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STRUCTURE AND REACTIVITY OF HALOSULFONIUM SALTS

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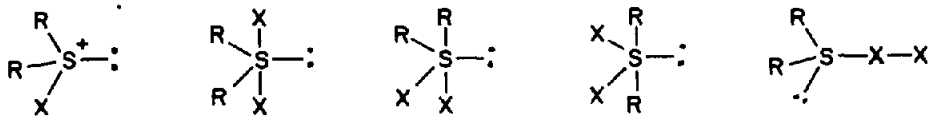
1. STRUCTURE

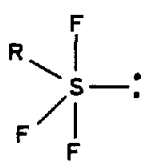
Some of the difficulties in generalization of the reactions of halosulfonium salts arise from the poor state of understanding of structural and medium effects on halosulfonium salt structure. The sulfur atom of a halosulfonium salt may exist as a pyramidal tricoordinate atom (**1**), as a trigonal bipyramid (**2–4**), or as a linear complex with the halogen (**5**). These three major forms (cation, sulfurane, and molecular complex) are in theory readily interconvertible by simple mechanistic steps. Each has been observed



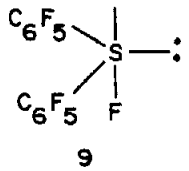
1 2 3 4 5

either in the solid state or in solution, but in only one case[1,2] has the halosulfonium salt of the same sulfide been observed in different forms in solution.

Sulfur tetrafluoride (**6**) is the simplest member of the family of sulfur-halogen compounds. It has been established by electron diffraction[3,4] and microwave[5,6] spectroscopy to be a distorted trigonal bipyramid with fluorine atoms in the axial position and the lone electron pair occupying one of the equatorial positions, completely in agreement with the geometry predicted for tetracoordinate compounds of Group IV elements based upon the electron-pair repulsion theory.[7,8] The temperature dependence of the ^{19}F NMR spectrum of carefully purified sulfur tetrafluoride[9] is consistent with rapid permutational isomerization of the axial and equatorial positions of the trigonal bipyramid via Berry pseudorotation.[10] Analysis of the temperature dependence of the ^{19}F NMR of (pentafluorophenyl)sulfur trifluoride indicated that any exchange process must be intramolecular; however, pseudorotation of the trigonal bipyramid (**7**), required by the spectral data, has an activation energy of at least 15–16 kcal/mol.[11,12] Both N,N-dimethyl- and N,N-diethylamino sulfur trifluorides (**8**) show ^{19}F NMR spectra[12–14] consisting of a doublet and triplet, J = 58 and 62 Hz, establishing these trigonal bipyramids to be static or slowly pseudorotating sulfuranes with two axial fluorine atoms. The ^{19}F NMR spectrum of di(pentafluorophenyl)difluorosulfurane (**9**) at 80° consists of five groups of resonances in the ratio 2:2:2:2:4, consistent with a trigonal bipyramidal sulfur atom and non-equivalent fluorines.[15]

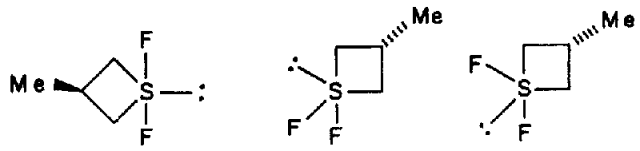


6 R = F
7 R = C_6F_5
8 R = Et_2N-, Me_2N-



9

The diaxial arrangement of halogens on a trigonal bipyramidal sulfur is apparently not obligatory. For the difluorosulfurane derived from 3 methyl-thietane, the ^{19}F NMR spectrum at $-78°$ shows two doublets with $J_{FF} = 167$ Hz uniquely consistent with the sulfurane structure **10** in which both fluorine atoms are apical and the three carbon atoms span the equatorial ligand positions.[16]

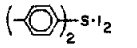
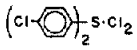
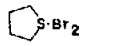
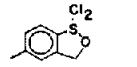
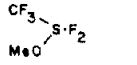
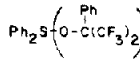
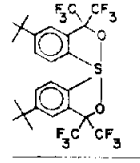


10 11a 11b

The spectral data are inconsistent with the alternative trigonal bipyramid structure **11**; for the method of synthesis would not be expected to provide stereospecifically only a single diastereomer (**11a** or **11b**). Apical–equatorial interchange would not interconvert **11a** and **11b** if both were present because this process would maintain chirality at sulfur, and pseudorotation involving **10** would result in equivalent fluorine atoms. The crucial feature in determining the lowest energy geometry is not associated in a simple way with the presence of a ring or its size, for difluorosulfurane **12** is considered to adopt a conformation close to **12a** rather than **12b** based upon the observation of two non-identical ^{19}F resonances ($J_{FF} = 31$ Hz) for both the CF_3 and SF moieties.[16] It is probable that the stable conformation in the case of cyclic dihalosulfuranes is a result of a delicate balance between the energy necessary to deform the bond angle at sulfur from its normal value of about 105° in acyclic sulfuranes (see Table 1) and the energy required to place an electronegative substituent in the equatorial position.

Halosulfonium salts of chlorine and bromine are notably unstable with respect to halogen and sulfide. Sulfur tetrachloride evolves chlorine in solution at room temperature;[15,25,26] however, the reaction of chlorine with sulfur in the presence of iodine provides trichlorosulfonium tetrachloroiodide, a stable salt for which X-ray analysis showed the trichlorosulfonium ion to be pyramidal.[27] Sulfur trichlorides are also unstable with respect to chlorine evolution.[28,29] Sulfide–chlorine complexes have variable stabilities

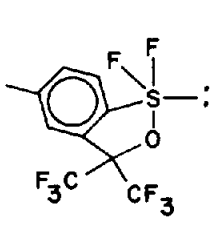
Table 1.

Structure	Structure Type	Bond Angles, ° R-S-R	S-X-X X-S-X	Ref.
	MC	93	179	18
	TBP	108.6	174.5	19
	MC	94.2	178	20
SF_4	TBP	101.5 103.8	186.9 183.2	4, 5 3, 6
	TBP	92.1	167.6	17
	TBP	104.6	171.5	21
	TBP	104.4	175.1	22, 23
	TBP	108.1 107.6	177.2* 178.2	24

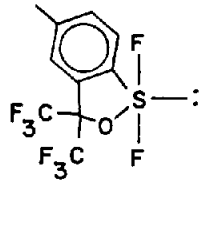
*Two forms exist in the crystal.

with respect to chlorine loss. The solid complex of chlorine with tetrahydrothiophene is stable at −20° and pressures as low as 10^{-5} Torr;[20] however, the solid complex with di(p-fluorophenyl)sulfide gradually loses chlorine at one atmosphere leaving the sulfide.[2]

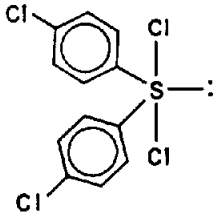
Bis-(p-chlorophenyl)dichlorosulfurane (**13**) is a slightly distorted trigonal bipyramid in the solid state with axial chlorine atoms.[19] An ^{19}F NMR study of the complexation of chlorine with bis-(p-fluorophenyl)sulfide (**14**) demonstrated rapid intermolecular exchange of chlorine and a complexed state which is either a molecular complex or a sulfurane.[1,2] Addition of mercuric chloride to an acetonitrile solution of the complex resulted in formation of the chlorosulfonium cation.[1,2]



12a

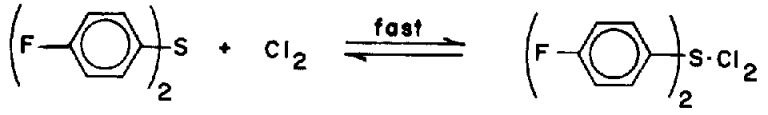


12b



13

Complexes of sulfides with bromine have been even less thoroughly investigated than the chlorine complexes. The product of bromination of tetrahydrothiophene (**15**) was found to have a linear sulfur–bromine–bromine arrangement of atoms with the sulfur atom pyramidal, the Br–Br distance 0.43 Å greater than that in the bromine molecule, and the S–Br distance only 0.09 Å greater than the normal covalent bond length.[20]



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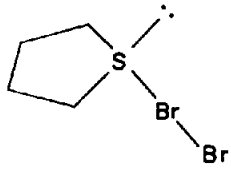

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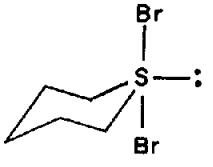
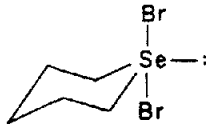


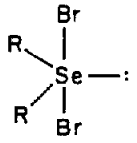
16

The ratio of the average trans vicinal coupling constant to the average cis vicinal coupling constant of a 6-membered ring is a sensitive indicator of flattening of the ring[31,32] which has been used to assess the nature of the thiane-bromine complex.[33] The validity of this approach was based on the assumption that formation of a trigonal bipyramid such as **16** will require a large C–S–C bond angle which will produce enormous ring distortions and a general flattening of the ring. Such a distortion was not observed for the thiane–bromine complex, and the conclusion was reached that the complex is of the charge transfer or molecular complex type[33] probably in equilibrium with a more polar species. This was supported by a very careful conductometric titration in ethylene chloride which showed an increase in the conductance up to the equivalence point followed by a rapid rise beyond it.[33] The molar conductivity of the complex increased by a factor of five when treated with silver fluoborate to form the bromosulfonium salt. In this regard it is perhaps worth noting that silver fluoborate was excluded as a reagent for generation of the chlorosulfonium salt from the bis(p-fluorophenyl)sulfide–chlorine complex when it was observed that it complexed with the sulfide to produce a large upfield fluorine chemical shift.[2] By contrast the complex of selenacyclohexane with bromine, **17**, was considered to be trigonal bipyramidal by virtue of a low ratio

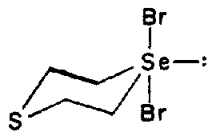
of the coupling constants and a low conductance up to the equivalence point.[33] This agrees well with X-ray structure determinations of the diphenylselenide-bromine (**18a**),[35] di-p-tolylselenide-bromine (**18b**),[34] and 1-thia-4-selenacyclohexane-4,4-dibromide (**19**)[36] structures. In the light of recent crystal



17



18 a. R = Ph
b. R = Tolyl



19

structure determinations of sulfuranes (Table 1), the assumption of a requisite large equatorial C–S–C angle in sulfuranes is probably not well-founded. In fact, the C–S–C angles observed are in the range 92–105°, quite comparable to the normal angles in a 6-membered ring.

The first report of a sulfide–iodine complex is that of the adduct of iodine with 1,4-dithiane.[37] The crystal structure of this adduct showed it to be a molecular complex with an S–I bond length of 2.87 Å and an I–I distance of 2.79 Å, only 0.11 Å longer than that in molecular iodine. The complex of iodine with thiane[33] has vicinal proton coupling constants the same as in the parent sulfide consistent with a molecular complex. The conductance of the complex in methylene chloride was less than 0.5% of that for the complex treated with silver fluoborate to form the iodosulfonium fluoborate.

