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Methylthiolation of Unsaturated Sulfides. Thiosulfonium Ions

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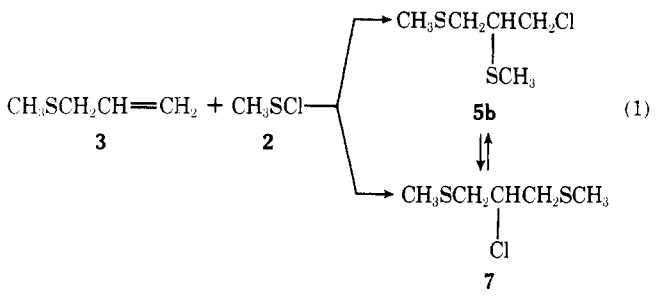
The reactions of methanesulfenyl chloride and dimethyl(methylthio)sulfonium fluoroborate with 2-propenyl methyl sulfide, 3-butenyl methyl sulfide, and 4-pentenyl methyl sulfide are described. Addition to the double bond occurs in each case. 1-Chloro-2,3-bis(methylthio)propane is the kinetic product of addition of CH_3SCl to 2-propenyl methyl sulfide, and this product rearranges on heating at 100 °C for 2–3 days to an equilibrium 34:66 mixture of 1-chloro- and 2-chlorobis(methylthio)propanes. The rate of the reaction was followed using the adducts of 2-propenyl methyl-d_3 sulfide and CH_3SCl, and the data provide support for the intervention of an unsymmetrical thiiranium intermediate. The adduct formed from 2-propenyl methyl sulfide and the sulfenyl salt $(CH_3)_2{}^+SSCH_3\ BF_4{}^-$ does not rearrange on heating. Methylthiolation of the higher homologues, 3-butenyl and 4-pentenyl methyl sulfides, produces adducts that do not rearrange and which do not show exchange or scrambling of alkylthio groups. The adduct of CH_3SCl and 3-butenyl methyl sulfide was identified as 1-chloro-2,4-bis(methylthio)butane. In contrast, the salt $(CH_3)_2{}^+SSCH_3\ BF_4{}^-$ forms a cyclic sulfonium salt with 3-butenyl methyl sulfide. In the case of 4-pentenyl methyl sulfide, only cyclic products were obtained on reaction with sulfenyl reagents.

In the preceding paper we described the reactions of allylic sulfides with sulfenyl reagents. Although the products of these reactions may appear to be formed by a straightforward addition of the sulfenyl reagent to the allylic double bond of the sulfide (cf. eq 1), the actual pathway is complex. The complexity is revealed by the incidence of alkylthio exchange and allylic rearrangement in the formation of the adducts, which we have explained as the result of initial attack of the sulfenyl reagent at *sulfur* rather than at carbon of the allylic sulfide. (See Scheme I of the preceding paper.)

In the present paper we describe further details of the reactions of sulfenyl compounds with alkenyl methyl sulfides. The objective was to see what effect the location of the double bond relative to the methylthio group of the sulfide has on the outcome of the reaction. To this end we report a comparative study of the methylthiolation of 2-propenyl, 3-butenyl, and 4-pentenyl methyl sulfides ($CH_3S(CH_2)_nCH{=}CH_2$, n = 1—3) with both dimethyl(methylthio)sulfonium fluoroborate (**1**) and methanesulfenyl chloride (**2**).

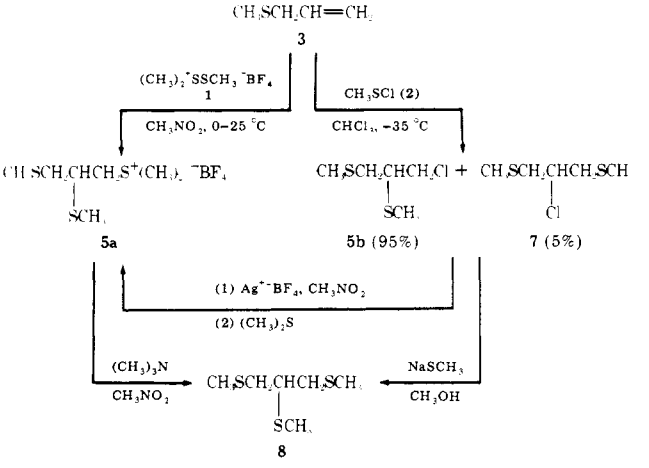
We also report herein a kinetic study of the equilibration of regioisomers **5b** and **7** that are formed in the addition of methanesulfenyl chloride to 2-pentenyl methyl sulfide (eq 1). The rearrangement of **5b** and **7** presumably passes through the same intermediate as in the addition reaction, and the results of the kinetic study allow for certain conclusions as to the nature of this intermediate.

Methylthiolation of 2-Pentenyl Methyl Sulfide.



(1)

Scheme I



Equilibration of Regioisomers. The reactions of 2-pentenyl (allyl) methyl sulfide (**3**) with sulfenyl compounds **1** and **2** were described in detail in preceding and earlier papers.[1] The overall results are summarized in Scheme I, which shows that under kinetic control a single adduct **5a** is obtained from **3** and the sulfenyl salt **1**, whereas a 95:5 mixture of regioisomers **5b** and **7** arises from **3** and methanesulfenyl chloride (**2**). Interconversion of the adducts was achieved by the displacement reactions shown in Scheme I, which served to verify structural assignments made largely on the basis of NMR and mass spectral data (see Table I and Experimental Section).

Detailed studies of sulfenyl halide addition to alkenes have shown that the initially formed adducts frequently rearrange to more stable regioisomers.[2] We therefore anticipated that the kinetic products of addition of methanesulfenyl chloride to **3** might rearrange on heating. In fact, the 95:5 mixture of **5b** and **7** obtained from the reaction of **2** and **3** in chloroform solution at −35 to 0 °C rearranged on heating at 100 °C in benzene in a sealed tube until, after 3 days, an equilibrium composition of **5b**/**7** = 34:66 was reached.

