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Alkylthiolation of Allylic Sulfides. [2,3] Sigmatropic Rearrangement of Thiosulfonium Ions

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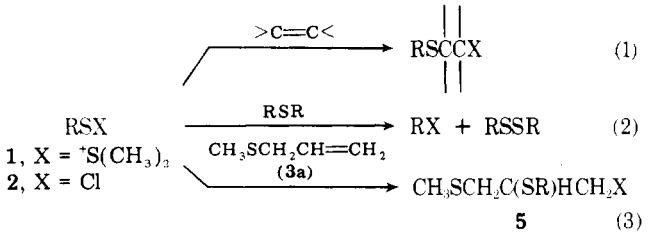
The reactions of sulfenyl compounds R′SX (X = Cl or $^{+}S(CH_3)_2$) with various alkyl allyl sulfides $RSCH_2CH{=}CH_2$ (R = CH_3, C_2H_5, i-C_3H_7, t-C_4H_9, C_6H_5, and $C_6H_5CHCH_3$) in nitromethane or chloroform solution have been investigated. The results show that sulfenyl reagents add to the allylic double bond by an involved sequence in which an alkylthio group is transferred initially to the sulfur atom of the allylic sulfide. The resulting thiosulfonium ions $CH_2{=}\overset{+}{C}HCH_2{}^{+}S(SR')R\ X^-$ are formed reversibly when X = $^{+}S(CH_3)_2$ and irreversibly when X = Cl. They undergo allylic rearrangement and alkyl migration depending on R and R′. The observed adducts are derived in part from thiosulfonium intermediates by intramolecular transfer of RS or R′S from positive sulfur to the double-bond carbons, and in part by direct addition of R′SX to the double bond of the sulfide. Rearrangement of thiosulfonium ions leads to scrambling of RS and R′S groups in the adducts and to alkylthio exchange in the starting sulfides. The extent of rearrangement decreases with increasing size of the alkylthio group. Negligible rearrangement occurs in the methylthiolation of phenyl allyl sulfide.

Alkenes generally react readily with sulfenyl compounds to form products of addition to the double bond (eq 1).[1-3] Sulfides also react readily with sulfenyl compounds to give predominantly substitution products (eq 2).[4-12] However, when both a double bond and a nucleophilic sulfur atom are present in the same molecule, the outcome of reaction with an electrophilic sulfenyl compound cannot easily be predicted.



(1)

(2)

(3)

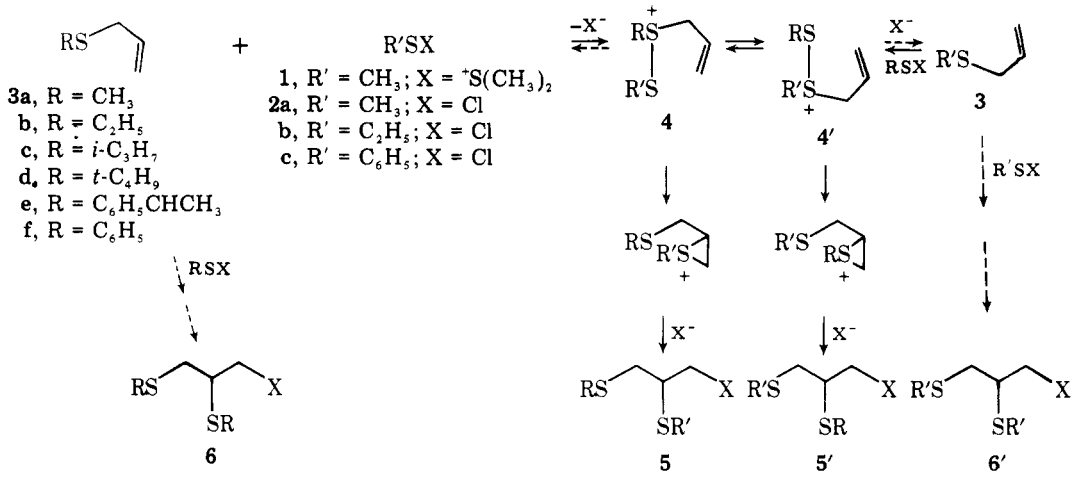
Recently, we reported that allyl methyl sulfide (**3a**) reacts with dimethyl(methylthio)sulfonium fluoroborate (**1**) and with methanesulfenyl chloride (**2**) to form adducts corresponding to addition of the sulfenyl compound to the double bond (eq 3).[9] We reported further that these reactions are more complex than they at first appear because on employing sulfide **3a** labeled with deuterium in either the methyl group or the allylic methylene the position of the label in the products is scrambled with the corresponding unlabeled group. A reaction pathway involving direct transfer of a methylthio group of either **1** or **2** to the double bond of the sulfide cannot adequately explain these results. Apparently, label scrambling occurs because the initial step involves attack of the sulfenyl compound at *sulfur* rather than at carbon. The product of this step is an intermediate allyl(alkylthio)sulfonium ion **4** that rearranges by a [2,3] sigmatropic shift of the allyl group from positive sulfur to neutral sulfur (Scheme I, R = R′ = CH_3). The rearrangement **4** → **4′** is degenerate and undetected unless the methyl or methylene group is labeled, in which case the 2,3-bis(methylthio)propane adducts that are isolated (**5** and **5′**) have the methyl-d_3-thio group distributed between C2 and C3 and the methylene-d_2 group between C1 and C3.[13]

In this paper we describe further details of the reactions of methyl, ethyl, isopropyl, *tert*-butyl, 1-phenylethyl, and phenyl allyl sulfides (**3a–f**) with several different sulfenyl compounds, notably the sulfenyl salt **1** and methane-, ethane-, and benzenesulfenyl chlorides (**2a, 2b,** and **2c,** respectively). The objective was to determine the degree to which the alkyl or aryl groups of the allylic sulfide and the sulfenyl reagent influence the outcome of reaction. It was hoped that the product compositions might indicate whether the initial thiolation step occurs partly or entirely by attack at sulfur. The results obtained, which are described herein, verify the complexity of the reaction sequence shown in Scheme I and confirm that rearrangement is indeed dependent on the nature of both the sulfide and the sulfenyl reagent.