2. EQUILIBRIA AND DYNAMICS

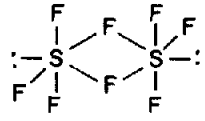
Clarification of the mechanisms of intermolecular exchange processes of halosulfonium salts may be highly significant in understanding their chemical reactions and the effects of media on these reactions. Information consistent with the concept of an ionic species as the reactive intermediate in the chemistry of these compounds has come largely from exchange studies of halosulfonium salts stable in the sulfurane form and from salts formed with a non-basic, non-nucleophilic counterion. Fluorine exchange in samples of SF_4 contaminated with SOF_2, SF_6, SiF_4, and S_2F_{10} was believed as early as 1958[39] to be caused by fluoride impurities. The activation energy for the exchange process was determined to be about 4 kcal/mol[38,39] with a frequency factor of 10^7–10^9 s^{-1} assuming first order kinetics.[38] For higher order kinetics the frequency factor would be larger. The exchange process was determined to be second or higher order[38] thus ruling out intramolecular exchange as the low energy pathway. The data did not allow discrimination between associative and dissociative processes. Possible mechanisms for intermolecular fluorine exchange are shown in eqns (1)–(6) below:

$$SF_4 \rightleftharpoons \overset{+}{S}F_3 + F^- \qquad \text{(Eq 1)}$$

$$SF_4 + F^- \rightleftharpoons SF_5^- \qquad \text{(Eq 2)}$$

$$SF_4 \rightleftharpoons \cdot SF_3 + F\cdot \qquad \text{(Eq 3)}$$

$$2\ SF_4 \rightleftharpoons$$



(Eq 4)

$$SF_4 + H_2O \rightleftharpoons SF_4(OH_2) \rightleftharpoons SF_3\overset{+}{(O}H_2) + F^- \qquad \text{(Eq 5)}$$

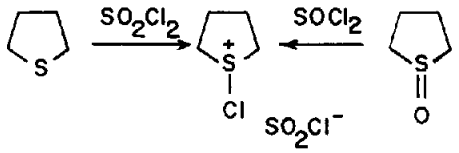
$$SF_4 + A \rightleftharpoons A\text{–}SF_4 \rightleftharpoons \overset{+}{A}\text{–}SF_3 + F^- \qquad \text{(Eq 6)}$$

The absence of solvent fluorination during exchange ruled out radical intermediates (eqn 3).[38] Strong Lewis acids (PF_5, AsF_5, SbF_5) were found by ^{19}F NMR to catalyze the exchange[40] and the efficiency of catalysis was found to parallel Lewis-acid strength. This would be compatible with the process shown in eqn (6). Hydrogen fluoride proved less effective than PF_5 at catalyzing exchange[40] as might be expected if coordination to the soft sulfur atom is important. Intermolecular site exchange in SF_4 was also observed using vibrational spectroscopy.[41,42] Because eqn (4), bimolecular association, can be ruled out as an exchange mechanism for averaging ^{19}F chemical shifts of rigorously purified SF^4, it can also be ruled out for intermolecular exchange. A similar argument allows exclusion of dissociation to fluoride ion and the trifluorosulfonium ion (eqn 1) as the dominant exchange mechanism. Addition of bis(trimethylsilyl)amine to SF_4 as a water and hydrogen fluoride scavenger led to a significantly lower exchange rate, thus lending credence to eqn (5) as a possible exchange mechanism.[43] Finally, detailed line shape analyses for all possible fluoride-catalyzed and bimolecular mechanisms of intermolecular fluoride exchange were inconclusive in delineating clearly a dominant exchange mechanism or mechanisms for exchange in impure samples of SF_4.[9]

Intermolecular fluorine exchange in competition with pseudorotation is also observed with sulfide difluorides[16,44] and with arylsulfur trifluorides, the rate for the latter compounds being retarded by dilution with an inert solvent.[12] Intermolecular exchange was observed by ^{19}F NMR for diethyl- and dimethylaminosulfur trifluoride,[13] and the process was retarded by addition of bis(trimethylsilyl)amine as a water trap.

Rapid halogen exchange is observed in both chloro- and bromosulfonium salts, and there is considerable physical evidence for the existence of halosulfonium cations in solution as well as in the solid state. Addition of chlorine to di(p-fluorophenyl)sulfide causes a progressive downfield shift of the fluorine resonance which levels off at a sulfide/halogen ratio of about 1 indicating rapid equilibration of all species in solution.[1,2] Similar results were observed for the α-protons of tetrahydrothiophene when it was treated with either chlorine or bromine.[20] The limiting shift of the α-protons moved downfield when the solvent was changed from methylene chloride to acetonitrile suggesting a stabilization of the more polar form in the higher dielectric constant solvent. The equilibrium reaction between di(p-fluorophenyl)sulfide and chlorine in methylene chloride or acetonitrile could be best represented as the formation of a covalent species with an association constant of about 4.5×10^5 and its further dissociation into an ionic species with an equilibrium constant of about 0.1,[2] thus making the covalent sulfurane or molecular complex the most abundant complex in solution.

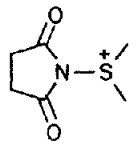
Treatment of $CDCl_3$ solutions of tetrahydrothiophene with sulfuryl chloride or reaction of the sulfoxide with thionyl chloride provided the same proton NMR spectrum presumably due to the chlorosulfonium cation **21**;[45] however, the spectrum obtained when one equivalent of chlorine was added to a $CDCl_3$ solution of tetrahydrothiophene at $-75°$ was appropriate for about an equal mixture of the sulfide and its chlorosulfonium salt **21**.[20] Given the chemical shift difference, the exchange lifetime for the equilibrium **20** $\rightleftarrows$ **21** in this case must be considerably shorter than $12 \cdot 10^{-6}$ s. The perchlorate,



20 21

fluoborate, and nitrate of the bromodimethylsulfonium ion have been isolated;[46] and the crystalline chlorodimethylsulfonium hexachloroantimonate and fluoborate have also been reported.[47] NMR spectroscopy has also been used to identify the trichloromercurate of the di(p-fluorophenyl)chlorosulfonium ion.[1,2] In light of the extreme lability of heteroatom ligands on the sulfur atom of a halosulfonium salt, predictions of solution chemistry based upon solid state structures or, indeed, any single solution structure must be carefully examined. The uncertainty is even more pronounced for potential halosulfonium salt intermediates formed from the reaction of sulfides with asymmetric reagents, such as N-halosuccinimides. In interpreting such reactions it should be borne in mind that mechanistic steps subsequent to the formation of the sulfonium salt may alter either the hydrogen ion or halide ion content of the medium and thus displace the equilibria. Furthermore, the reactions of halosulfonium salts are carried out in nonpolar

solvents such as hexane and in polar-protic solvents such as water-methanol mixtures, thus dramatically affecting the activities of the proton and halide ions. Several reactions brought about by treatment of sulfides with N-halosuccinimides deserve reexamination. Initial interpretations of these reactions assumed a halosulfonium salt intermediate. Following the isolation of succinimidyldimethyl-sulfonium chloride (**22**) as a stable crystalline solid from the reaction of dimethylsulfide with N-chlorosuccinimide in methylene chloride, most authors have interpreted their results in terms of the succinimidylsulfonium salt.[48] To date, however, the true nature of the reactive species has not been unequivocally demonstrated.



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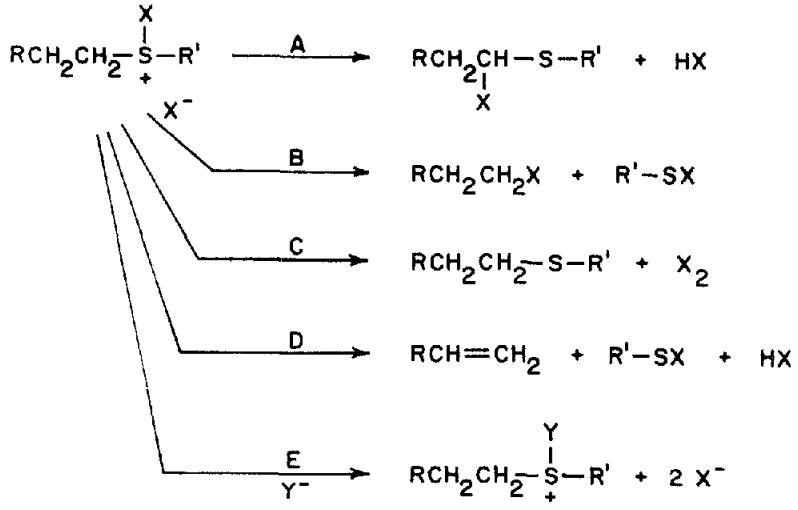
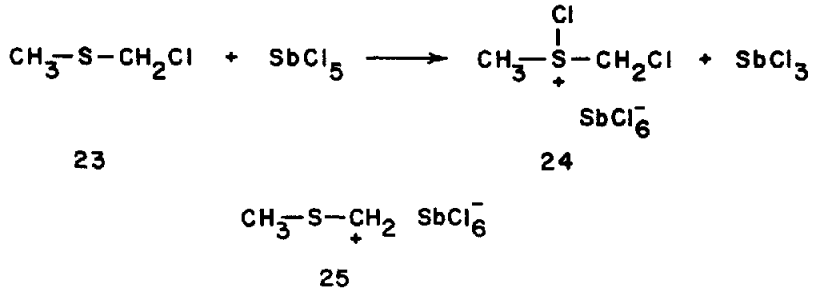
3. BROMINATION AND CHLORINATION OF SULFIDES

Generation of a bromosulfonium or chlorosulfonium salt as a reactive intermediate may be followed by a number of transformations involving the sulfur atom and the α- or β-carbon atom. These are summarized in Scheme 1 below. The pathways of the halosulfonium salt reactions often compete so that the product distributions are usually complex. Further, the course of the reaction is often dependent upon the effective anion present and upon the solvent and temperature. The remainder of this review is divided into sections based largely upon the transformations of halosulfonium salts subsequent to their formation. Most widely studied is the Pummerer rearrangement exemplified by path A of Scheme 1. A set of reactions which often compete quite favorably with the Pummerer reaction and which have been used in several synthetic schemes are the fragmentation reactions, paths B and D. The oxidation of sulfides to sulfoxides, the reduction of sulfoxides to sulfides by hydrogen iodide, and the racimization of sulfoxides by aqueous hydrochloric acid involve displacement on the sulfur atom, path E. Finally, halosulfonium salts participate in electrophilic reactions and act as a source of halogen.