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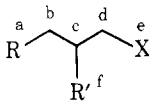
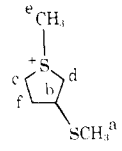
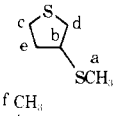
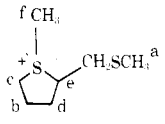
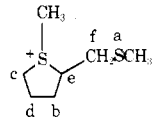
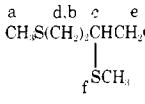
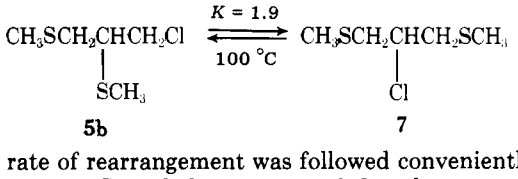
Table I. NMR Parameters (δ) of Adducts



compd	R	R′	X	chemical shift[a] (multiplicity) a	f	e	d	b	c
5a[b]	CH_3S	CH_3S	$^+S(CH_3)_2$	2.19 (s, 3 H)	2.17 (s, 3 H)	3.05 (s, 3 H)	~3.69 (m, 2 H)	2.8 ~ 3.4 (m, 3 H)	
5b	CH_3S	CH_3S	Cl	1.81 (s, 3 H)	1.68 (s, 3 H)	3.01 (s, 3 H)	~3.55 (m, 2 H)	~2.65 (m, 3 H)	
7	CH_3S	Cl	CH_3S	1.78 (s, 3 H)		1.78 (s, 3 H)	~2.60 (m, 4 H)		3.95 (p, 1 H)
8	CH_3S	CH_3S	CH_3S	1.82 (s, 3 H)	1.78 (s, 3 H)	1.82 (s, 3 H)	2.72 (s, 4 H)		2.85 (m, 1 H)
13[b]				2.23 (s)[c] 2.27 (s)	2.33–2.93 (m)	2.97 (s)[c] 3.08 (s)		3.3–4.1 (m)	
14				2.15 (s)		1.7–2.4 (m)		2.4–3.4 (m)	
17[b]				2.27 (s)	3.15 (s)	4.5 (m)	2.1–2.7 (m)		3.5–4.0(m)
19				2.17 (s)	2.68 (d)	3.57 (p)	1.81–2.27 (m)		2.72–2.99 (m)
15				2.05 (s)	2.10 (s)	2.40–2.80 (m)[d]	1.46–2.5 (m)	2.40–2.80 (m)	2.72–3.12 (m)

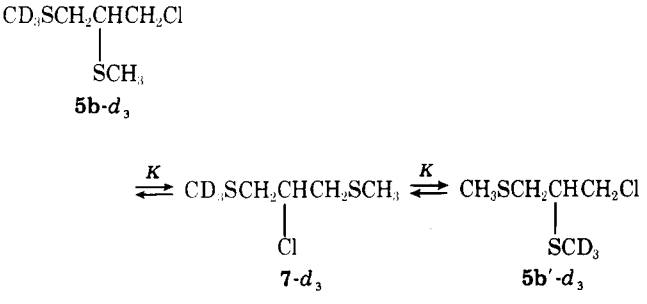
[a] Solvent: C_6D_6 except for **5a**, **13**, and **17** (CD_3NO_2) and **14**, **15**, and **19** ($CDCl_3$). [b] As BF_4^- salt. [c] 3:1 mixture of diastereomers. [d] Eight-line AB pattern of ABX spectrum: J_{AB} = 12 Hz J_{AX} = 6 Hz, J_{BX} = 10 Hz.



5b **7**

The rate of rearrangement was followed conveniently by NMR since the *S*-methyl resonances of **5b** and **7** appeared as well-resolved singlets in benzene (Figure 1). In the special case where the initial adducts were derived from the addition of methanesulfenyl chloride to 2-propenyl methyl-d_3 sulfide, it was possible to follow the rate of disappearance of the isotopically distinguishable forms of **5b**-d_3 and **5b′**-d_3 to the symmetrical adduct **7**-d_3. Initially, the composition of the mixture of **5b/5b′/7** was 62:33:5 (see Figure 1a), but after equilibration at 100 °C the labeled forms of **5** were present in equal amounts (**5b** = **5b′** = 17%) and the symmetrical adduct **7** was the major component (66%, Figure 1b). The change in the relative amounts of **5b**, **5b′**, and **7** with time is plotted in Figure 2, which shows that the rate of formation of **7** (equivalent to the rate of disappearance of **5**, where **5** = **5b** + **5b′** is initially first order ($k = 2 \times 10^{-5}$ s^{-1} at 100 °C) but deviates somewhat from first order after about 15% conversion to **7** as the reverse reaction becomes significant.

At one time during this investigation we considered the possibility that the label scrambling observed in the addition of sulfenyl reagents **1** or **2** to labeled allylic sulfide **3** resulted from the formation of a symmetrical intermediate such as **9** or **10** (see Scheme II).[3] We now believe this possibility is untenable because the label in the initially formed adduct **5** is incompletely scrambled[1] and because the kinetics of rearrangement of **5b**, **5b′**, and **7** do not support the intervention of a symmetrical intermediate common to all three products. This conclusion can be deduced from the data of Figure 2 as applied to the sequence in Scheme II. The argument is as follows. Because **5** is the kinetic product of addition of methanesulfenyl chloride to **3**, an addition intermediate such as **9**, **10**, or **11** must react with Cl^- to give **5** more rapidly than it reacts with Cl^- to give **7** (i.e., $k_{-1} > k_{-2}$). In fact, the composition of the initially formed adducts suggests that k_{-1}/k_{-2} = 95:5. If the intermediate is a symmetrical ion, **9** or **10**,[3] this would require that **5b** and **5b′** interconvert more rapidly than either rearranges to **7**. In more exact terms, the rate of interconversion of **5b** and **5b′** by way of **9** or **10** can be expressed by the rate equation $-d[\mathbf{5b} - \mathbf{5b'}]/dt = k_1[\mathbf{5b} - \mathbf{5b'}]$, and the *initial* rate of rearrangement of **5** to **7** by the same route is