Results and Discussion

The reactions of all six allylic sulfides (**3a–f**) employed in this study were run in essentially the same manner. Reactions of the sulfenyl salt **1** were carried out in dry nitromethane as solvent at 0–3 °C and appeared to be complete under these

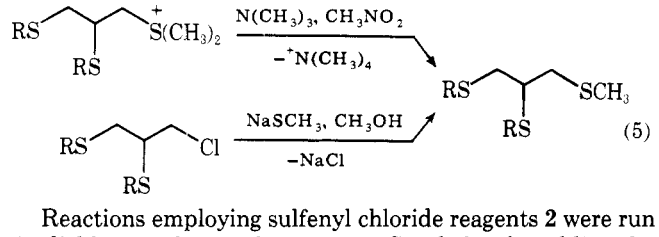
Scheme I



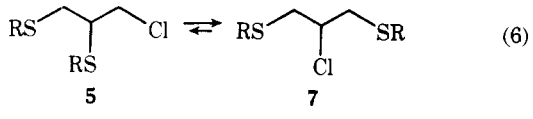
conditions within 1 h. In each case, a modest excess of sulfide to sulfenyl compound was used so that unreacted sulfide could be recovered and checked for alkylthio exchange with the sulfenyl reagent. We have noted previously[9] that methylthiolation of methyl-d_3 allyl sulfide with **1** is reversible and that reversibility combined with [2,3] sigmatropic rearrangement **4** ⇄ **4'** accounts for the recovery of labeled and unlabeled sulfides, **3a**-d_3 and **3a**. A similar process between other alkyl allyl sulfides and **1** also should lead to recovery of mixtures of the starting sulfide and methyl allyl sulfide (eq 4).

$$RSCH_2CH{=}CH_2 + CH_3SX \quad (1,\ X = {}^+S(CH_3)_2) \rightleftharpoons CH_3SCH_2CH{=}CH_2 + RSX \quad (4)$$

To analyze the reaction mixtures obtained from **1**, the volatile products first were separated from the salt adducts by flash distillation at reduced pressures. The composition of the volatile fraction was then determined by NMR, mass spectrometric, and GPC methods aided by comparisons with authentic samples where possible. Analysis of the involatile products was more of a problem, and we found it necessary to convert the mixture of sulfonium salts to the corresponding mixture of tris(alkylthio)propanes by demethylation with excess trimethylamine (eq 5).[14] This reaction was rapid, quantitative, and produced volatile products that were readily analyzed by NMR, mass spectrometric, and GPC methods.



Reactions employing sulfenyl chloride reagents **2** were run in dichloromethane solution at 0 °C or below by adding the sulfenyl chloride to a slight excess of the sulfide. Although the adducts of this reaction are chlorides and therefore volatile, analysis proved tricky because of the ease with which the 1-chloropropane adducts **5** rearranged to the more stable 2-chloropropanes **7** (eq 6) at the elevated temperatures required for distillation and GPC analysis. Analysis of the crude reaction mixtures by NMR gave the most reliable estimate of the product composition of kinetic control. Conversion of the



chlorides to a mixture of tris(alkylthio)propanes by displacement of the halogen with sodium methiolate in methanol (eq 5) also proved useful in determining the gross structural composition of the mixture, although some rearrangement (eq 6) took place under the reaction conditions.

Alkylthio Exchange. The key results are summarized in Tables I–III, which show, respectively, the composition of recovered unreacted sulfides, the composition of the adducts derived from the sulfenyl salt **1**, and the composition of the adducts derived from the sulfenyl chlorides **2**. As already noted, alkylthio exchange between the starting sulfide and the sulfenyl reagent is a reflection of reversibility in the formation and rearrangement of (alkylthio)sulfonium ions **4**. With specific reference to Table I, it is apparent that extensive alkylthio exchange and hence reversible alkylthiolation at sulfur with rearrangement occur in reactions of allylic sulfides with the sulfenyl salt **1** (eq 4). The only allylic sulfide that did not exchange with the methylthio group of **1** was phenyl allyl sulfide (**3f**). Otherwise, the extent of exchange decreased somewhat in the order $CH_3 > C_2H_5 > i\text{-}C_3H_7$ and was less than expected for a 1:2 statistical distribution of exchanged/nonexchanged sulfide **3a/3** based on the 1.0:1.5 mol ratio of sulfenyl salt/starting sulfide. This is apparent also in the results of the reaction of 3-(methylthio)propene-*3,3*-d_2 with **1**; only 32% of the recovered sulfide had the deuterium label at the terminal carbon of the allyl group, whereas 50% should be labeled at this position if the label was scrambled completely (eq 7). The results imply that equilibrium is not completely established in either the initial methylthiolation step of Scheme I or the rearrangement step (**4** ⇄ **4'**), or possibly in both.

$$\underset{68\%}{CH_3SCD_2CH{=}CH_2} \xrightleftharpoons{CH_3SS^+(CH_3)_2} \underset{32\%}{CH_3SCH_2CH{=}CD_2} \quad (7)$$

The behavior of secondary and tertiary alkyl allyl sulfides **3d** and **3e** with **1** was anomalous in several respects. With *tert*-butyl allyl sulfide (**3d**), not only was the amount of methyl allyl sulfide (**3a**) formed surprisingly high (34%), but the anticipated sulfides **3a** and **3d** recovered in the volatile fraction comprised only 29% of the total. The other major volatile products were *tert*-butyl and allyl *disulfides* (see footnote *f*, Table I). A similar complex mixture of symmetrical and unsymmetrical sulfides and disulfides was formed in the reaction of 1-phenylethyl allyl sulfide (**3e**) with **1** (see footnote *g*, Table I). With isopropyl allyl sulfide (**3c**), only 6.5% of the anomalous byproduct was formed which was identified as diisopropyl disulfide. The significance of these observations will be discussed later.

Table I. Composition of Allylic Sulfides Recovered from Reaction of Excess Sulfide with Dimethyl(methylthio)sulfonium Fluoroborate[a]

starting sulfide $RSCH_2CH{=}CH_2$	recovered sulfides (% composition)		yield,[b] %
$CH_3SCD_2CH{=}CH_2$[c]	$CH_3SCD_2CH{=}CH_2$	$CH_3SCH_2CH{=}CD_2$	
	68	32	100
R	$RSCH_2CH{=}CH_2$	$CH_3SCH_2CH{=}CH_2$	
CD_3[d]	70	30	100
C_2H_5	78	22	100
i-C_3H_7	88	12	93.5[e]
t-C_4H_9	66	34	28.5[f]
$C_6H_5CH(CH_3)$	72	28	79[g]
C_6H_5	>99	trace	100

[a] In CH_3NO_2 at 0–3 °C; mole ratio of sulfide/salt was 1.5:1. [b] Percentage of allylic sulfides present in the volatile products. [c] Reference 9. [d] See also ref 9. The reaction was repeated here using a 1.5:1 mol ratio of sulfide/salt at 0 °C. [e] Other volatile product was diisopropyl disulfide (6.5%). [f] Other volatile products included t-$C_4H_9SSCH_2CH{=}CH_2$ (31%), t-$C_4H_9SSC_4H_9$-t (21%), t-$C_4H_9SSCH_3$ (15%), t-$C_4H_9SCH_3$ (2%), and t-$C_4H_9SC_4H_9$-t (1.5%). [g] Other volatile products included $C_6H_5CH(CH_3)SCH_3$ (12%), $(CH_2{=}CHCH_2)_2S$ (10%), $CH_2{=}CHCH_2SSCH_2CH{=}CH_2$ (2%), and $CH_3SSCH_2CH{=}CH_2$ (2%).