Halosulfonium salts are formed upon direct treatment of the sulfide with either chlorine[17,19,49] bromine[20,33] or iodine[18,50] in a suitable non-nucleophilic solvent. Phenyliodosyl dichloride,[51] sulfuryl chloride,[47] sulfur dichloride,[52] 1-chlorobenzotriazole,[53] the bromine complex of diazabicyclooctane,[54] and N-halosuccinimides[55] also have been used to oxidize sulfides to the halosulfonium salt. In the case of N-chlorosuccinimide, available data[48] indicate that the most stable sulfonium salt is the succinimidyl-sulfonium salt **22**. In one instance the treatment of α-chloromethyl methyl sulfide **23** with $SbCl_5$ has been shown to generate chlorosulfonium salt **24**[56] rather than the sulfocarbonium ion **25** as previously suggested.[57] Difluorosulfuranes, for which very little of the chemistry has been elucidated, have been formed by the reaction of the sulfide with trifluoromethyl hypofluorite,[16] AgF_2,[17] or xenon difluoride.[44]



Scheme 1.

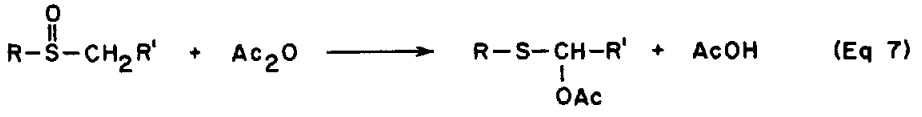


23 24 25

Sulfides also react with the pseudohalogen cyanogen bromide to produce the cyanosulfonium salt.[58] Reactions of cyanogen bromide with the methionine of peptides is a generally used method for cleaving peptides during sequencing.[59] Extensive coverage of this reaction is outside the scope of this review. Cleavage of sulfides by the pseudohalogen thiocyanogen to form the thiolthiocyanates has been effected,[60] probably by way of the corresponding sulfonium salt.

4. PUMMERER REARRANGEMENTS

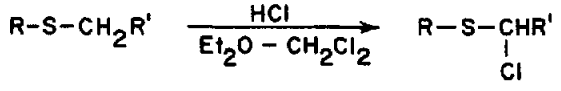
The reactions of sulfoxides with acetic anhydride to form α-acetoxysulfides and the acid-catalyzed α-rearrangement of sulfoxides are the classical examples of the Pummerer rearrangement[61] (eqn 7).



(Eq 7)

Recognition of the mechanistic similarity of the classical reaction to the α-rearrangements of other sulfonium salts[62] led to the redefinition of the reaction to include the family of transformations which result in simultaneous oxidation of the α-carbon atom and reduction of the sulfur atom of a sulfonium salt. Under appropriate conditions the reaction leads cleanly to products in high yields.

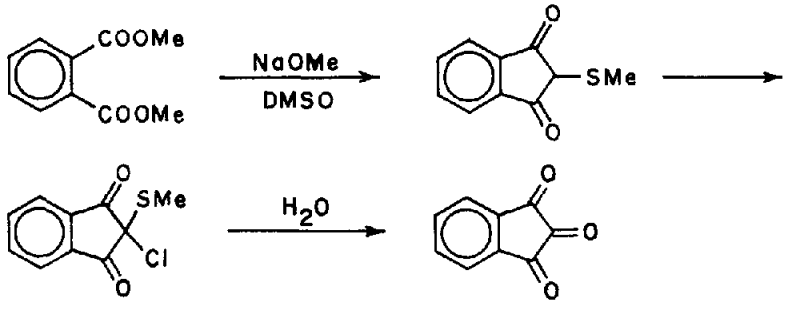
The reaction of sulfoxides with HCl in ether–methylene chloride solutions gives the corresponding α-halosulfides **26** in good yield provided a water scavenger such as molecular sieves[63] is included to drive the reaction.



26

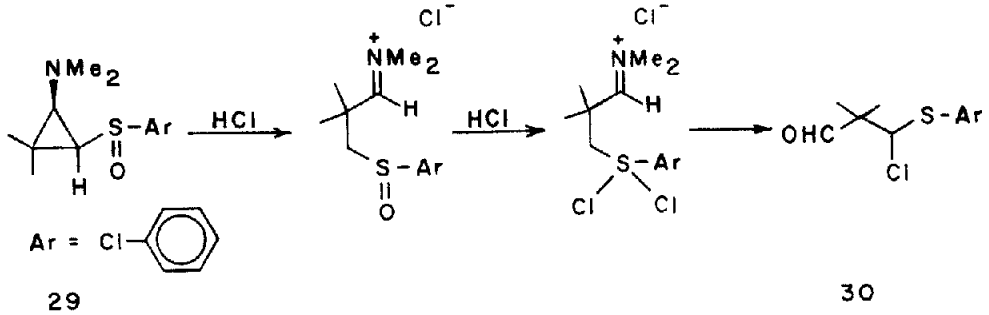
R	R'	Yield (%)
Me	H	77
Tol	H	73

A simple synthesis of ninhydrin (**28**) involves the hydrolysis of **27** generated by Pummerer rearrangement of the condensation product of DMSO and diethylphthalate.[64,65]



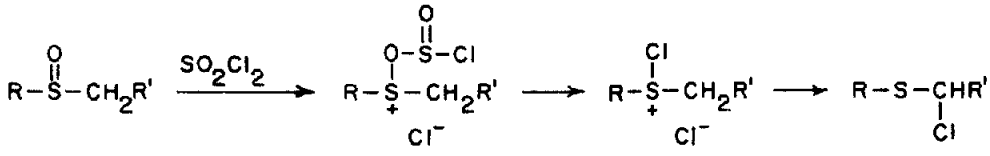
27 28

In a complex series of events, the aminocyclopropyl sulfoxide **29** is converted into the α-chlorosulfide **30**.[66] For this reaction the iminium salt serves as the water scavenger.



29 30

When a number of sulfoxides were treated with sulfuryl chloride, the resulting product was the α-chlorosulfide **32** possibly, but not necessarily, by way of the chlorosulfonium salt **31**.[67] Pummerer products generated *in situ* are useful reagents. Triethylammonium salts of carboxylic acids, when



31 32

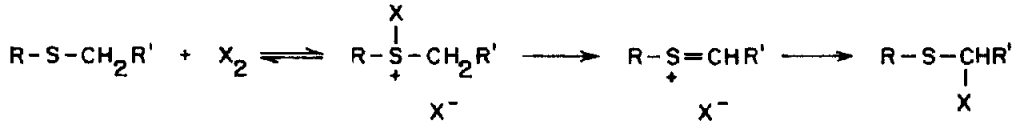
R	R'	Yield (%)
Me	H	92
Et	Me	40
Cl	H	90
Me	Ph	75
t-Bu	H	39

admixed with the preformed halosulfonium salt of dimethyl sulfide at −70° and allowed to warm to room temperature, provide the methyl thiomethyl esters[68] (eqn 8).

(Eq 8)

α-Chlorination of sulfides can be effected with molecular chlorine,[49,69,70] thionyl chloride,[71] sulfuryl chloride,[67,71] or N-chlorosuccinimide.[48,55,72–75] α-Bromination has been carried out with bromine[20,30,76–78] and with N-bromosuccinimide.[78,79]

For synthetic applications, the reagents of choice for α-halogenation are often NCS or chlorine, both of which react to provide clean products. By contrast, NBS often causes carbon-sulfur bond cleavage if an alkyl chain is present,[75,78–82] or halogenation of an aromatic nucleus.[75,79,81,82] A comparison of the methods of halogenation is available for only dibenzyl sulfide. For this case the reactions with chlorine, bromine, NCS, and NBS were compared in two solvents (Table 2). Both bromine and NBS produced significant amounts of cleavage products. Although chlorine produced no carbon–sulfur bond cleavage in carbon tetrachloride, it did lead to a significant amount of α,α-disubstituted product. The Pummerer



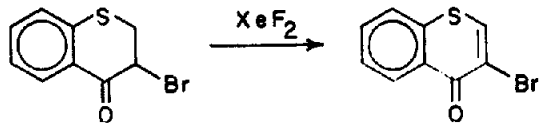
Scheme 2.

Table 2. Distribution of halogenation products of dibenzyl sulfide in carbon tetrachloride and in deuteriochloroform solutions

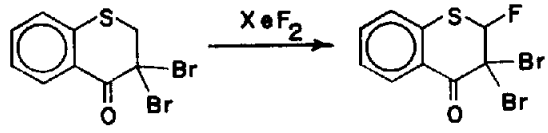
	Carbon tetrachloride[a]		Chloroform-d[a]	
	% α substitution	% cleavage	% α substitution	% cleavage
Cl_2	86[b]	0	c	c
Br_2	34.7	64.8	41.5	57.8
NCS	87.2	2.62	77.7	21.6
NBS	60.3	30.4	22.5	77.2

a. 0.208 M benzyl sulfide at 35°C for 30 min. b. Includes 25% yield of α,α-dichlorobenzyl benzyl sulfide. c. Quantitative assay was not possible because the internal standard was also chlorinated.

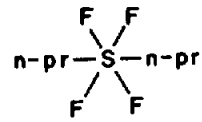
rearrangement of the intermediate chlorosulfonium salts is now generally thought to proceed thro intermediates depicted in Scheme 2. There are only two reports which discuss the α-fluorina sulfides.[44,83] Sulfide **33** reacted with XeF_2 to form the vinyl sulfide **34**; however, for **35**, in wl β-hydrogen was available, the α-fluorosulfide **36** was obtained. Di-n-propyl sulfide was reported t with excess CF_3OF to yield di-n-propyltetrafluoropersulfurane **37**.[16]