5b-d_3 **7**-d_3 **5b′**-d_3

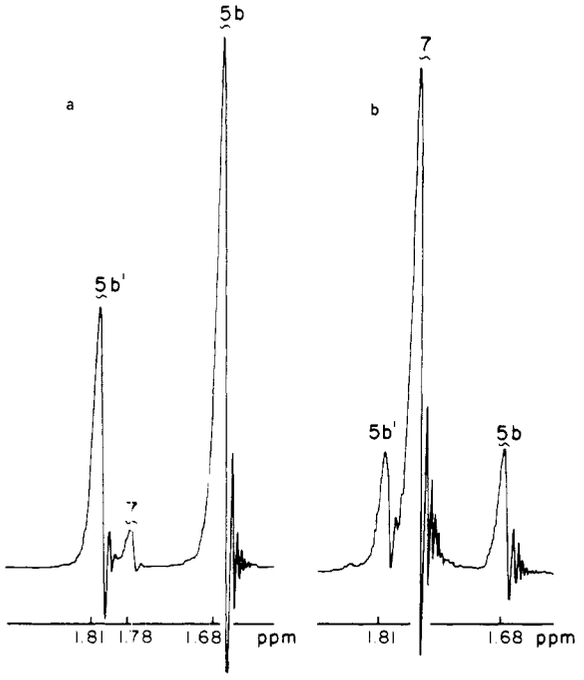


Figure 1. (a) NMR spectrum at 60 MHz of the methylthio resonances of adducts $CD_3SCH_2CH(SCH_3)CH_2Cl$ (**5b**), $CH_3SCH_2CH(SCD_3)CH_2Cl$ (**5b'**), and $CD_3SCH_2CH(Cl)CH_2SCH_3$ (**7**) formed under kinetic control in the reaction of methanesulfenyl chloride with $CD_3SCH_2CH{=}CH_2$. (b) Same as in a except that the equilibrium composition of **5b, 5b',** and **7** is represented.

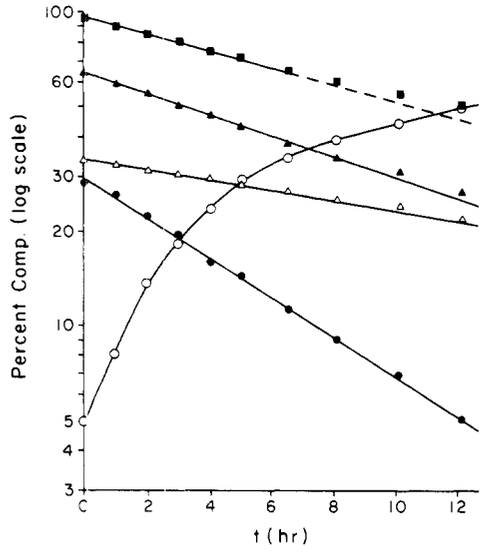
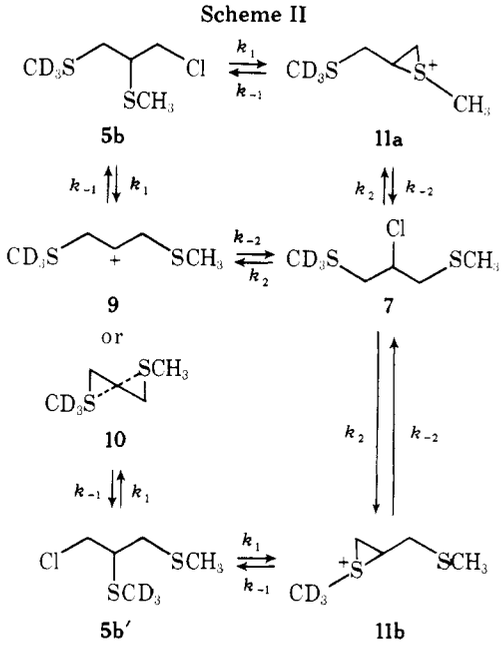


Figure 2. First-order plot of the change in percentage composition of adducts **5b, 5b',** and **7** with time: ■ represents change in [**5b** + **5b'**]; ● represents [**5b** − **5b'**]; ▲ represents [**5b**]; △ represents [**5b'**] and ○ represents [**7**].

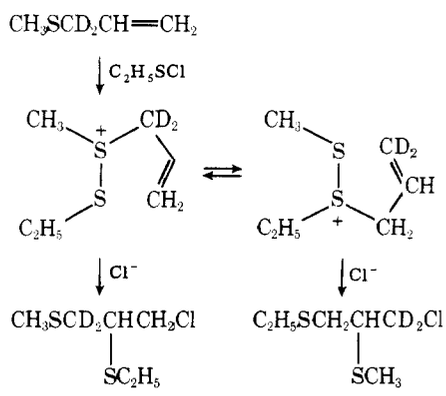
given by the equation $-d[\mathbf{5b} + \mathbf{5b'}]/dt = k_1[\mathbf{5b} + \mathbf{5b'}]/20$ (see Experimental Section for details). These equations predict that the rate of interconversion **5b** ⇄ **5b'** should be 20 times the initial rate of rearrangement **5** → **7**. However, this is contrary to observation. Figure 2 shows that the specific rate constant for decay of [**5b** − **5b'**] is 4×10^{-5} s^{-1}, and the decay of [**5b** + **5b'**] is about 2×10^{-5} s^{-1} at 100 °C. A similar kinetic analysis of rearrangement by way of unsymmetrical thiiranium ions (**11a** and **11b**) predicts that the rate of interconversion should be *equal* to the initial rate of rearrangement. Within the limitations of the experimental data, this prediction is approximately true. That is, $-d[\mathbf{5b} - \mathbf{5b'}]/dt \approx -d[\mathbf{5b} + \mathbf{5b'}]/dt \approx 2\text{–}4 \times 10^{-5}$ s^{-1} at 100 °C. While the data are imprecise, they certainly support a route by way of unsymmetrical thiiranium ions **11** in preference to symmetrical ions **9** or **10.**

Scheme II



In comparison with the behavior of **5b,** the corresponding adduct **5a** obtained by the addition of salt **1** to 2-propenyl methyl sulfide did not rearrange. Either **5a** is both the thermodynamic and kinetic product or else it dissociates to **11** so slowly that the reaction is essentially irreversible. However, the finding that **7** can be converted to **5a** in the presence of Ag^+ and methyl sulfide (Scheme I) suggests that **5a** is both the kinetic and the most thermodynamically stable product.