Table II. Products of Reaction of Allylic Sulfides with Dimethyl(methylthio)sulfonium Fluoroborate after Demethylation

$$RSCH_2CH{=}CH_2 \xrightarrow[CH_3NO_2,\ 0\ °C]{(CH_3)_2{}^+SSCH_3} \text{adducts} \xrightarrow[CH_3NO_2,\ 25\ °C]{(CH_3)_3N} \text{1,2,3-tris(alkylthio)propanes}$$

	% composition of products				
$RSCH_2CH{=}CH_2$ 3	$RSCH_2C(SCH_3)HCH_2SCH_3$ 5	$CH_3SCH_2C(SR)HCH_2SCH_3$ 5′	$RSCH_2C(SR)HCH_2SCH_3$ 6	$CH_3SCH_2C(SCH_3)HCH_2S$-CH_3 6′	% rearrangement (5′ + 6′) 100/ (5 + 5′ + 6 + 6′)
R = CD_3	29	26	33	12	38
R = C_2H_5[a]	24	18	36	11	33
R = i-C_3H_7	45	17	27	10	27
R = t-C_4H_9[b]	48	18	5	29	47
R = C_6H_5	98	2	0	0	0.2

[a] Higher molecular weight material (unidentified) accounted for 11% of the products. [b] Yield of adducts was less than 50%. Other products were $(CH_3)_2S^+C_4H_9\ {}^-BF_4$ and $(CH_3)_2S^+CH_2CH{=}CH_2\ {}^-BF_4$.

Table III. Products of Addition of Alkanesulfenyl Chlorides to Alkyl Allyl Sulfides

$$RSCH_2CH{=}CH_2 + R'SCl \xrightarrow{CH_2Cl_2} \text{adducts}$$

reactants		temp,	% composition of products			% rearrangement (5′ × 100)/ (5 + 5′)
R	R′	°C	$RSCH_2C(SR')HCH_2Cl$ 5	$R'SCH_2C(SR)HCH_2Cl$ 5′	$RSCH_2C(Cl)HCH_2SR'$ 7	
CD_3[a]	CH_3	−20	65	32	3	33
C_2H_5	CH_3	−55	69	24	7	26
i-C_3H_7[b]	CH_3	−20	73	24	3	25
t-C_4H_9	CH_3	−20	79	15	6	16
C_6H_5	CH_3	0	91	4	5	4
CH_3[c]	C_2H_5	−55	66	22	5	25
CH_3	C_6H_5	0	68	22	10	24

[a] Reference 9. [b] 1-Chloro-2,3-bis(methylthio)propane (6′) and 1-chloro-2,3-bis(isopropylthio)propane (6) were detected by mass spectral analysis in 1.4 and 1.2% yields, respectively. [c] Approximately 7% of 1-chloro-2,3-bis(methylthio)propane was also formed.

In contrast to the behavior of 1 with allylic sulfides, the sulfenyl chlorides 2 studied produced *no* alkylthio exchange with the starting sulfides. That is to say, the equilibrium of eq 4 does not occur with X = Cl. An obvious explanation of the absence of exchange is that reactions with 2 occur by direct addition to the double bond of 3 rather than by attack at sulfur. However, this explanation does not account for the fact that the adducts obtained in these reactions show extensive scrambling of alkylthio groups (Table III). The details are described in the following section, which will clarify that scrambling of alkylthio groups in the adducts can arise through rearrangements of intermediate (alkylthio)sulfonium ions 4. Therefore, to the extent that sulfenyl chlorides attack the sulfur atom of 3, the (alkylthio)sulfonium ions so formed do *not* revert measurably to sulfide and sulfenyl chloride. Evidently, the counter nucleophile (Cl^-) is less reactive toward the electrophilic sulfur of 4 than it is toward the carbon of 4. The reverse is true of a sulfur nucleophile, $(CH_3)_2S$, reacting with 4.

Nature of the Adducts. Regarding the products of reaction of the sulfenyl salt 1 with allylic sulfides, formation of *four* different sulfonium salt adducts may be inferred from the composition of the sulfides 8–11 obtained on demethylation of the salt mixture (Table II). These products correspond to the four possible adducts derived from a mixture of the sulfenyl salt 1, the starting allylic sulfide 3, and their alkylthio-

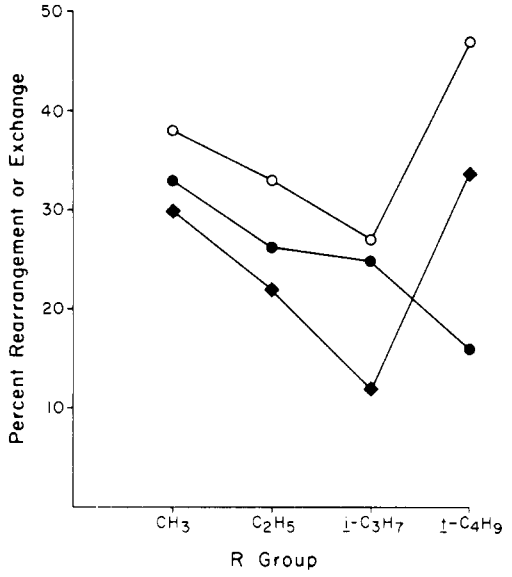
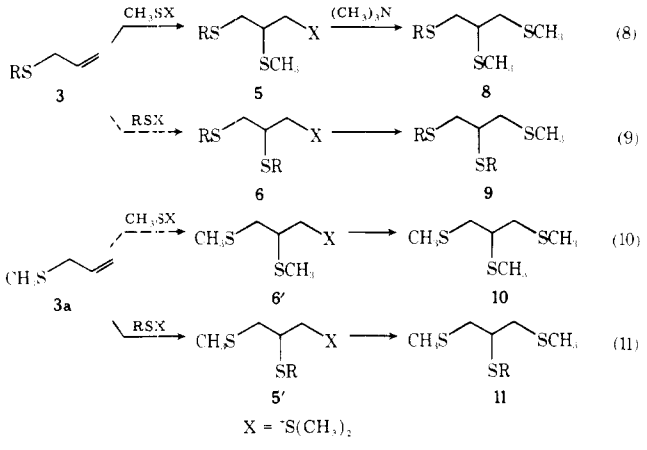
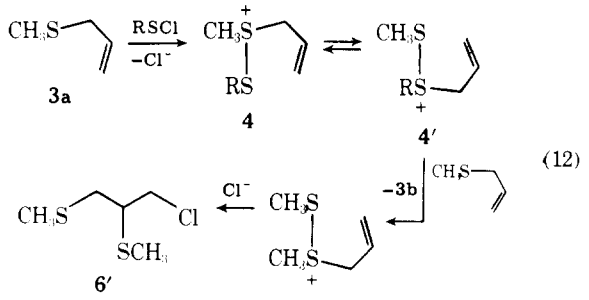


Figure 1. Percent of $CH_3SCH_2CH{=}CH_2$ recovered in the reaction of excess **3** with $CH_3SS^+(CH_3)_2{}^-BF_4$ (**1**) (Table I, ♦), and percent alkylthio rearrangement in the products of addition of **3** and **1** (Table II, ○) and **3** and **2** (Table III, ●).