33 34

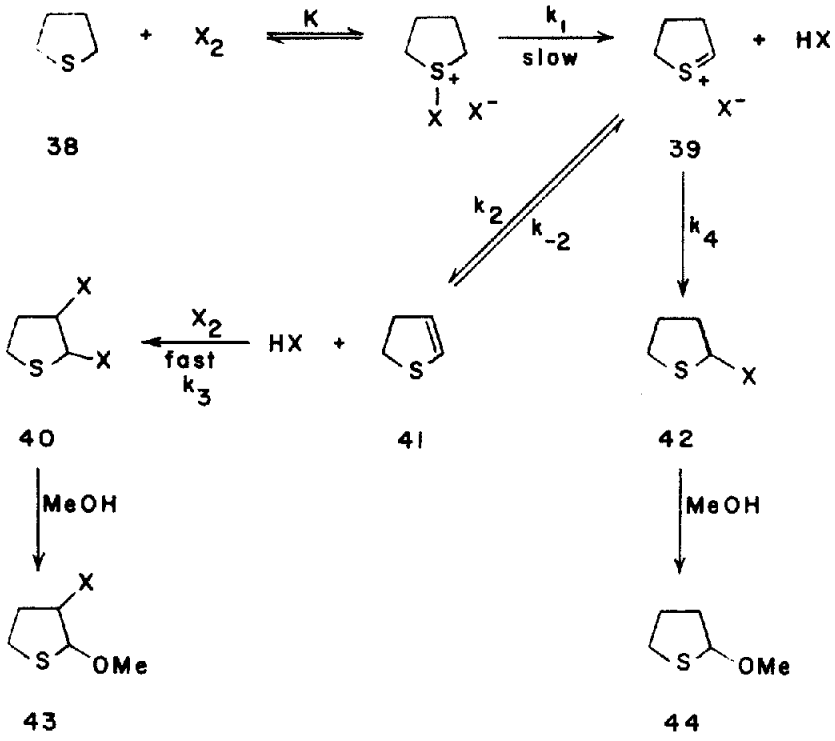


35 36



37

Details of the mechanism of the Pummerer rearrangement of halosulfonium salts have e slowly and from a variety of laboratories. Much of the early mechanistic work was doi N-chlorosuccinimide, but this is presented later because of the ambiguity now associated v structure of the reactive intermediate. Of particular interest in the Pummerer reaction was proo intermediacy of a sulfocarbonium ion and establishment of the mode of elimination of HX to f The existence of a sulfocarbonium ion in the halogenation reaction of tetrahydrothiophe established by a careful study of the products as a function of reaction medium. The products reaction, trans-2,3-dichlorotetrahydrothiophene (**40**) and 2-chlorotetrahydrothiophene (**41**), quan the stable methoxy derivatives **43** and **44**, arise by halogen trapping of a vinyl sulfide (**41**) and the Pummerer reaction respectively. Under the reaction conditions neither product-forming st reversible.



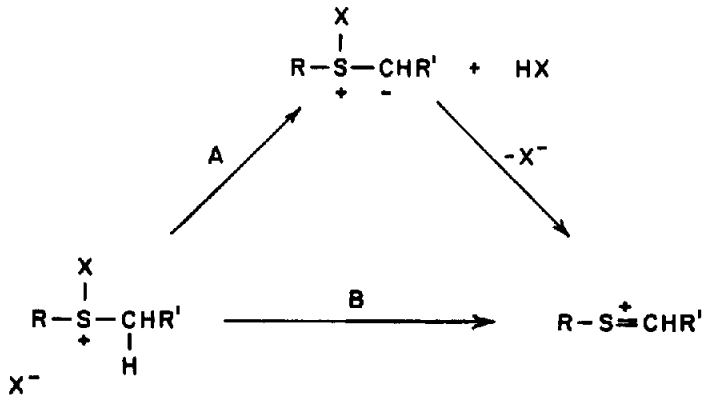
Scheme 3.

Table 3. Medium effects on the chlorination of tetrahydrothiophene

Added Reagent	Solvent	42/41
None	CCl_4	18.3
	PhH	14.5
	CH_2Cl_2	2.5
	$PhNO_2$	1.4
	CH_3CN	0.5
	CH_3NO_2	0.5
HCl	CH_2Cl_2	>80.
Lutidinium chloride		>80.
CF_3COOH		0.3
TsOH		0.3
BF_3		0.2

The demonstrated irreversibility of the steps to form **40** and **42** was exploited to gain insight into the mechanism (Scheme 3). Thus, conducting the reaction in polar solvents, which stabilize **39**, and addition of the common ion, increased the ratio **44**/**43** (Table 3). However, reagents such as toluenesulfonic acid, boron trifluoride, and trifluoroacetic acid, which reduce the halide ion concentration either by complexation with chloride ion to form a non-basic, non-nucleophilic counterion or by protonating it, directed the reaction toward the dihalogenated product (**40**).

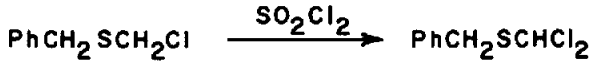
Sulfocarbonium ion generation from a halosulfonium ion could take place by either the ylid route (A) or the direct elimination route (B) of Scheme 4. Efforts to demonstrate the mode of HX elimination have centered on the regioselectivity of the Pummerer reaction and the kinetic isotope effects. The



Scheme 4.

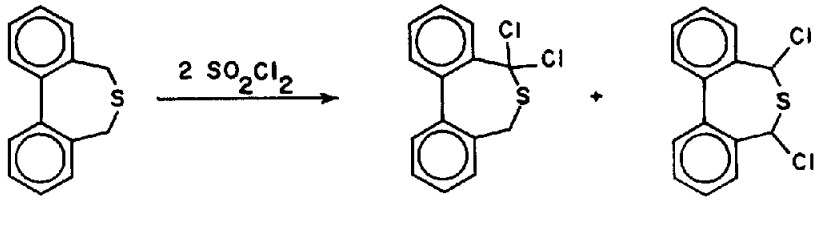
regioselectivity studies, which are the result of contributions from many laboratories over the course of thirty years, are summarized in Table 4.

Regioselectivity in the Pummerer reaction was observed early by Truce *et al.*[71] in their careful, classic study of the chlorination of dimethyl sulfide with sulfuryl chloride. These workers found a continuous progression from a predominance of monochlorodimethylsulfide over more highly chlorinated dimethylsulfides to exclusive production of hexachlorodimethylsulfide as the amount of chlorinating agent was increased. A particular characteristic of the reaction was trichlorination of one carbon atom prior to chlorination of the second. The chlorination rate was found to vary inversely with the degree of chlorination. Further chlorination of the halogenated carbon atom also occurs with benzyl chloromethyl sulfide (**45**) to produce benzyl dichloromethyl sulfide (**46**).[89] Although dichlorination of dibenzyl sulfide



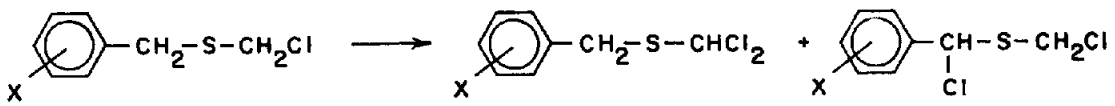
45 **46**

produces only the asymmetric product, the dichlorination of **47** gives a mixture of α,α-dichlorosulfide **48** and α,α'-dichlorosulfide **49** in 3.6:1 ratio.[90] A careful study of the chlorination of a series of substituted



3.6 1

47 **48** **49**



X = p-F, p-Cl, m-CF_3, p-NO_2

50 **51** **52**

Table 4. Regioselectivity for a-halogenation of sulfides.

$RR'CH\text{-}S\text{-}CH_2R' \longrightarrow RR'C(Cl)\text{-}S\text{-}CH_2R'' + RR'CH\text{-}S\text{-}CHR''(Cl)$ (α α)

R	R'	R''	Reagent	k/k α α	Reference
CH_3	H	H	NCS	5.1	55
CH_3CH_2	H	H		5.5	55
CH_3	CH_3	H		30	55
CH_3	CH_3	CH_3		4.8	55
Cl	H	CH_3		25	55
CH_3	CH_3	Cl		4.0	55
Ph	H	CH_3		5.6	55
CN	H	CH		>50	55
Ph	H	p-$MeOC_6H_4$		.51	73
Ph	H	p-MeC_6H_4		.75	73
Ph	H	m-MeC_6H_4		.91	73
Ph	H	p-ClC_6H_4		1.6	73
Ph	H	m-FC_6H_4		2.1	73
p-ClC_6H_4	H	p-NCC_6H_4		3.0	73
p-ClC_6H_4	H	m-$O_2NC_6H_4$		3.5	73
p-ClC_6H_4	H	p-$O_2NC_6H_4$		4.4	73
Ph	H	CH_3	SO_2Cl_2	b	84
Cl	Cl	Cl		.02	84
Cl	Cl	CH_3		c	84
EtOOC	H	H		b	85
CN	H	Ph		b	85
$PhSO_2$	H	Ph		b	85
CH_3SO_2	H	Ph		b	86
CH_3SO_2	Cl	Ph		b	86
Ph	H	H		b	87
ClC_6H_4	H	Ph		1.63	87
Cl	H	Ph		b	87
---- C_5H_{10} ----		Cl		c	87
FC_6H_4	H	Cl		c	87
ClC_6H_4	H	Cl		c	87
$F_3CC_6H_4$	H	Cl		c	87
$O_2NC_6H_4$	H	Cl		1.5	87
$O_2NC_6H_4$	Cl	Cl		b	87
Cl	Cl	$O_2NC_6H_4$		b	87
CH_3	H	CH_3SO_2	Cl_2	c	88
CH_3	Cl	CH_3SO_2		c	88

[a] Relative rate per hydrogen atom.

[b] Only a-substitution was observed.

[c] Only α'-substitution was observed.

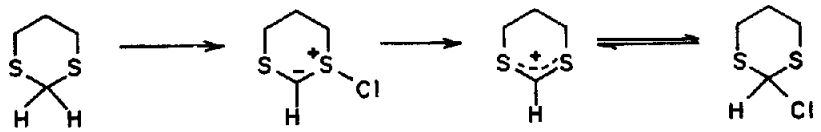
benzyl chloromethyl sulfides **50**[87] showed selective chlorination of the chloromethyl group except for the case of the p-nitro derivative for which a 1.5:1 ratio of the α,α-dichlorosulfide (**51**) to α,α'-dichlorosulfide (**52**) was obtained.

The preferential loss of a benzylic proton, which was considered to be the most acidic proton of the benzyl chloromethyl sulfide, led Paquette[87] to conclude that α-chlorination probably proceeded via an ylide intermediate in which the kinetically most acidic proton is abstracted. However, recent work of Ahren *et al.*[88] has demonstrated that the base-catalyzed exchange rate of the methylene proton of benzyl methyl sulfone is about twice that for the methylene proton of methyl chloromethyl sulfone and

considerably greater than that for methyl proton exchange. The exchange of benzylic protons p-nitrobenzyl methyl sulfone is, however, much faster than that of the chloromethyl protons. Thus, if ylide mechanism of proton removal were operative, one would expect that, contrary to the observati the ratio **51/52** would be higher for $X = NO_2$ than for the other substituents.

Direct observation of the ylide **54**, derived from chlorination of **53** with sulfuryl chloride, v claimed[91] based upon a 6.90 ppm proton chemical shift assigned to the proton on C-2 of **54**; however, t chemical shift is not consistent with those of known sulfur ylides, and may be an averaged shift arising fr a rapid equilibrium between **55** and **56**.[84]

Presently the ylide route to the sulfocarbonium ion from chlorosulfonium salts is considered unlik in view of the near maximum competitive isotope effect for proton removal in α-chlorinations (see Ta 5), the absence of proton exchange in the chlorination of sulfides such as **57–59** where the ylide should resonance stabilized,[85] the arguments against the kinetic acidity hypotheses, and a failure to demonstr the α-proton exchange expected for an ylide.