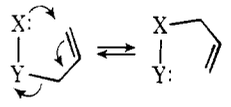
The conclusion that adducts **5b** and **7** do not equilibrate by way of symmetrical intermediates is significant because it bears on the nature of the intermediates involved in the *addition* reaction of sulfenyl compounds and allylic sulfides. Thus, to account for the formation of rearranged adducts in the addition reaction under conditions of *kinetic* control, we have proposed that intermediate thiosulfonium ions are involved which undergo allylic rearrangement through a pericyclic transition state (see Scheme I of preceding paper). Evidence to support this proposal was obtained by a double-labeling experiment with ethanesulfenyl chloride and 2-propenyl-*1,1-d*$_2$ methyl sulfide.[1] The finding that the deuterium label was selectively located at C3 in the normal adduct and at C1 in the rearranged adduct supports the suggested [2,3] sigmatropic rearrangement over a [1,2] shift or a dissociative process.



However, the observed label distribution could also arise

by way of symmetrical intermediates analogous to **9, 10,** or rapidly interconverting thiiranium ions **11a** ⇄ **11b.** Because the kinetic results of rearrangement of adducts under equilibrium conditions do not support the intervention of intermediates equivalent to **9, 10,** or **11a** ⇄ **11b,** they are also excluded as intermediates in the addition process. We conclude, therefore, that rearrangement during adduct formation under conditions of kinetic control occurs by a step that is *not* on the pathway to equilibration of adducts, namely, by sigmatropic rearrangement of thiosulfonium ions.

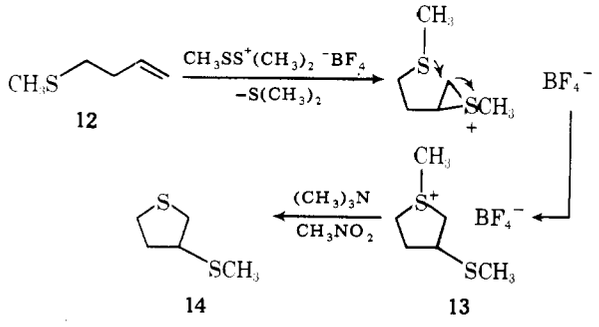
Symmetry allowed [2,3] sigmatropic rearrangements are remarkably general in allylic systems and include migration to and from various atom types and charge types, as summarized in eq 2.[4-12] The present results add to this list the case of allylic rearrangement from S^+ to S:. In fact, the special case of rearrangement from S^+ to S^- has been suggested previously in reactions of allylic sulfides with elementary sulfur. The products are disulfides that are probably formed by allylic rearrangement of transient thiosulfoxide intermediates.[12]



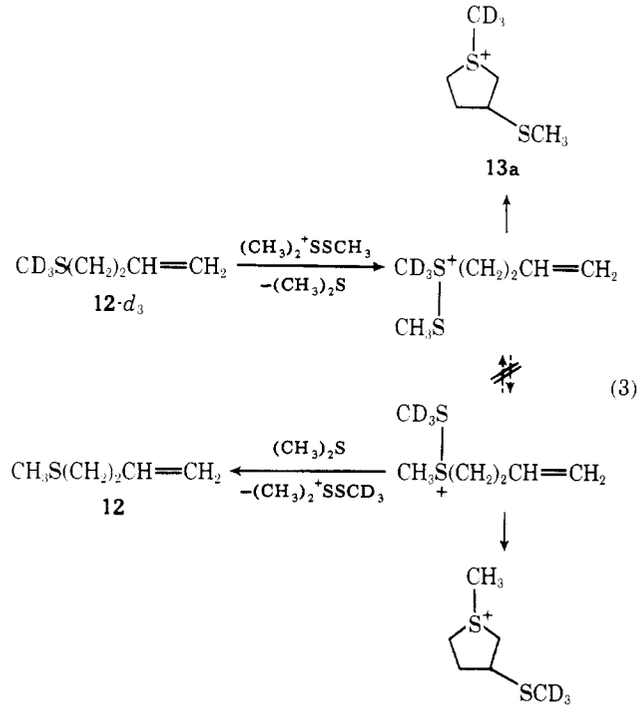
(2)

X:	Y	X:	Y
C^-	S^{+4}	O^-	S^{+8}
C^-	N^{+5}	O^-	N^{+9}
C^-	O^6	N	N^{+10}
C^-	C^7	N^-	S^{+11}
S	S^+	S^-	S^{+12}

Methylthiolation of 3-butenyl methyl sulfide (12) was originally undertaken with the idea that if methylthiolation takes place at sulfur, the intermediate thiosulfonium ion might possibly dissociate by way of a homoallyl cation which could lead to cyclobutyl and cyclopropylmethyl rearrangement products.[13] Although no such process took place, the reaction gave interesting results. Thus, methylthiolation of **12** with salt **1** in dichloromethane at 0 °C produced dimethyl sulfide and a heavy oil which separated from solution. The oil was induced to crystallize as a low-melting solid (mp 38–40 °C) and from its solubility characteristics and NMR and IR spectra it was clearly a sulfonium fluoroborate. However, the finding that dimethyl sulfide was also a major product meant that the product was *not* a homologue of **5a** formed by a simple addition of **1** to the double bond. The product was assigned the cyclic sulfonium structure **13** on the basis of elemental analysis, NMR, and its subsequent reactions which will shortly be described. Evidently, methylthiolation of **12** gives an intermediate thiiranium salt that reacts with a sulfur nucleophile by *intra*molecular addition rather than by intermolecular addition.