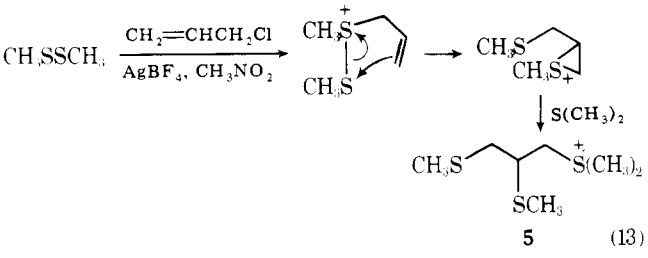
exchanged analogues (eq 8–11). Mechanistically, formation



of the adducts can be explained by the sequence of steps in Scheme I involving *reversible* alkylthiolation at sulfur and reversible rearrangement of thiosulfonium ion intermediates followed by *irreversible* addition to the double bond. But, from the data of Table II alone, it is not possible to tell whether the adduct-forming step is intermolecular (as implied by eq 8–11) or intramolecular by alkylthio transfer from S^+ of thiosulfonium ions **4** to carbon by way of episulfonium ions (as implied in Scheme I). However, we favor the latter circumstance because the results obtained in the case of sulfenyl chloride addition (Table III) require that the adducts be formed at least in part by *intra*molecular alkylthio transfer from sulfur to carbon. Thus, only *two* major adducts were obtained in addition reactions with sulfenyl chlorides, corresponding to the normal and rearranged isomers **5** and **5′** (X = Cl). Isomeric products in which the positions of the two alkylthio groups are interchanged cannot arise by way of direct addition to the double bond. However, their formation can be explained as the result of *irreversible* attack at sulfur followed by allylic rearrangement and then rearrangement to episulfonium ions. In keeping with this picture, the possible cross products **6** and **6′**, corresponding to addition of RSCl to exchanged sulfide or addition of exchanged sulfenyl chloride to $RSCH_2CH{=}CH_2$ (eq 9 and 10, X = Cl), either were not formed or were formed in very small amounts. The highest percentage of cross products was observed in the addition of ethanesulfenyl chloride to methyl allyl sulfide; about 7–9% of **6′** was detected in the product mixture, and its formation can be explained most reasonably as the result of methylthio transfer from the rearranged ion intermediate **4′** to a second molecule of the starting sulfide (eq 12). This pathway is clearly of minor importance and does not lead to detectable amounts of sulfide exchange.



Further evidence to suggest that (alkylthio)sulfonium ions may collapse intramolecularly to episulfonium ions and thence to adducts stems from an independent route to the adducts. We have found that dimethyl disulfide can be alkylated with 3-chloropropene in the presence of silver fluoroborate in nitromethane.[9] On addition of methyl sulfide to the reaction mixture, a nearly quantitative yield of **5** was produced, presumably by the reaction sequence of eq 13.



Finally, the compositions of the adducts reported in Tables II and III represent the product distributions formed under conditions of kinetic control. Although the sulfonium salts produced in reactions of **1** showed no tendency to rearrange to more stable adducts, the adducts from sulfenyl chloride addition were more labile. Briefly, the adduct **5** (R = R′ = CH_3), formed in the addition of methanesulfenyl chloride to **3a**, rearranged to a 34:66 mixture of 1-chloro- and 2-chloropropane isomers, **5** and **7**, on heating at 100 °C in benzene for 48 h (eq 6). The kinetics of this process are described in more detail in the succeeding paper. Rather surprisingly, the ethyl analogues **5** and **5′** (R = C_2H_5, R′ = CH_3), formed by addition of ethane- or methanesulfenyl chloride to **3a** or **3b**, were more labile and rearranged to **7** (R = CH_3, C_2H_5) readily in benzene at 25 °C within 48 h.

Evaluation of the extent of rearrangement that occurs in the alkylthiolation of allylic sulfides is complicated in the case of **1** by the reversibility of the first step and by the fact that the starting sulfide was in excess. Nonetheless, the adducts **5′** and **6′** shown in Table II can be considered as a measure of the extent of rearrangement **4** ⇄ **4′** as they are both derived directly or indirectly from the rearranged ion **4′**. That is to say, **5′** and **6′** may be considered to arise from exchanged sulfide and **5** and **6** from nonexchanged sulfide. The percentage of **5′** + **6′** present should then be a measure of the amount of rearrangement occurring in adduct formation. It is apparent from the data in the right column of Table II that this percentage decreases as the alkyl group of **3** changes from methyl, to ethyl, to isopropyl, meaning that the extent of rearrangement decreases in that order. The data from both Tables I and II are plotted for convenient reference in Figure 1, and it is apparent that the extent of sulfide exchange from

1 parallels the amount of rearrangement in the adducts formed from **1**. Again, the amount of rearrangement is anomalously high in the adducts derived from *tert*-butyl allyl sulfide and almost negligibly small in adducts from phenyl allyl sulfide.

The data for the sulfenyl chloride adducts reported in Table III are more straightforward to interpret because sulfide exchange is unimportant. The two major adducts **5** and **5′** represent the normal and rearranged adducts, respectively. Clearly, the percent of **5′**, and hence the percent rearrangement, decreases with increasing size of the alkyl group in the starting sulfide (see Figure 1). Unlike the data for **1**, the amount of rearrangement in the methylthiolation of *tert*-butyl allyl sulfide with **2a** is small. Phenyl allyl sulfide gives almost no rearranged adducts with either **1** or **2a**.