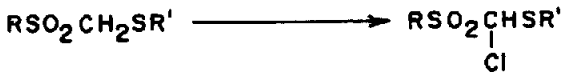


53 54 55 56

57

a R = Cl

b R = EtO



58

	R	R'	Ref.
a	Ph	CH_2Ph	85
b	Me	CH_2Ph	85, 86
c	Me	$CHPh_2$	86
d	Me	CPh_3	86

59

At this point, the curious fact remains that in a simple product controlling step the α-carbon atc a chlorosulfonium salt, supposedly quite adept at supporting negative charge, becomes a some positively charged sulfocarbonium ion. This suggests that one of the basic concepts is in error.

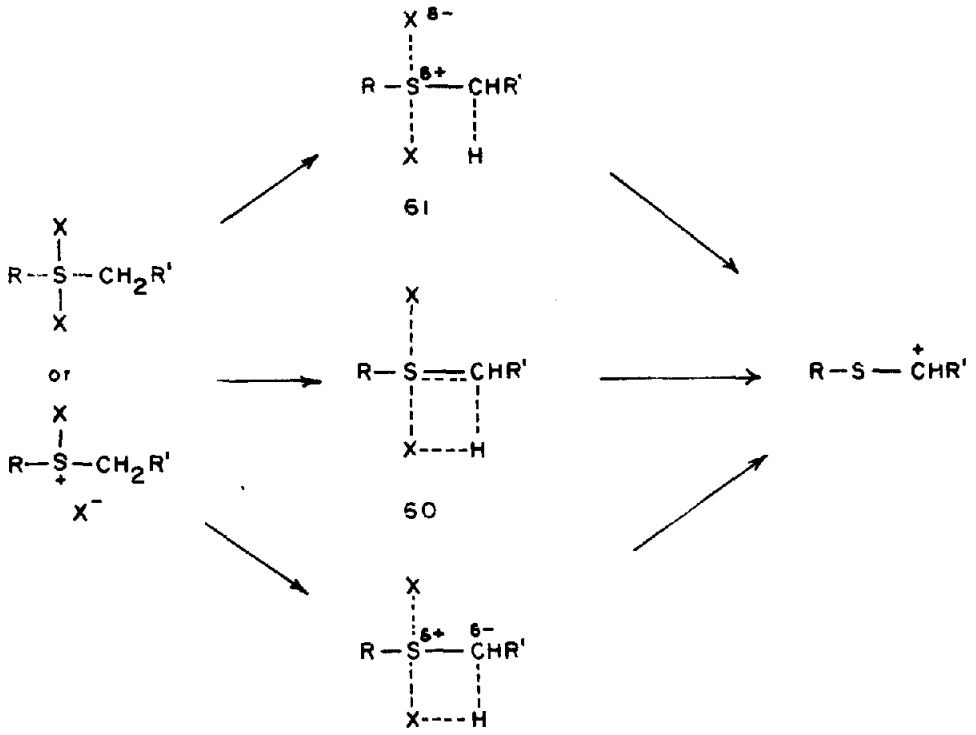
As previously noted, Ahrens *et al.*[88] refuted the hypothesis of substitution at the kinetically most acidic position of the benzyl chloromethyl chlorosulfonium salts, the basis for many of the mechanistic interpretations, arguing it to be inconsistent with their data for kinetic acidity of similar protons adjacent to a sulfone with the proviso that the acidifying effect of a sulfone group is satisfactorily analogous to that of the chlorosulfonium ion. Their data predict that only the benzylic carbon of p-nitrobenzyl chloromethyl sulfide should be chlorinated and that the benzyl and chloromethyl groups should be competitive in each of the other benzyl chloromethyl sulfides studied by Paquette.[87] Based upon recent SCF-MO calculations[92] on CH_2SH^+ and CH_2OH^+, which show a higher proportion of positive charge on sulfur than on oxygen and a substantially larger π-bond order for protonated thioformaldehyde, they propose that selectivity in removal of a proton from either the α- or α'-carbon atom will be determined by the electronegativity of the attached substituents so as to maximize electron transfer from sulfur to carbon in an E2 transition state. Although this rule is claimed to predict qualitatively the regioselectivity in every case known, the number of cases is small and the transformation from one direction of chlorination to the other seems to take place over a small portion of the range of electronegativity differences.

A detailed proposal for the mechanisms of sulfocarbonium ion formation consistent with available data for chlorosulfonium chlorides, bromosulfonium bromides, and the presumed succinimidyl sulfonium chlorides and bromides from NCS or NBS treatment of sulfides has been advanced.[76] This scheme (Scheme 4) involves simultaneous bond formation of an attacking anion to the sulfonium sulfur and to the α-hydrogen atom. The E2S transition state upon which this proposed mechanism was based is analogous to the central transition state in the variable E2 transition state theory; and in the case of a halosulfonium salt, such a central transition state (**60**) may be considered to possess the geometry of a sulfurane in which S–X bond making is about equally advanced as S–X bond breaking and in which an H–X bond is simultaneously being formed. The E1-like extreme of this variable transition state (**61**) has cleavage of the S–X bond more advanced than H–X bond rupture. The ElcB extreme (62) is characterized by H–X bond making more nearly complete than scission of the S–X bond to the other halogen atom thereby leading to an ylide-like transition state. An attractive characteristic of this interpretation is that the sulfocarbonium ion formation can be looked at as a branch point in the normally rapid sulfonium salt exchange process. Weakly basic anions which form relatively strong S–X bonds would be expected to react through central transition states (**60**) leading to rapid exchange accompanying the Pummerer rearrangement. This should include the chloro- and fluorosulfonium salts since both of these form stable sulfuranes. On the other hand, strongly basic anions would tend to abstract a proton thus favoring the ElcB extreme.

The competitive kinetic isotope effect should be high for the relatively central transition state (**60**) and unity for the other two extremes. The value of ρ for an intramolecular competitive α-halogenation is expected to be small and positive or small and negative for the central mechanism, large and positive for an ylide mechanism, and strongly negative for the E1 extreme. These trends are indeed observed (Table 5). The observed isotope effects (Table 5) eliminate the extreme transition states as possibilities in the Pummerer rearrangement of halosulfonium halides; however, the relative magnitudes of these effects for chlorination and bromination can be rationalized with the proposed theory. Because the sulfur atom of a halosulfonium salt should be moderately hard in anology with the sulfur atom of sulfinyl and sulfonyl

Table 5. Competitive kinetic isotope effects in the halogenation of sulfides

Sulfide	Solvent	Reagent	k_H/k_D	Reference
THT	CCl_4	Cl_2	5.1	76
	CCl_4	Br_2	3.6	76
$PhCD_2SCH_2Ph$	CCl_4	Cl_2	6.55	78
	$CDCl_3$	Cl_2	4.62	78
	CCl_4	Br_2	2.59	78
	$CDCl_3$	Br_2	2.11	78
PhCHO-S-Ph	CCl_4	NCS	5.7	72
	$CDCl_3$	NCS	5.9	72
	CCl_4	NBS	4.23	72
	$CDCl_3$	NBS	3.14	72

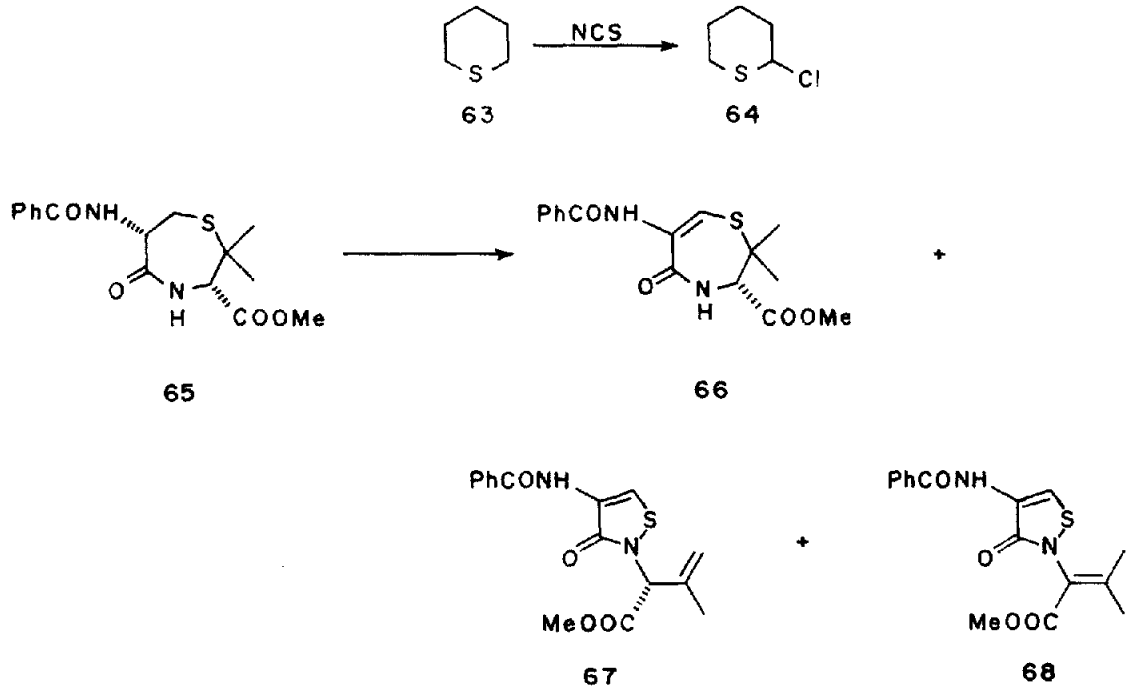


derivatives[93,94] bonding to chlorine should be stronger than bonding to the softer bromine. Similarly, chlorine should associate with the α-proton more easily. Thus, bromination should tend toward the El extreme transition state (**61**).

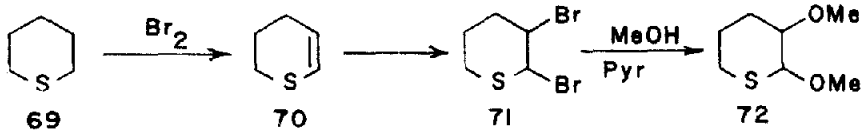
All linear free energy studies of α-halogenations have employed NCS. In view of the identification of N-succinimidyl dimethylsulfonium chloride (**22**) as the crystalline product from the reaction of NCS with dimethyl sulfide,[48] mechanistic conclusions based upon these outdated data are risky. Additionally, values of ρ for intermolecular competition such as that for NCS chlorination of phenyl benzyl sulfides (-0.8)[72] may reflect substituent effects on the halogen-halosulfonium salt equilibrium as well as on the elimination step. NCS chlorination of dibenzyl sulfides and benzyl isopropyl sulfides gave intermolecular competitive ρ values of 1.05[73] and 1.1[55] respectively. Unfortunately, no Hammett σ–ρ data is available for halogenations with sulfuryl chloride or chlorine.