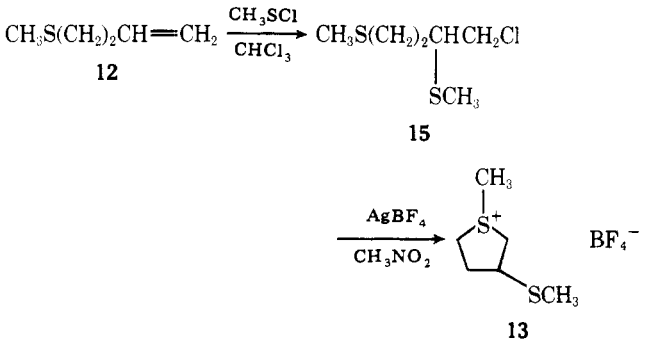
The salt **13** is apparently formed as a mixture of diastereomers since both the methylsulfonium and methylthio proton NMR resonances appear as *two* singlets in a ratio of 3:1. The configuration of the major isomer is not known, but upon reaction of the mixture with excess trimethylamine in nitromethane demethylation occurred to give a single product identified as 3-(methylthio)thiacyclopentane (**14**). It is not clear from the results whether **13** is formed by direct methylthiolation of the double bond or indirectly by methylthiolation at sulfur. As explained earlier, methylthiolation at sulfur could lead to dissociation and homoallylic rearrangement, but the latter circumstance cannot be significant since no rearrangement products were detected. The possibility remains that the homoallyl group could migrate from S^+ to S without rearrangement of the carbon skeleton, and to test this possibility the reaction of **1** and 3-butenyl methyl-d_3 sulfide was investigated. In the event of alkyl migration, the *S*-methyl-d_3 group should be scrambled between the positive and neutral sulfur atoms of **13** (eq 3). In fact, no scrambling was observed. The salt product showed *no* proton resonance near 3 ppm for CH_3S^+, indicating that all of the label in the starting sulfide was retained as CD_3S^+, as in **13a.** Furthermore, recovered unreacted sulfide showed no exchange of CD_3S for CH_3S. Therefore, we conclude that if methylthiolation of **12** occurs by initial attack at sulfur, the intermediate thiosulfonium ion does not rearrange.



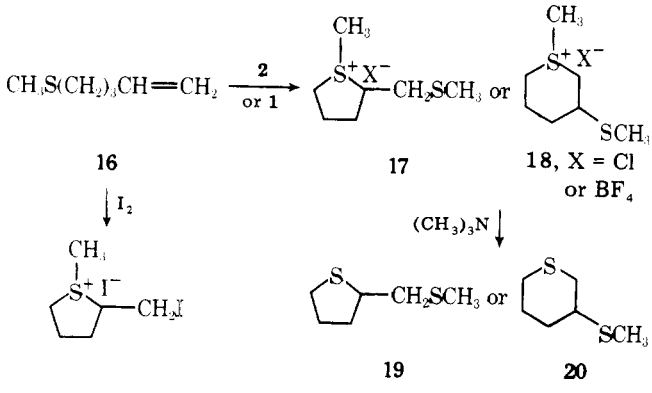
(3)

In contrast to the reaction of the butenyl sulfide **12** with salt **1**, the reaction of **12** with methanesulfenyl chloride gave an acyclic adduct. Only one regioisomer appeared to be formed, and it was assigned structure **15** on the basis of its NMR spectrum. The key to this assignment was the appearance of an eight-line two-proton resonance centered at 2.6 ppm that conforms to the AB part of an ABX pattern consistent with the grouping $>CHCH_2Cl$, as in **15.** Upon reaction of **15** with an equivalent of $AgBF_4$ in nitromethane, it was converted quantitatively into **13,** the product of methylthiolation of **12** with salt **1.**

Methylthiolation of 4-pentenyl methyl sulfide (16) gave comparable results with both sulfenyl reagents, **1** and **2.** Thus, methanesulfenyl chloride (**2**) and the salt **1** gave cyclic products on reaction with **16** that were either five- or six-membered cyclic sulfonium salts, **17** or **18,** formed as a mixture of diastereomers. The complexity of the NMR spectra of these products made it impossible to determine their structures unequivocally by NMR alone. However, demethylation of the products with trimethylamine gave a neutral sulfide that appeared to be a single compound. The NMR spectrum of the

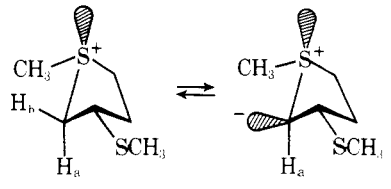


sulfide was not helpful in distinguishing between a five- or six-ring structure, **19** or **20**, but the mass spectrum was definitive. The base peak had *m/e* 87, corresponding to the loss of 61 mass units, or CH_2SCH_3, from the molecular ion of *m/e* 148. This observation provides strong support for structure **19**, which in turn implies that the major product of methylthiolation of **16** is the five-ring salt **17**. Our structural assignment is also supported by a literature report that the related iodination of 4-pentenyl methyl sulfide gives a five-ring sulfonium salt product.[14] While there is little doubt that **17** is the major product, we cannot exclude the possibility that some **18** is also formed.



The observation that 4-pentenyl methyl sulfide gave cyclic adducts with both **1** *and* **2** was somewhat unexpected based on the results with 3-butenyl methyl sulfide, which gave a cyclic adduct with **1** but not with **2**. It is not obvious to us why the inclusion of one methylene group should make the difference between a cyclic vs. an acyclic adduct only in the case of methanesulfenyl chloride addition to an alkenyl sulfide.