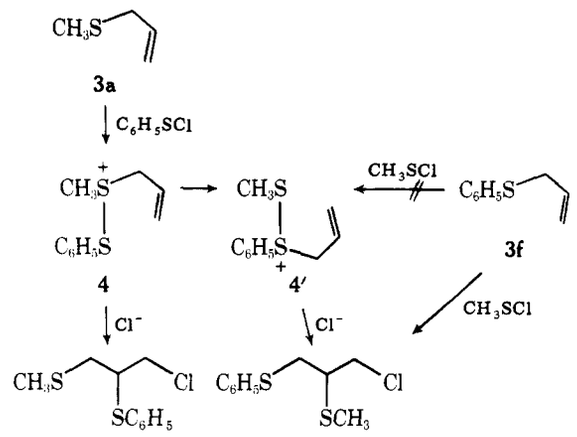
There are several factors that could affect the ratio of normal/rearranged adducts in sulfenyl chloride additions. The normal adduct could be derived in part by direct addition to the double bond. Also, the position of equilibrium in the rearrangement step **4** ⇄ **4′** may influence the ratio of **5/5′**, or, if equilibrium is not fully established, the relative rates at which **4** and **4′** collapse to products will affect the ratio of **5/5′**. In the case of methyl-d_3 allyl sulfide, rearrangement is degenerate (K = 1) and could lead to equal amounts of **5** and **5′** on methylthiolation with **2a**. The observed ratio is actually closer to 2:1 (Table III), which means that either the ions **4** and **4′** (R = CD_3) do not equilibrate completely or some 33% of the reaction occurs by direct addition. A similar ambiguous situation exists in the reactions of ethyl and methyl allyl sulfides with methane- and ethanesulfenyl chlorides. Here the intermediates **4** and **4′** (R = C_2H_5) are formed by two independent routes, methylthiolation of **3b** or ethylthiolation of **3a**, and while the products are the same the distributions are different. Equilibration of **4** and **4′** is therefore incompletely established or else some 65–67% of **5** is formed by direct addition.

It is certainly reasonable to expect less alkylthiolation at sulfur and therefore more direct alkylthiolation at carbon when the alkyl group of the sulfide is large, and the trends in the data point to this conclusion. A second effect of size is that the rate at which (alkylthio)sulfonium ions **4** collapse to adducts **5** or **6** appears to be slower the larger the size of the alkylthio group. This is more explicitly discussed in the case of the *tert*-butyl group in the next section, but it is qualitatively apparent from the data of Table II, which show a steady decrease in the amount of adduct **6** with increasing size of the alkyl groups R.

Phenyl allyl sulfide appears to react with **1** and **2** almost entirely by direct addition to the double bond. This is not surprising because the nucleophilicity of a phenylthio group toward electrophilic sulfur is known to be low. For example, the equilibrium in the exchange of phenyl sulfide with **1** is unfavorable ($K < 1$, eq 14), whereas exchange with alkyl sulfides has $K > 1$.[11] Although methylthiolation of the phenylthio group of **3f** to give **4′** does not occur to any great extent, it is interesting that **4** can be formed by the alternative reaction of **3a** with benzenesulfenyl chloride. In this case, rearrangement is significant and implies that the initially formed (phenylthio)sulfonium ions **4** rearrange to (methylthio)sulfonium ions **4′**.

$$R_2S + CH_3SS^+(CH_3)_2 \underset{R = C_2H_5,\ K = 4.5}{\overset{R = C_6H_5,\ K = 4.7 \times 10^{-3}}{\rightleftharpoons}} R_2S^+SCH_3 + S(CH_3)_2 \quad (14)$$

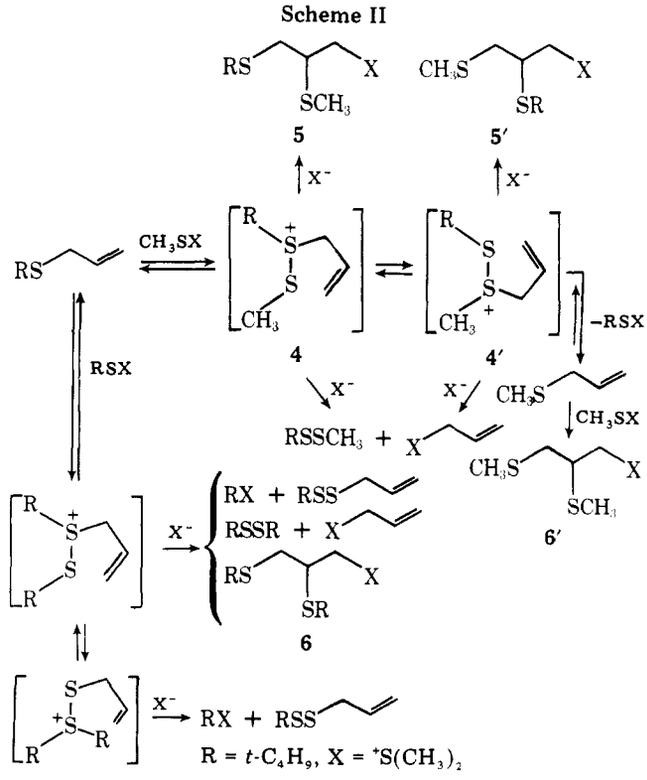
Methylthiolation Reactions of *tert*-Butyl Allyl Sulfide (3d). Although complex mixtures of products were obtained on methylthiolation of **3d** with the sulfenyl salt **1**, the products are revealing as to the ease with which both the *tert*-butyl and the allyl groups are transferred between each of the sulfur



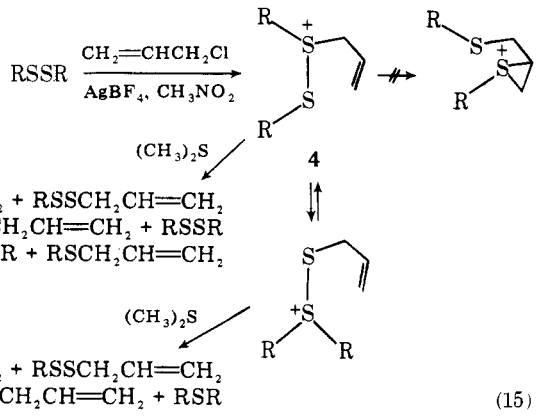
atoms present. The overall yield of salt adducts **6**, **5′**, **6**, and **6′** was low (45%) and consisted of an abnormally high proportion of the bis(methylthio) adduct **6′** (Table II). Two other salt byproducts were identified as *tert*-butyldimethylsulfonium fluoroborate (~35%) and allyldimethylsulfonium fluoroborate (~15%). Numerous volatile products were also formed. Alkylthio exchange in the starting sulfide was high, but only 29% of the volatile fraction consisted of the anticipated sulfides **3a** and **3d**. The other volatile products were mainly disulfides together with traces of alkyl sulfides (Table I).