Other factors being equal, a preference for removal of the most acidic proton may be expected; however, a high sensitivity of regioselectivity to steric effects in the separate halves of the molecule may also be expected.[76] High selectivity for deprotonation of sulfoxides has been observed and might be considered a model for proton removal from halosulfonium salts; however, for sulfoxides the selectivity appears to be due in part to complexation with the cations.[95] If stereoelectronic effects are important for the proton removal step in the Pummerer reaction, attention will have to be paid to the factors which determine rotameric preferences around the S–C bond in the sulfonium salts and/or sulfuranes. The α-chlorination preference methyl < ethyl n-propyl < isopropyl observed for the NCS chlorination reaction[55] may be an example of stereoelectronic control of regioselectivity. Both halogenating reagent and reaction temperature affect the regioselectivity of proton abstraction from methyl ethyl sulfide.[55] The ethyl : methyl substitution ratio decreased from 3.4 to 2.8 for SO_2Cl_2 chlorination and from 4.9 to 2.7 for the NCS reaction over a temperature range of 4–40°.

Sulfides bearing β-hydrogen atoms may undergo elimination under the reaction conditions to give α,β-unsaturated sulfides which may undergo further reactions leading to α,β-dihalosulfides. These reactions exhibit a solvent dependence (Table 3) with α,β-dihalogenated product formation favored in more polar solvents. For example, halogenation of tetrahydrothiophene with sulfuryl chloride[45,67] and with molecular chlorine or bromine[30,76] gives trans-2,3-dihalotetrahydrothiophene (**40**) in addition to the α-halosulfide; however, chlorination of both tetrahydrothiophene (**38**) and thiane **63** with NCS could be controlled to give only the α-substitution products **42** and **64**.[45,96] The chlorination of **65** gave a complex

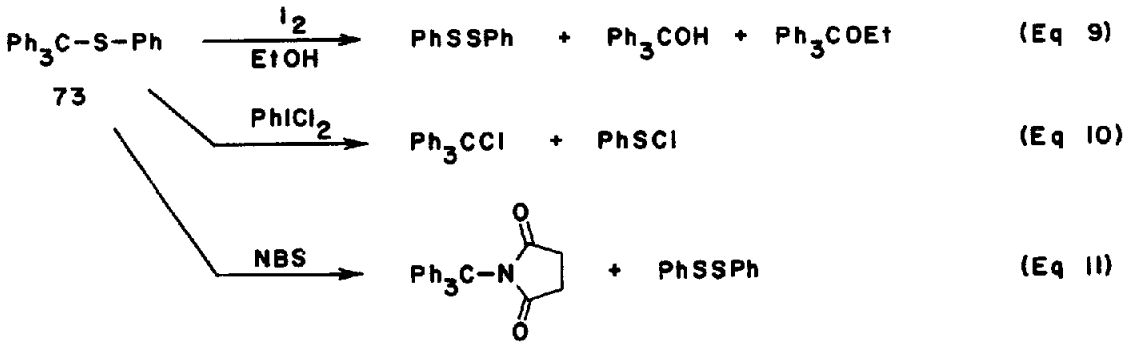


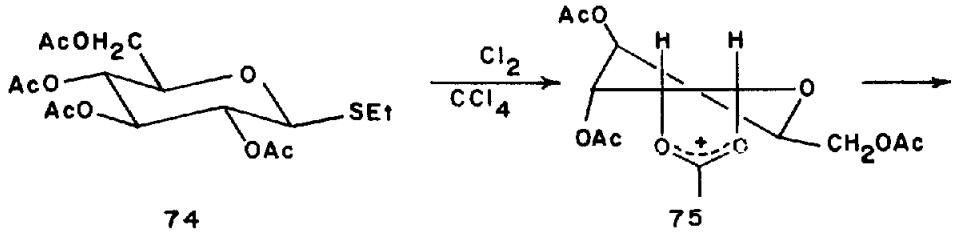
mixture of products, **66–68**, the latter two of which are derived from the α,β-unsaturated product **66**.[97,98] The chlorination of thiane with sulfuryl chloride is reported to provide a product believed to be 2-thiene **70**,[67] but thermal decomposition of the bromosulfonium salt of thiane in refluxing carbon tetrachloride followed by methanol–pyridine treatment yielded equal amounts of thiane and trans-2,3-dimethoxythiane **72**.[99] This observation, like that for tetrahydrothiophene halogenation,[30] is consistent with bromination of the intermediate 2-thiene **70** by either the intermediate bromosulfonium salt or free halogen available from it.



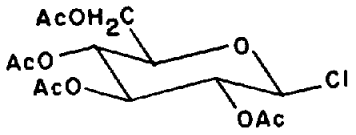
5. CARBON-SULFUR BOND CLEAVAGE REACTIONS

Carbon–sulfur bond cleavage is a major pathway of halosulfonium salt reaction competitive with, and sometimes dominant over, the Pummerer rearrangement. When the salt is a bromosulfonium salt or when the α-carbon can support a positive charge, the cleavage reaction is favored. Phenyl trityl sulfide **73** reacts with iodine in ethanol to produce a mixture of diphenyl disulfide, trityl alcohol, and ethyl trityl ether (eqn 9),[100] but cleavage is found with other electrophilic reagents such as HBr, $AlBr_3$ and $AgNO_3$. The cleavage of phenyl trityl sulfide in inert solvent is also effected by phenyl-iodosyl dichloride to produce trityl chloride and phenylsulfenyl chloride (eqn 10).[101] Reaction of **73** with NBS leads to N-tritylsuccinimide and phenyl disulfide (eqn 11), presumably by way of an intermediate sulfenyl bromide. When a neighboring acyl group can aid in displacement of the sulfenyl chloride, the cleavage is stereospecific. Halogenation of aryl-[102,103] and alkythioglucosides[104,105] such as **74** with chlorine in CCl_4[104,105] or bromine in acetic acid[102,103] leads to the 1-haloglucoside **76** probably via stabilized carbocation **75**. It is tempting to conclude that C–S bond rupture of a halosulfonium salt is unimolecular and produces the most stable carbocation; however, such is not always the case. Chlorination or bromination of thietane **77** in chloroform leads to **78**[106,67] and halogenation of substituted thiiranes (**79**) produced mixtures of products **80** and **81** most consistent with dominant bimolecular displacement of a sulfenyl chloride from the halosulfonium intermediate.[107,108]

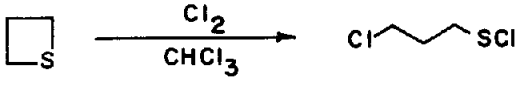




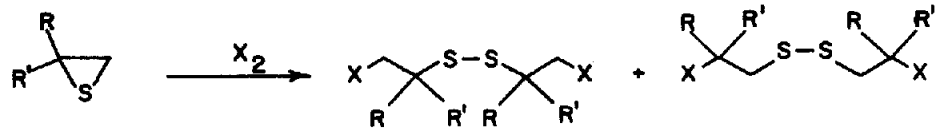
74 75



76



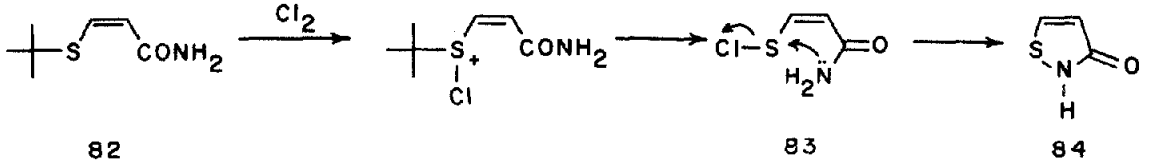
77 78



79 80 81

R	R'	X	80:81
Me	H	Cl	55:45
		Br	62:38
Me	Me	Cl	40:60
$ClCH_2$	H	Cl	85:15

Retention of optical activity in the chlorine-promoted rearrangement of the 1,4-thiazepine **65** to the 3-isothiazolones **67** and **68** observed by Leonard and Wilson[97,98] is also inconsistent with the intermediacy of a carbocation. The facts that **67** retained its optical activity and that it was isomerized to **68** by triethylamine argue for a stereoselective proton removal in the rearrangement. Chlorination of **66**, which

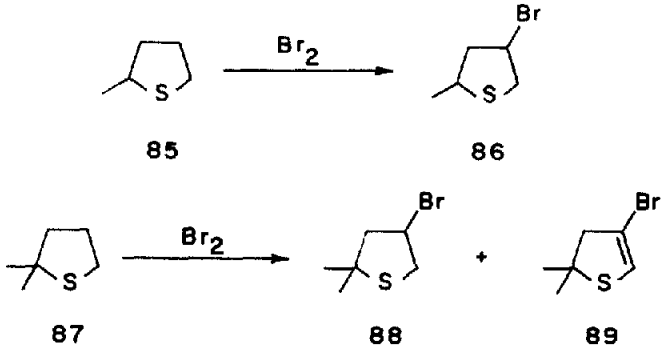


82 83 84

Scheme 5.

certainly arises by way of Pummerer rearrangement, provides the isothiazolone. To demonstrate generality of the isothiazolone synthesis, the parent ring **84** was obtained from sulfide **82** by chlorination, possibly by the mechanism shown in Scheme 5[97,98] in which sulfonium salt fragmentation is followed by nucleophilic attack of the amide nitrogen atom on the sulfenyl chloride **83**.