Deuterium Exchange Studies. In one experiment designed to verify that the product **13** was indeed a methylsulfonium salt, we attempted to show that the hydrogens adjacent to the positive sulfur were acidic and could be exchanged for deuterium in the presence of base. Dissolution of **13** in D_2O containing a catalytic amount of NaOD caused the methyl singlets at 2.97 and 3.08 ppm to disappear within 30 min at 35 °C, confirming their structural identity as CH_3S^+ groups. However, the ring methylene hydrogens ($-CH_2S^+CH_2-$) exchanged less rapidly, and in fact were incompletely exchanged after several days and after repeated treatment with 99% D_2O and base. From the change in the intensity of the $-(CH_2)_2S^+$ resonances near 3.7 ppm it appears that only two of the four methylene protons exchange readily. At first we were surprised by this result, but we learned subsequently that similar exchange behavior has been observed in cyclic sulfonium salts.[15] The phenomenon is an interesting one, and is thought to be a manifestation of the *gauche effect*[16] or *stereoelectronic control*, which, in the context of the present work, is the influence of heteroatom lone pairs on an adjacent carbanion. Assuming that the preferred conformation of **13** places the sulfonium methyl in a *quasi*-equatorial position, then the adjacent proton of highest kinetic acidity is predicted to be suprafacial to the sulfur lone pair (i.e., H_b)[16] since this maximizes the number of gauche interactions between adjacent lone pairs. Unfortunately, the present data do not allow for a distinction between H_a and H_b, but in the unsubstituted 1-methylthietane salt there is evidence that H_a is removed faster than H_b,[15] contrary to prediction. Clearly, the phenomenon warrants further investigation. Regardless of interpretation, the configuration at the resulting carbanion center must be stable because reprotonation occurs with retention of configuration. If it did not, all four methylene protons adjacent to S^+ would be exchanged.



13 (one diastereomer)

Deuterium exchange in **17** gave similar results to **13**, but the complexity of the NMR spectrum of **17** due to overlapping resonances made it difficult to study the exchange quantitatively. Qualitatively, the $^+SCH_3$ protons exchanged first, whereas exchange of the ring protons adjacent to positive sulfur was relatively slow and incomplete.

Summary

(1) The major product **5b** of methanesulfenyl chloride addition to 2-propenyl methyl sulfide (**3**) has been shown to rearrange to an equilibrium mixture of regioisomers **5b** and **7** in a ratio of 34:66 at 100 °C. A kinetic study of the rate of interconversion of deuterium labeled adducts **5b**-d_3 and **5b'**-d_3 compared to the rate of rearrangement to **7**-d_3 provides support for the intervention of an unsymmetrical thiiranium ion **11** in the addition and rearrangement reactions. Rearrangement by way of symmetrical ions **9** or **10** or rapidly interconverting thiiranium ions **11a** ⇌ **11b** is, therefore, discounted.

(2) 3-Butenyl methyl sulfide (**12**) was found to react with **1** to give a cyclic sulfonium salt **13** presumably by intramolecular attack of the methylthio group of the thiiranium ion intermediate. In contrast to the reactions of the allylic sulfide **3**, no skeletal rearrangements or alkyl migration from S^+ to S were observed. Methanesulfenyl chloride gave only a single adduct **15** that was readily converted to **13** with silver fluoroborate. 4-Pentenyl methyl sulfide (**16**) gave cyclic sulfonium salts **17** on reaction with both **1** and **2**.

(3) Deuterium exchange studies with the cyclic sulfonium salt **13** led to rapid H–D exchange of the CH_3S^+ protons and a slower exchange of two of the four S^+ methylene protons. Complete exchange of the ring *S*-methylene protons could not be achieved. These results are thought to be a manifestation of the *gauche* effect.

Experimental Section

Methanesulfenyl chloride and **dimethyl(methylthio)sulfonium fluoroborate** were prepared according to literature procedures.[17,18] **Sodium methiolate** was required for the preparation of methyl sulfides and was obtained either by neutralization of sodium methoxide or ethoxide with methanethiol[19] or by the cleavage of dimethyl disulfide with sodium in liquid ammonia.[20] The latter method was the preferred route to sodium methiolate-d_3 starting with dimethyl-d_6 disulfide. To obtain good yields in subsequent displacement reactions using sodium methiolate, it was necessary to prepare the salt immediately prior to use.

2-Propenyl methyl sulfide was prepared from 3-chloropropene and sodium methiolate in methanol, ethanol, or pentane.[12a] **2-Propenyl methyl-d_3 sulfide** was prepared from 2-propenethiol as follows. To a solution of sodium methoxide in methanol (1.72 M, 100 mL) at −10 °C was added freshly distilled 2-propenethiol (12.8 g, 0.173

mol) in 10 mL of methanol. The solution was stirred and cooled to −15 to −10 °C as methyl-d_3 iodide (99% D, 25 g, 0.174 mol) in 5 mL of methanol was added slowly. Thereafter, the cooling bath was removed and the temperature was allowed to rise to 30 °C. After being refluxed for 30 min, the mixture was distilled. The product was collected as an azeotrope with methanol, bp 62–64 °C (lit.[21] 61.8 °C). The distillate was diluted with five times its volume of water, and the organic layer was separated, washed with water, dried ($MgSO_4$), and distilled to give 7.0 g (40%) of 2-propenyl methyl-d_3 sulfide (99% D), bp 91.5–92.5 °C (lit.[21] 92.2–92.4 °C).

3-Butenyl methyl sulfide was obtained by adding 4-bromo-1-butene (30 g, 0.2 mol) dropwise to a stirred ice-cooled solution of sodium methiolate in ethanol (1.2 M, 185 mL). After being stirred at room temperature for 12 h, the mixture was diluted with water (125 mL) and extracted twice with dichloromethane (125 and 75 mL). The organic extract was washed repeatedly with water, dried ($MgSO_4$), and distilled. The product (8.2 g, 39%) had bp 124 °C [lit.[22] 124 °C (724 mm)]; NMR δ 2.02 (s, 3), 2.4 (complex, 4), 4.75–5.17 (complex, 2), 5.48–6.05 (complex, 7). **3-Butenyl methyl-d_3 sulfide** was prepared in 30% yield by the same procedure as described for the unlabeled sulfide by using sodium methiolate-d_3.[20] **4-Pentenyl methyl sulfide** was similarly obtained by the displacement of halogen from 5-bromo-1-pentene with sodium methiolate in ethanol: yield 65%; bp 134 °C (lit.[14] 128–129 °); NMR δ 2.1 (s, 3) superimposed on 1.5–2.5 (complex, 6), 4.6–5.1 (complex, 2), 5.4–5.9 (complex, 1).