The reason for the complex product mixtures is evidently related to the reversibility of the first step and to the reactivity of (alkylthio)sulfonium ions **4** bearing labile alkyl groups at positive sulfur. Besides [2,3] sigmatropic rearrangement of allyl groups, [1,2] rearrangement of alkyl groups can also occur, particularly when the alkyl group can separate as a stabilized carbocation.[8,10a,12] Therefore, some of the products are probably derived from the dissociation of **4** to disulfide and *tert*-butyl cation, which is then trapped by the available sulfur nucleophiles. As an independent example, it is known that *tert*-butyl sulfide reacts with **1** to give *tert*-butyl methyl disulfide and *tert*-butyldimethylsulfonium fluoroborate.[11] The entire reaction sequence in the case of **3d** is summarized in Scheme II. Although the scheme is speculative, the product

Scheme II



distribution supports the intervention of (alkylthio)sulfonium ions **4** and **4'** (R = *tert*-butyl). The low yield of 2-*tert*-butylthio adducts **5'** implies that transfer of a bulky *tert*-butylthio group from S^+ to carbon is less facile than alternate pathways such as transfer of a *tert*-butyl or allyl group from S^+ to a sulfur nucleophile. In support of this, an alternate route to **6** by way of allylation of di-*tert*-butyl disulfide (eq 15) was unsuccessful and led instead to allyldimethylsulfonium and *tert*-butyldimethylsulfonium salts as well as di-*tert*-butyl disulfide, *tert*-butyl allyl disulfide, and the corresponding monosulfides. The products are rationalized by the reaction sequence of eq 15. The main point is that intermediate (*tert*-butylthio)sulfonium ions of type **4** evidently rearrange by migration of the *tert*-butyl group to neighboring sulfur rather than to carbon.



(15)

In contrast to **1**, addition of methanesulfenyl chloride to **3d** was straightforward. Only two major adducts were formed, **5** and **5'**, corresponding to 16% rearrangement. The absence of byproducts and the reduction in the amount of rearrangement compared with **1** are striking (compare percent rearrangement with **1** and **2a** in Figure 1). It seems probable that the difference in behavior occurs because methanesulfenyl chloride attacks the double bond in preference to sulfur in the case of **3d**. If in fact reaction between **2a** and **3d** occurred primarily by initial attack at sulfur, the reactivity of **3d** would be expected to be less than that of the smaller analogues (**3a–c**). However, this is not the case because a competition experiment in which methanesulfenyl chloride competed for an excess of an equimolar mixture of sulfides **3a, 3b, 3c,** and **3d** depleted **3d** slightly faster than the others. The relative reactivities of **3a/3b/3c/3d** were determined in this manner as 1.0:1.1:1.2:1.5.

The behavior of 1-phenylethyl allyl sulfide with **1** was very similar to that of the *tert*-butyl analogue. Extensive exchange occurred with formation of a complex mixture of sulfides and disulfides, all of which can be rationalized by a process analogous to Scheme II (R = $C_6H_5CHCH_3$). The adducts were not analyzed.

In summary, the results of this study confirm that sulfenyl reagents attack both sulfur and carbon of allylic sulfides competitively. Attack at sulfur leads to thiosulfonium ions that rearrange by a facile [2,3] sigmatropic shift of the allyl group from S^+ and S and by a [1,2] rearrangement of an alkyl group in the case of *tert*-butyl and 1-phenylethyl allyl sulfides. The fate of the thiosulfonium ion intermediates depends not only on the substituents at sulfur but on the counter nucleophile, X. When X is chloride, there is no reversal to starting material. When X is $^+S(CH_3)_2$, reversal is extensive. Apparently, sulfide nucleophiles are more reactive toward electrophilic sulfur than toward carbon. The extent of alkylthio exchange in the allylic sulfides and the extent of rearrangement in the adducts decrease with increasing size of the alkyl group in the initial sulfide, which possibly means that alkylthiolation at sulfur becomes progressively less important as the size of the alkyl group of the sulfide increases.

Experimental Section

The **sulfenyl chlorides 2** employed in this study were freshly prepared before use by chlorination of the appropriate disulfide by standard literature procedures.[15] **Dimethyl(methylthio)sulfonium fluoroborate (1)** was prepared from methyl disulfide and trimethyloxonium fluoroborate[16] and could be stored indefinitely if kept cold and protected from moisture. Details of the alkylthiolation reactions of allylic sulfides with **1** and **2** have been described previously.[9,17]

The alkyl allyl sulfides were prepared from 3-chloro- or 3-bromopropenes and the appropriate sodium alkanethiolate. A typical procedure follows for the synthesis of **allyl isopropyl sulfide (3c).** A solution of the sodium salt of 1-methylethanethiol was prepared by adding 105 mL of 4 M sodium methoxide in methanol to a cooled solution of the thiol (30.4 g, 0.4 mol) in 50 mL of methanol. 3-Chloropropene (33 g, 0.44 mol) was added slowly with stirring to the thiolate solution. Sodium chloride separated immediately. The mixture was refluxed for 1 h, cooled, and filtered. The filtrate was evaporated under reduced pressure until about 50 mL remained. The residue was fractionally distilled and gave 38 g (82%) of **3c:** bp 123 °C (lit.[18a] 127–128 °C); NMR ($CDCl_3$) δ 1.26 (d, J = 7 Hz, CH_3, 6 H), 2.90 (heptet, J = 7 Hz, CH, 1 H), 3.18 (m, CH_2S, 2 H), 4.9–6.2 (m, $CH{=}CH_2$, 3 H).

A similar procedure for the synthesis of **methyl allyl sulfide (3a)** has been described elsewhere.[17] **Ethyl allyl sulfide (3b)** was similarly prepared from ethanethiol in 76% yield: bp 56 °C (90 mm) (lit.[18b] 115–116 °C); NMR ($CDCl_3$) δ 1.21 (t, J = 7 Hz, CH_3CH_2, 3 H), 2.48 (q, J = 7 Hz, CH_3CH_2, 2 H), 3.14 (m, CH_2S, 2 H), 4.9–6.2 (m, $CH{=}CH_2$, 3 H). **Phenyl allyl sulfide (3f)** was obtained from 3-bromopropene and benzenethiol in 93% yield and had bp 92–93 °C (6 mm) [lit.[22] 84–86 °C (4.9 mm)]; NMR ($CDCl_3$) δ 3.5 (m, SCH_2, 2 H), 4.9–6.2 (m, $CH{=}CH_2$, 3 H), 7.3 (m, C_6H_5, 5 H). **1-Phenylethyl allyl sulfide**[19] **(3e)** was prepared from 3-bromopropene and 1-phenylethanethiol in 82% yield: bp 62 °C (0.25 mm); NMR ($CDCl_3$) δ 1.48 (d, J = 7 Hz, CH_3, 3 H), 2.80 (m, CH_2S, 2 H), 3.80 (q, J = 7 Hz, CH, 1 H), 4.8–6.0 (m, $CH{=}CH_2$, 3 H), 7.2 (m, C_6H_5, 5 H).