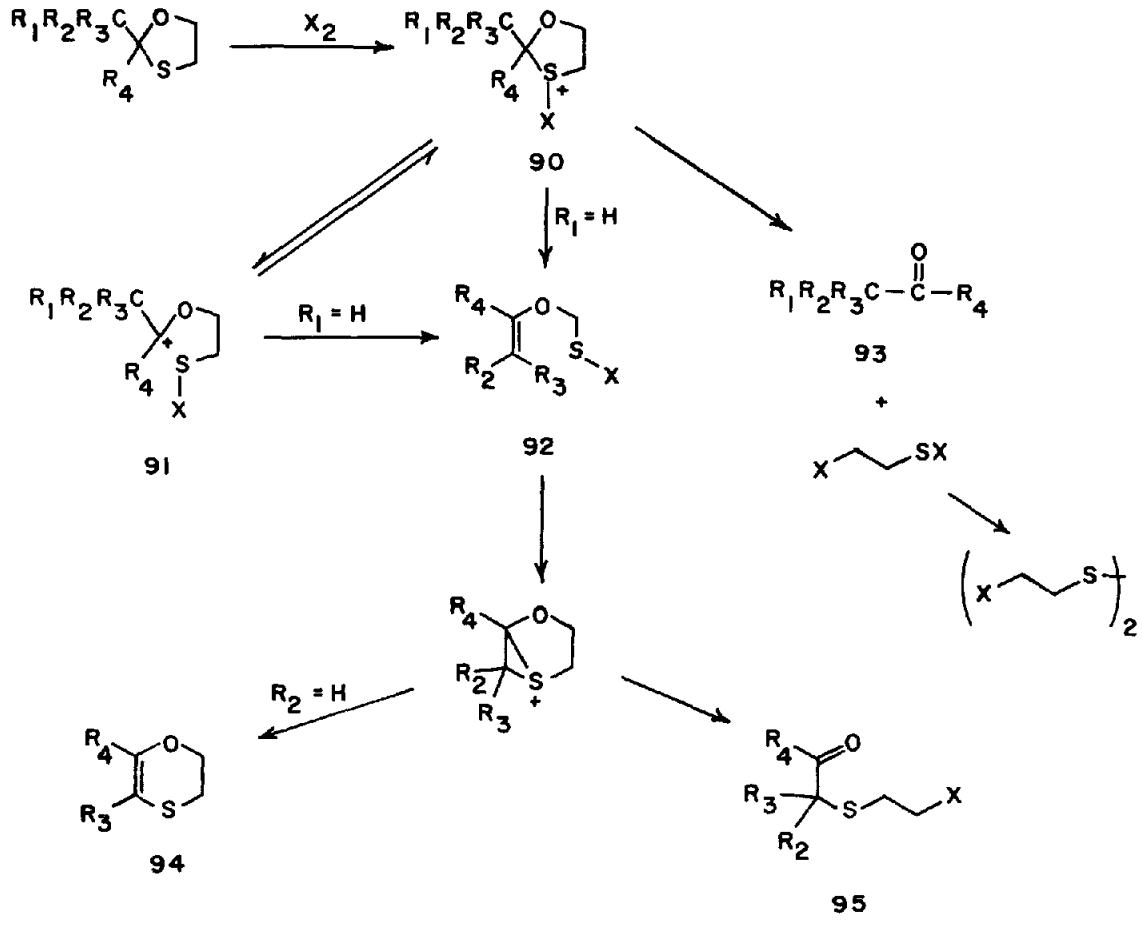
Enhancement of the probability of carbon–sulfur cleavage in halosulfonium salts of the tetrahydrothiophene system by α-methylation was expected because of the increased stability of the carbocation; however, bromination of **85** led to previously unobserved β-halogenation giving 4-bromo-2-methyltetrahydrothiophene (**86**).[99] Bromination of the α,α-dimethyl derivative (**87**) with one equivalent of bromine produced equal amounts of the two brominated products **88** and **89** in addition to an equal amount of recovered **87**.[99]



85 86 87 88 89

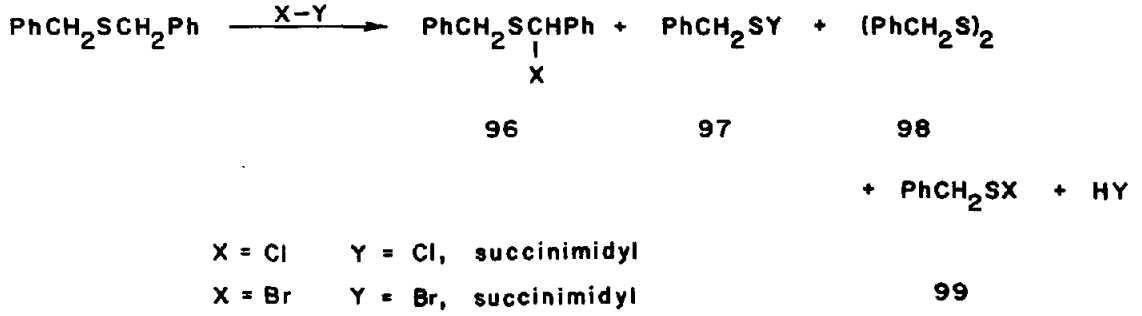
Studies of the chlorination and bromination of 1,3-oxathiolanes have increased our understanding of structural and electronic effects on the cleavage of carbon-sulfur bonds in halosulfonium salts.[109,110] The reactions may be summarized by the steps shown in Scheme 6. Oxathiolanes with no protons on either substituent at C-2 undergo simple halogen-induced cleavage to the ketone and β-haloethylsulfenyl halide which may dimerize to the disulfide. For 2,2-diphenyl-1,3-oxathiolane this reaction is quantitative. Oxathiolanes with at least one α-proton on a C-2 substituent rearrange to 1,4-oxathienes or to α-haloethylthioketones. The effect of structure on the distribution between the latter two products provide evidence that even in this case the carbon–sulfur bond cleavage is probably bimolecular. If partitioning of **90** between ketone and rearranged products occurred by way of oxocarbonium ion **91**, the ratio of ketone to rearranged products **93**/(**94** + **95**) should be relatively insensitive to the substituents at C-2 because the substituents should have only an indirect effect on carbocation stability. Although this was found to be true for bromination of a number of oxathiolanes derived from cyclic ketones which gave about equal amounts of ketone and rearranged products, the product ratios from oxathiolanes of a series of cyclic ketones demonstrated the existence of a ring size effect with the oxathiolane from cycloheptanone providing only cycloheptanone and those from cyclohexanone, cyclopentanone, and cyclooctanone providing predominately rearranged products. If carbocation **91** were formed as an intermediate, the product ratio **93**/(**94** + **95**) should be higher for the oxathiolane of cyclopentanone rather than for that of cyclohexanone as observed. This supports the theory that sulfenyl halide elimination proceeds in a concerted manner from **90**.

Aspects of the α-substitution-cleavage competition of halosulfonium salts in inert solvents have been extensively investigated using benzyl sulfides (Scheme 7 and Table 2).[78] Bromination of dibenzyl sulfide with NBS or molecular bromine favored cleavage products **97**–**99**, and the percent cleavage increased slightly with solvent polarity. The ratio of cleavage products to α-substitution product, studied as a function of bromosulfonium salt concentration, was nearly constant to about 0.35M after which it



Scheme 6.

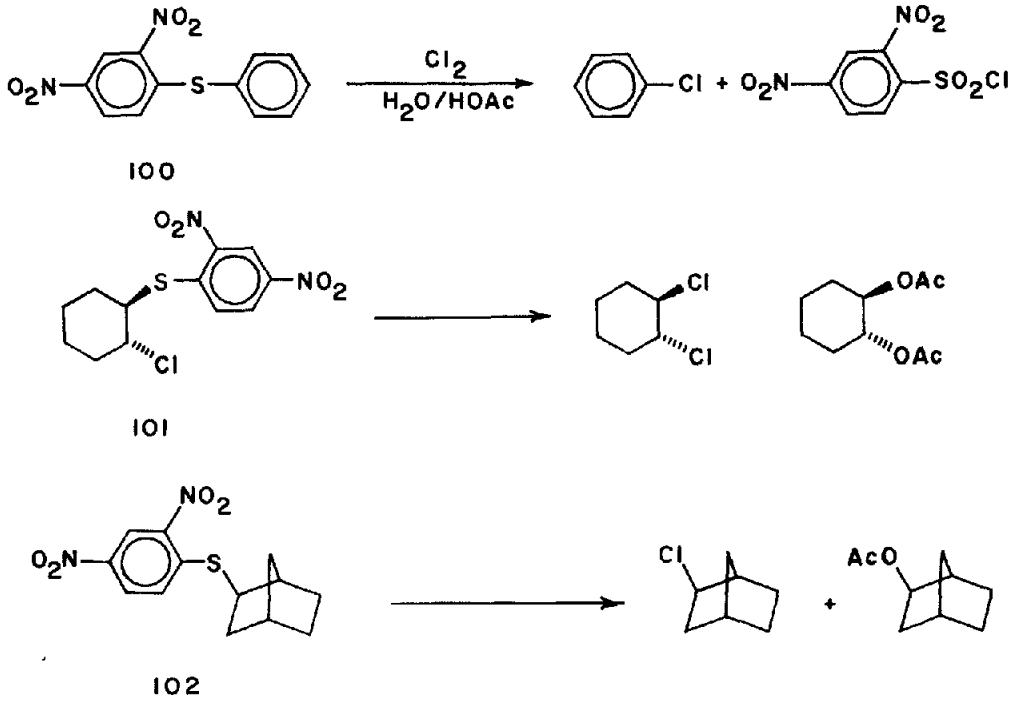
increased sharply. Such behavior might be expected if the halosulfonium salt aggregated at higher concentration and if the decomposition of the aggregates favored cleavage.



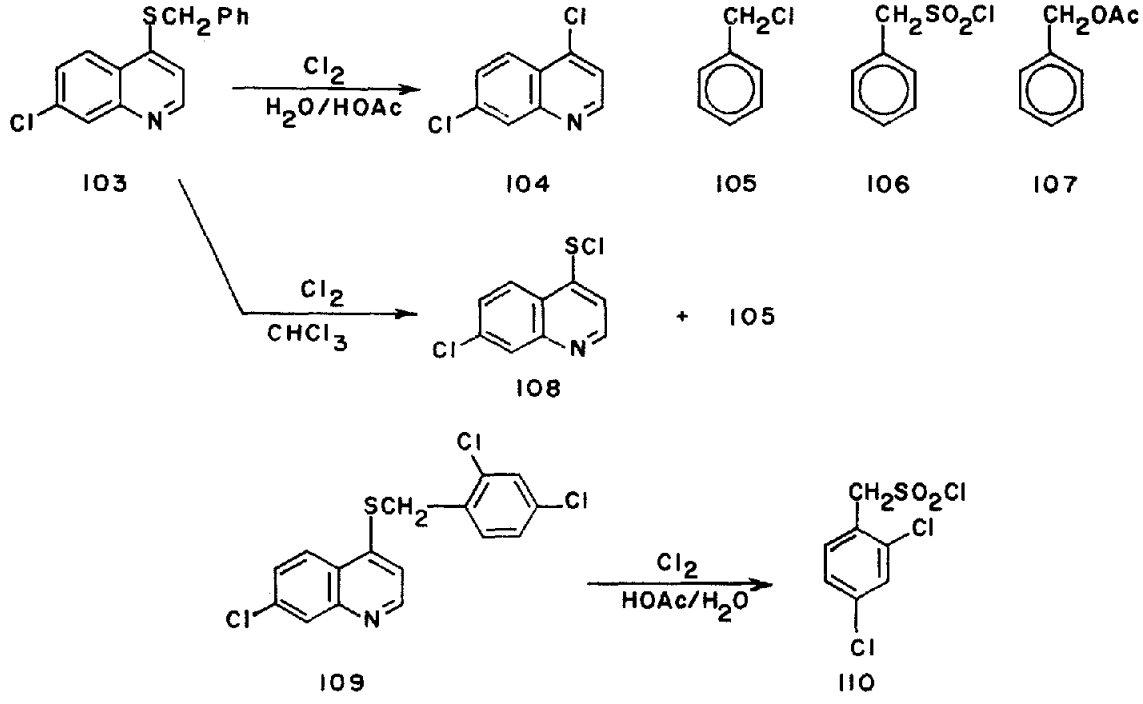
Scheme 7.

