether (190.6) < 1,4-dioxane (191.8) < 2-methylpropene (193.1) < **methyl disulfide** < ethyl methyl ether (194.3) < acetone (195.6) < methyl sulfide (198.8).

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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Received April 15, 1981

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).

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