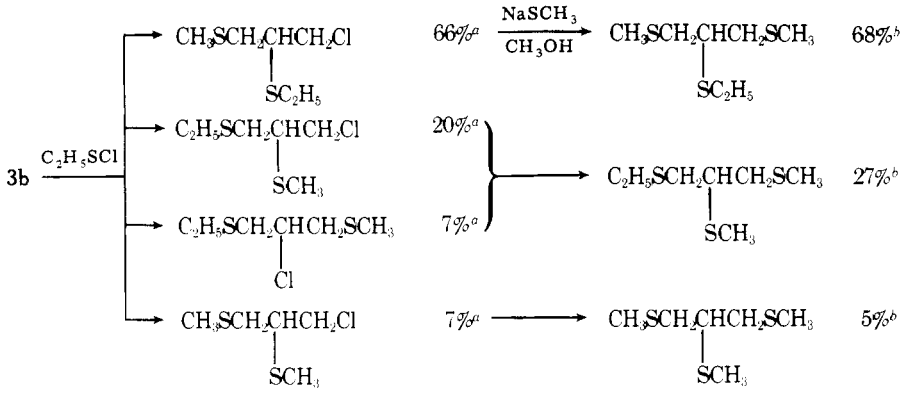
2-Propenyl-*1,1-d*$_2$ methyl sulfide was prepared from propenoic (acrylic) acid following the steps described by Stempel[23] and Mislow[24] with minor modifications. Propenoyl (acryloyl) chloride was obtained from propenoic acid and benzoyl chloride as described by Stempel et al.[23] Reduction of the product to 2-propen-1-ol-*1,1-d*$_2$ was accomplished with lithium aluminum deuteride (99.5% D) in 58% yield.[25] The alcohol was converted to the bromide by reaction with carbon tetrabromide and triphenylphosphine or tri-*n*-butylphosphine in 39–48% yield.[26] The bromide was converted to the sulfide by reaction with excess sodium methiolate in refluxing pentane[20] (73% yield). The isotopic purity of the 2-propenyl-*1,1-d*$_2$ methyl sulfide obtained was determined by NMR to be greater than 97%.

1,1-Dimethylethanethiol, as the sodium salt, was required for the synthesis of ***tert*-butyl allyl sulfide (3d)** and was prepared as follows. To a solution of *tert*-butyl disulfide (17.8 g, 0.1 mol) in 200 mL of liquid ammonia was added 4.6 g (0.2 g-atom) of metallic sodium in small pieces until a deep blue color of dissolved metal persisted for 0.5 h. The ammonia was allowed to evaporate, and the resulting white solid was dissolved in methanol (100 mL). 3-Chloropropene (15.2 g, 0.2 mol) was added, and the mixture was refluxed for 2 h. Water (300 mL) was added to the cooled reaction mixture, which was then extracted with three 30-mL portions of chloroform. The combined extracts were washed with water, dried ($MgSO_4$), and distilled. The product was collected at bp 138 °C (lit.[20] 139–41 °C): 23 g (88%); NMR ($CDCl_3$) δ 1.33 (s, CH_3, 9 H), 3.22 (m, CH_2S, 2 H), 4.9–6.2 (m, $CH{=}CH_2$, 3 H).

***tert*-Butyl methyl disulfide** was prepared from 1,1-dimethylethanethiol as follows. Methanesulfenyl chloride (12.5 g, 0.15 mol) was added dropwise to a rapidly stirred slurry of the thiol (14 g, 0.15 mol) and sodium bicarbonate (15 g) in 200 mL of dry methanol. The temperature of the mixture was kept below 5 °C during the addition, and thereafter the mixture was left at room temperature for 10–12 h. The solvent was removed by rotary evaporation. The residue was diluted with water (200 mL) and extracted with three 30-mL portions of ether. The combined ether extracts were dried ($MgSO_4$) and distilled to give 9 g (66%) of product of bp 68–69 °C (40 mm) [lit.[21] 69 °C (42 mm)]. Analysis by GLC indicated that the product was 98% pure with less than 1% each of the symmetrical disulfides, dimethyl disulfide and di-*tert*-butyl disulfide.

Demethylation of Sulfonium Salts. The salt adducts obtained from the reactions of **1** with sulfides **3** were converted to mixtures of

Scheme III



[a] NMR analysis. [b] GC analysis.

tris(alkylthio)propanes by the addition of a twofold molar excess of trimethylamine (2 M in nitromethane) to a solution of the adducts in nitromethane. The mixture was stirred overnight at room temperature and then filtered to remove tetramethylammonium fluoroborate, which precipitated out quantitatively. The filtrate was evaporated at reduced pressure to remove the solvent, and the residue was analyzed by GLC using an 8-ft long ⅛-in. d. column packed with 5% Carbowax 20 M on Chromosorb P at a column temperature of 130–180 °C and 30–40 cm³/min flow rate of helium carrier gas. The percent composition of the mixture was computed by a minicomputer (HP5830A) interphased with the GC. Each peak was identified by the retention time matching technique of authentic samples. Most of the authentic samples required for this analysis were prepared by demethylation of salt adducts of known structure and/or by displacement of chloride from chloropropane adducts of known structure with the appropriate sodium alkanethiolate. Identity of the mixtures was also confirmed by NMR and mass spectrometric analyses.

The percent composition of reaction mixtures produced from **1** were inferred from the percent composition of the mixture of demethylated adducts (see Table II). The results were reproducible and agreed with the results of direct NMR analysis of the salt adducts where this was possible. To obtain the product distribution reported in Table II for the reaction of **1** with **3a**-d_3 required a combination of quantitative analysis of the 90-MHz NMR spectrum of the salt adducts and mass spectral analysis of the demethylated adducts.

The percent composition of reaction mixtures produced from **2** was determined by quantitative analysis of the 90-MHz NMR spectrum of the chloropropane adducts and from the composition of tris(alkylthio)propanes produced from the chloropropanes and sodium methiolate. A typical analysis of the adducts from **3b** and **2a** is shown in Scheme III.