Methylthiolation Reactions. In a typical procedure, dimethyl(methylthio)sulfonium fluoroborate (1, 30 mmol) was dissolved in nitromethane (3 mL) or suspended in chloroform or dichloromethane contained in a 50-mL flask equipped with a dropping funnel, a thermometer, a drying tube, and a magnetic stirring bar. The flask and contents were cooled to 0 °C or below, and a slight excess of the desired methyl alkyl sulfide (36 mmol in 3 mL of solvent) was added slowly with stirring. Thereafter, stirring was continued at room temperature for 30–60 min, following which the flask was evacuated to 0.3 mm and the volatile material condensed into a cold trap. The distillate of unreacted sulfide and solvent was analyzed by NMR, MS, and GC. The residual nonvolatile product was analyzed first by NMR and then purified insofar as possible by repeated dissolution in nitromethane and reprecipitation with cold ether. Adduct **5** from 2-propenyl methyl sulfide and adduct **17** from 4-propenyl methyl sulfide failed to crystallize and were consistently obtained as colorless oils. Adduct **13** from 3-butenyl methyl sulfide was obtained as a crystalline solid, mp 38–39 °C, in 62% yield. Anal. Calcd for $C_6H_{13}S_2BF_4$: C, 30.52; H, 5.55. Found: C, 30.34; H, 5.45.

Methylthiolation with methanesulfenyl chloride was carried out as described for the salt **1**, except that methanesulfenyl chloride was always freshly made[17] and distilled before use and was added to the sulfide instead of the sulfide to the sulfenyl reagent. Spectroscopic data for the adducts obtained in these experiments are summarized in Table I.

Adducts **5b** and **15** of addition of methanesulfenyl chloride to 2-pentenyl and 3-butenyl methyl sulfides, respectively, were converted to the corresponding adducts of sulfenyl salt **1**, namely **5a** and **13**, as follows. **5b** or **15** in nitromethane solution was cooled to −30 °C and mixed with an equivalent of silver tetrafluoroborate in nitromethane. In the case of conversion of **5b** to **5a**, excess methyl sulfide was added. After the mixture was stirred for 1 h at −30 °C, silver chloride was removed by filtration and the solvent was removed from the filtrate by vacuum distillation. The residue was identified by NMR as **5a** from **5b** and **13** from **15**.

Dimethylalkylsulfonium salts **5a, 13,** and **17** were demethylated almost quantitatively to neutral sulfides as follows. The appropriate sulfonium salt was dissolved in nitromethane and cooled to 0 °C. An excess of trimethylamine was added by simply bubbling the gaseous amine slowly through the cooled solution. A white precipitate of tetramethylammonium fluoroborate separated almost immediately on adding the amine. The salt was removed by filtration or centrifugation, and the solvent was evaporated under vacuum from the supernatant. The residual sulfides were then vacuum distilled and analyzed by GC, MS, and NMR. The product of demethylation of **5a** was **1,2,3-tris(methylthio)propane (8).**[23] Demethylation of **13** gave **3-(methylthio)thiacyclopentane (14),** bp 85 °C (8 mm) [lit.[14] 88–90 °C (12 mm)]. Anal. Calcd for $C_5H_{10}S_2$: C, 44.73; H, 7.52. Found: C, 45.05; H, 7.18.

The product of demethylation of **17** (either as the chloride or fluoroborate salt) was assigned the structure 2-[(methylthio)methyl]-thiacyclopentane (**19**) and had bp 48 °C (1 mm); MS *m/e* 148 (M^+), 87 (base peak). Anal. Calcd for $C_6H_{12}S_2$: C, 48.60; H, 8.16. Found: C, 48.61; H, 7.73.

Kinetics of Rearrangement. Applying the steady-state treatment to the concentrations of reactive intermediates in the rearrangement sequence of Scheme II and assuming that $k_{-1}/k_{-2} = 95:5$, it can be derived that the *initial* rate of disappearance of [**5b** + **5b′**] by way of **9, 10,** or **11** conforms to eq 4. The *difference* in the percentages of isotopically labeled forms [**5b** − **5b′**] decays at a rate given by eq 5 when interconverting and rearranging through **9** or **10** and by eq 6 in the case of reaction through **11a** and **11b.**

$$-d[\mathbf{5b} + \mathbf{5b'}]/dt = k_1[\mathbf{5b} + \mathbf{5b'}]/20 \quad (4)$$

$$-d[\mathbf{5b} - \mathbf{5b'}]/dt = k_1[\mathbf{5b} - \mathbf{5b'}] \quad (5)$$

$$-d[\mathbf{5b} - \mathbf{5b'}]/dt = k_1[\mathbf{5b} - \mathbf{5b'}]/20 \quad (6)$$

Experimentally, the rate of reaction was followed by observing the change in the relative areas of the SCH_3 resonances at 1.68, 1.81, and 1.78 ppm of **5b, 5b′,** and **7**, respectively, in benzene-d_6 at 100 °C as a function of time. The spectra of pertinent resonances are shown in Figure 1.