Reaction of Methyl Disulfide with 3-Chloropropene. To a mixture of methyl disulfide (0.5 g, 5.3 mmol) and 3-chloropropene (0.4 g, 5.3 mmol) in CD_3NO_2 (1.1 g) cooled in an ice bath was added $AgBF_4$ (1 g, 5.1 mmol) in one portion. After being stirred for 0.5 h, the mixture was left at room temperature for 2 h. To the mixture was added dimethyl sulfide (0.4 g, 65 mmol). After the mixture was stirred for 1 h at room temperature, the excess sulfide and solvent were removed under vacuum. The residue was redissolved in CD_3NO_2 and analyzed by NMR. The spectrum obtained was identical with that of the product from the reaction of **3** and **1**. The only impurities detected were $(CH_3)_3S^+ {}^-BF_4$ and $(CH_3)_2S^+CH_2CH{=}CH_2\ BF_4^-$ with methyl proton resonances at δ 2.96 and 2.90, respectively. The total percentage of impurities was less than 10% based on the integration.

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Registry No.—**1**, 5799-67-7; **2a**, 5813-48-4; **2b**, 1496-75-9; **2c**, 931-59-9; **3a**, 10152-76-8; **3a**-d_3, 68345-75-5; **3b**, 5296-62-8; **3c**, 50996-72-0; **3d**, 37850-75-2; **3e**, 69652-49-9; **3f**, 5296-64-0; **5** (R = CD_3, R′ = Me), 68345-76-6; **5** (R = Et, R′ = Me), 68345-80-2; **5** (R = *i*-Pr, R′ = Me), 69652-50-2; **5** (R = *t*-Bu, R = Me), 69652-51-3; **5** (R = Ph, R′ = Me), 69668-76-4; **5** (R = Me, R′ = Et), 68345-81-3; **5** (R = Me, R′ = Ph), 69652-52-4; **5′** (R = CD_3, R′ = Me), 68345-77-7; **5′** (R = *i*-Pr, R′ = Me), 69652-53-5; **5′** (R = *t*-Bu, R′ = Me), 69652-54-6; **7** (R = CD_3, R′ = Me), 69631-97-6; **7** (R = Et, R′ = Me), 69652-55-7; **7** (R = *i*-Pr, R′ = Me), 69652-56-8; **7** (R = *t*-Bu, R′ = Me), 69652-57-9; **7** (R = Ph, R′ = Me), 69652-58-0; **8** (R = CD_3), 69652-59-1; **8** (R = Et), 69652-60-4; **8** (R = *i*-Pr), 69652-35-3; **8** (R = *t*-Bu), 69652-36-4; **8** (R = Ph), 69652-37-5; **9** (R = CD_3), 69652-38-6; **9** (R = Et), 38091-90-6; **9** (R = *i*-Pr), 69652-39-7; **9** (R = *t*-Bu), 69652-40-0; **10**, 69631-98-7; **11**, (R = CD_3), 69652-41-1; **11** (R = Et), 69652-42-2; **11** (R = *i*-Pr), 69652-43-3; **11** (R = *t*-Bu), 69652-44-4; **11** (R = Ph), 69652-45-5; 2-propenyl-*1,1*-d_2 methyl sulfide, 41865-20-7; 2-propenyl-*3,3*-d_2 methyl sulfide, 68388-59-0; *tert*-butyl allyl disulfide, 67421-89-0; *tert*-butyl disulfide, 110-06-5; *tert*-butyl methyl disulfide, 35166-82-6; *tert*-butyl methyl sulfide, 6163-64-0; *tert*-butyl sulfide, 107-47-1; α-methylbenzyl methyl sulfide, 13125-70-7; allyl sulfide, 592-88-1; allyl disulfide, 2179-57-9; allyl methyl disulfide, 2179-58-0; dimethyl-*tert*-butylsulfonium fluoroborate, 69652-46-6; dimethylallylsulfonium fluoroborate, 27557-59-1 1-chloro-2,3-bis(methylthio)propane, 68345-73-3; 1-chloro-2,3-bis(isopropylthio)propane, 69652-47-7; 3-chloropropene, 107-05-1; 3-bromopropene, 106-95-6; sodium methylthiolate, 5188-07-8; sodium ethylthiolate, 811-51-8; sodium isopropylthiolate, 20607-43-6; sodium *tert*-butylthiolate, 29364-29-2; sodium α-methylbenzylthiolate, 69652-48-8; sodium phenylthiolate, 930-69-8; propenyl chloride, 814-68-6; 2-propen-1-ol-*1,1*-d_2, 10475-51-1; 2-propene-*1,1*-d_2 1-bromide, 39580-54-6; dimethyl disulfide, 624-92-0; dimethyl sulfide, 75-18-3; trimethylsulfonium fluoroborate, 676-88-0.

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Methylthiolation of Unsaturated Sulfides. Thiosulfonium Ions

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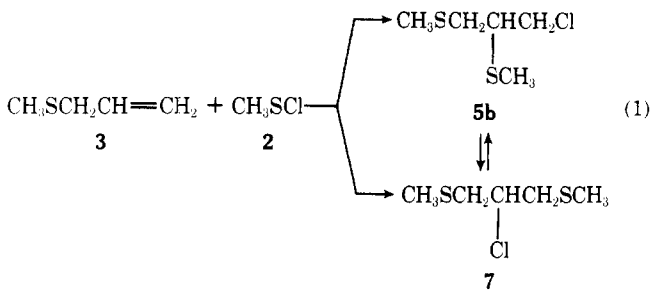
The reactions of methanesulfenyl chloride and dimethyl(methylthio)sulfonium fluoroborate with 2-propenyl methyl sulfide, 3-butenyl methyl sulfide, and 4-pentenyl methyl sulfide are described. Addition to the double bond occurs in each case. 1-Chloro-2,3-bis(methylthio)propane is the kinetic product of 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**).

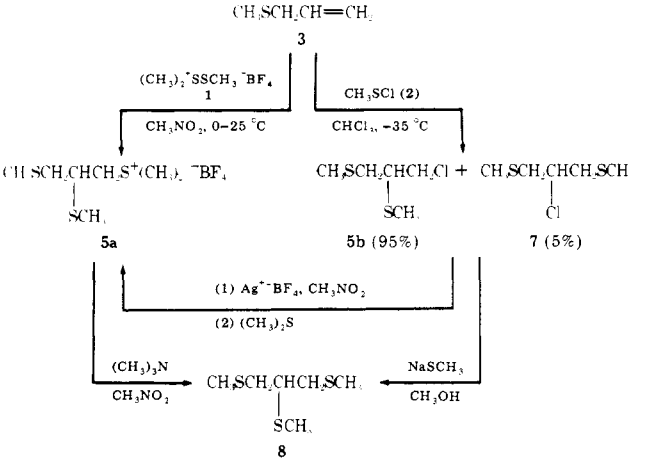
We also report herein a kinetic study of the equilibration of regioisomers **5b** and **7** that are formed in the addition of methanesulfenyl chloride to 2-pentenyl methyl sulfide (eq 1). The rearrangement of **5b** and **7** presumably passes through the same intermediate as in the addition reaction,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