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Registry No.—**1,** 5799-67-7; **2,** 5795-20-0; **3,** 10152-76-8; **5a,** 68345-88-0; **5b,** 68345-73-3; **5b**-d_3, 68345-76-6; **5b′**-d_3, 68345-77-7; **7,** 69631-96-5; **7**-d_3, 69631-97-6; **8,** 69631-98-6; **12,** 20582-83-6; *cis*-**13,** 69632-00-4; *trans*-**13,** 69632-02-6; **14,** 69632-03-7; **15,** 69632-04-8; **16,** 69632-05-9; **17,** 69632-07-1; **19,** 69632-08-2; 2-propenethiol, 870-23-5; 4-bromo-1-butene, 5162-44-7; 2-propenyl methyl-d_3 sulfide, 68345-75-5; methyl-d_3 iodide, 865-50-9; sodium methiolate, 5188-07-8; sodium methiolate-d_3, 67212-77-5.

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Solvomercuration–Demercuration. 7. Regio- and Stereochemistry of the Oxymercuration–Demercuration of Alkyl-Substituted Cyclohexenes and Cyclopentenes[1]

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The oxymercuration–demercuration (OM–DM) of several methyl- and *tert*-butylcyclohexenes and -cyclopentenes has been investigated. The conformationally flexible 4-methylcyclohexene undergoes hydration in a nonregioselective but remarkably stereoselective fashion, giving a 50:50 ratio of the *trans*-3- and *cis*-4-methylcyclohexanols with only ~1% each of the other two isomers. In the case of 3-methylcyclohexene, hydration occurs both regio- and stereoselectively to give 79% *trans*-3-, 12% *cis*-2-, 5% *cis*-3-, and 4% *trans*-2-methylcyclohexanols. A similar, but higher, selectivity is observed for the conformationally locked 3-*tert*-butyl analogue. In contrast, both 4-methyl- and 4-*tert*-butylcyclopentene exhibit a strong preference, 4:1 and 7:1, respectively, for cis hydration. Furthermore, the 3-alkylcyclopentenes give still different results. The 3-methyl derivative undergoes hydration preferentially at the 3 position with a 6:1 preference for the *trans*-alcohol. On the other hand, the 3-*tert*-butyl olefin shows no significant regioselectivity, but a strong, 93:7, preference for trans hydration. 3,4-Dimethylcyclopentene results in a 9:1 predominance of the 3 isomer with only a slight preference for the *cis*-cyclopentanol. The presence of a methyl group in the 1 position of this system results in the formation of only the two tertiary alcohols, however, with a 3:1 favoring of the *trans*-alcohol. Virtually identical regio- and stereochemical results are observed for 2,3-dimethylcyclopentene.

The oxymercuration–demercuration (OM–DM) procedure provides a convenient synthetic method for effecting the Markownikoff hydration of a carbon–carbon double bond.[5-7] The oxymercuration reaction usually proceeds with no rearrangements and unhindered acyclic olefins react with amazingly high regioselectivity. Pasto and Gontarz[8] have examined the OM of several conformationally rigid cyclohexenes. In view of this, as well as the remarkable results obtained with the acyclic and simple cyclic olefins, it appeared desirable to examine several other alkyl-substituted cyclohexenes as well as cyclopentenes.

Results and Discussion

Monoalkylcyclohexenes. 4-Methylcyclohexene (**1**) undergoes the oxymercuration reaction rapidly (T_1 = 16 s). After 30 min, T_2, in situ demercuration with aqueous alkaline sodium borohydride results in a mixture of four alcohols in 90% yield. (For definitions[5] of T_1 and T_2, see General Procedure, Experimental Section.) The major products are *trans*-3-methylcyclohexanol in 47% yield and the *cis*-4 derivative in 51% yield. The other two possible isomers were observed in ~1% yield each (Scheme I).

This high stereoselectivity, coupled with the absence of regioselectivity which is exhibited by this conformationally flexible olefin, is virtually identical with that realized by Pasto[8] and Whitham[9] for the conformationally locked 4-*tert*-butylcyclohexene (**2**). In this case, both the mercury and the hydroxyl groups were introduced in an axial fashion[10] (Scheme II).

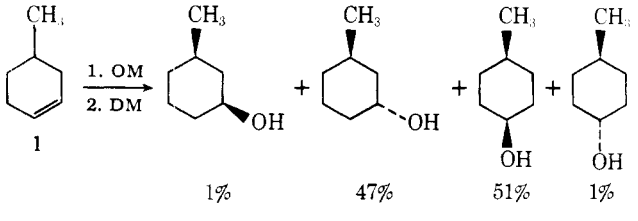
In contrast, both 3-methyl- (**3**) and 3-*tert*-butylcyclohexenes (**4**) undergo reaction with high regio- and stereoselectivity for the *trans*-3-alkylcyclohexanol (Schemes III and IV). In the case of **4**, however, the OM stage is unusually slow (T_1 = 42 min). Thus, after 5 h only a 78% yield of the four alcohols is obtained.

While a 4-alkyl group exerts no significant steric effect on the oxymercuration of **1** and **2**,[8] a 3-alkyl group clearly does in the case of **3** and **4**.

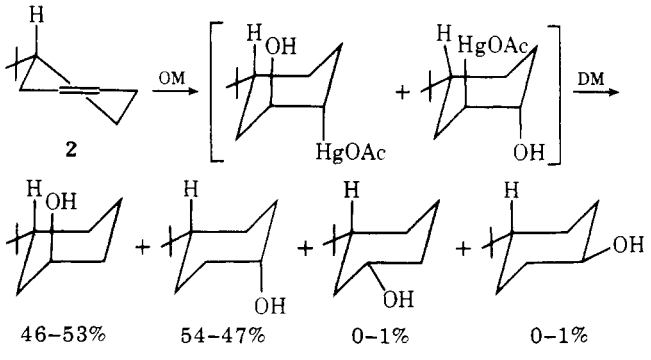
If one assumes trans diaxial addition, then the more stable equatorial conformer of **3** undergoes hydration in a highly regioselective fashion. On the other hand, hydration of the less stable axial conformer is nonregioselective (Scheme V).

In the case of olefin **4**, only the *trans*-3- and the *cis*-2-alcohols can arise from diaxial addition to the equatorial con-

Scheme I



Scheme II



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