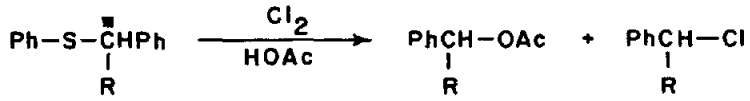
Chlorinolysis of carbon–sulfur bonds is favored in acetic acid–water with the sulfur moiety being further oxidized to a sulfonyl chloride or sulfate ion. Thus, **100**, **101** and **102** are all converted into the halide or acetate with the same relative stereochemistry.[111] These transformations are all considered to proceed by a unimolecular cleavage.

Chlorination of 4-benzylthio-7-chloroquinoline (**103**)[112] in acetic acid solution led to **104** and **105** in 91% and 47% yields respectively together with **106** (*ca.* 10%), a material inferred to be **107**, and sulfate ion. The facts that **106** was stable to the reaction conditions and that chlorination in dry chloroform led to sulfenyl chloride **108** suggests that cleavage occurs mainly to give the benzyl cation. On the other



hand, formation of *ca.* 10% of **106** from **103** and 17% of **110** from **109** indicate that destabilization of the benzyl cation can result in aryl-sulfur cleavage perhaps by an addition–elimination sequence[113,114] which occurs only when the sulfur atom is conjugated to an imine or a vinylogous imine. It is interesting, however, that simple displacement by an addition–elimination sequence on an aryl substrate activated to nucleophilic attack probably is not the operative mechanism because both phenyl 2,4-dinitrophenyl sulfide and phenyl 2,4,6-trinitrophenyl sulfide are stable to chlorine treatment in acetic acid.[113] Studies of the stereochemistry and kinetics of chlorinolysis on benzyl phenyl sulfides and α-ethylbenzyl phenyl sulfide in acetic acid were carried out by Kwart *et al.* (Scheme 8).[115,116] Net inversion of configuration

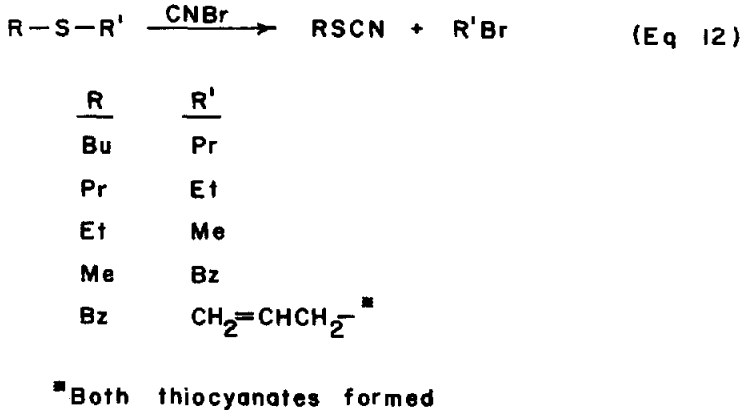




Scheme 8.

was observed for both benzyl acetate and benzyl chloride. Addition of lithium perchlorate to the medium led to a special salt effect increase of the reaction rate suggesting the presence of more than one reactive sulfonium ion-pair species. With added lithium chloride the rate increased linearly but slowly, and added chloride ion depressed the special salt effect of lithium perchlorate.[116] The product ratio of benzyl acetate to benzyl chloride paralleled the non-linear special salt affect as did the decline in optical purity of the inverted acetate. The optical purity of the inverted chloride tended linearly toward racemization with added lithium perchlorate, but increased slightly with added lithium chloride. Thus it is clear that the racemizations of the acetate and chloride products occur from completely different causes.[116] The unraveling of the mechanism behind these interesting observations is still at an early stage and would benefit from an increased understanding of the structure of chlorosulfonium salts in solvents such as acetic acid.

The pseudohalogen cyanogen bromide reacts with sulfides cleaving the carbon-sulfur bond to a thiocyanate and a halide (eqn 12).[117,118]



(Eq 12)

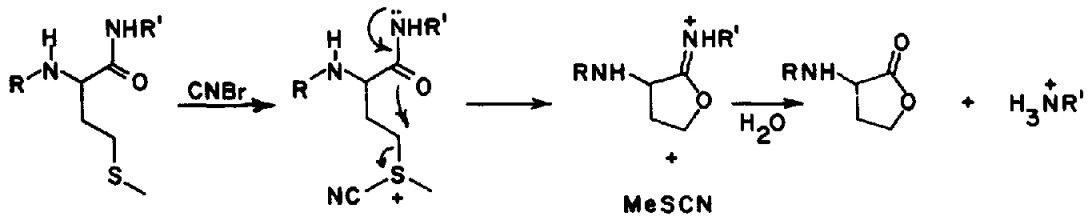
R	R'
Bu	Pr
Pr	Et
Et	Me
Me	Bz
Bz	$CH_2{=}CHCH_2{-}$ *

*Both thiocyanates formed

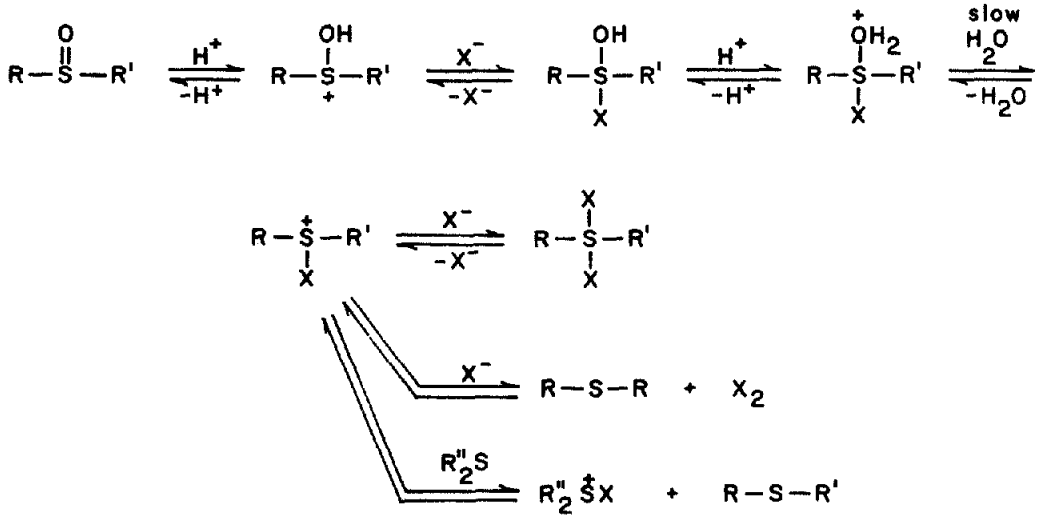
Reaction of cyanogen bromide with the methionine group of proteins leads to selective cleavage of the methionine amide bonds as shown in Scheme 9.[119] Since its first application on ribonuclease,[120] the method has found wide application.

6. REACTIONS OF SULFOXIDES VIA HALOSULFONIUM SALTS

Exposure of sulfoxides to halide ions in acid solution can lead to a variety of reactions including racemization at sulfur,[122–124,126] oxygen exchange,[122,123,127,128] and reduction of the sulfoxide group (Scheme 10; see, for example, references 63, 129–135) all involving an intermediate halosulfonium salt. The particular phenomenon observed depends upon the halide ion used and the reaction conditions. In 1964 Mislow *et al.* reported a specific hydrogen chloride catalyzed racemization of a number of p-tolylsulfoxides under mild conditions in aqueous dioxane.[123] In similar experiments they found



Scheme 9.

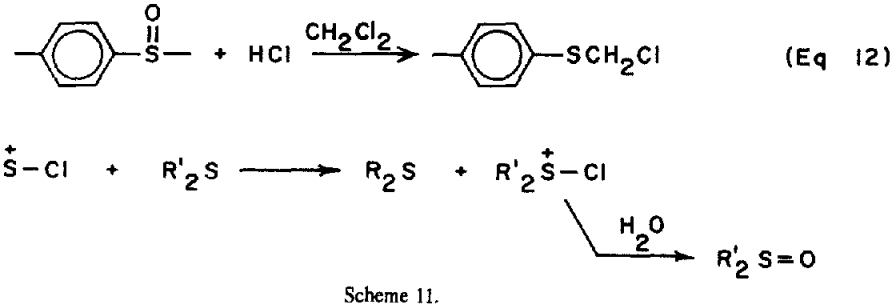


Scheme 10.

hydrogen fluoride to be an effective catalyst, and hydrogen bromide to induce sulfoxide decomposition with formation of bromine. This latter observation is probably evidence for sulfoxide reduction, but that was not reported. In the hydrogen chloride catalyzed racemization reaction, the rate of oxygen exchange was found to be equal to the rate of racemization, and the probable intermediacy of a halosulfonium salt was suggested. At about the same time the observation that sulfoxides could be reduced by iodide ion in acid solution[136] was being explored mechanistically.[129,134,137-142] These reductions are thought to occur by attack of iodide ion on the iodine atom of an iodosulfonium salt. The distinction between the course of this reaction and the hydrogen chloride catalyzed racemization may arise either because the iodosulfonium salt is more prone to attack by halide ion on the halogen atom than is the chlorosulfonium salt or because the sulfide, once formed by displacement on iodine, is incapable of reoxidation by the iodine.

In a reaction related to sulfoxide reduction, Krueger observed reduction of the dimethyl azasulfonium cation by iodide ion.[143] Similarly, hydrogen chloride catalyzed oxygen exchange between sulfoxides and sulfides[144,145] occurs probably via the halosulfonium salt as shown in Scheme 11.

The kinetics of these reactions are remarkably similar, and it is generally concluded that they all involve a rate-determining formation of a halosulfonium salt as shown in Scheme 10. Details of the complex dependence of the rates of these reactions on acidity have gradually emerged from several laboratories.[122,124,135,146] Essential to the unraveling of the story was the observation that sulfoxides are substantially protonated in the range of acid concentrations where suitable reaction rates are observed.[124] Thus substituent effects for the reduction of phenyl methyl sulfoxides by iodide ion in perchloric acid result from changes in sulfoxide basicity, not from changes in the reactivity of the protonated sulfoxide with respect to iodide ion.[124] This is also probably true for observed substituent effects on the rates of hydrogen chloride catalyzed oxygen exchange of phenyl methyl sulfoxides.[122] With respect to racemization and exchange of sulfoxide oxygen it is interesting that these reactions have been found to be catalyzed by a diverse set of acids including sulfuric acid at a number of concentrations, although hydrochloric acid is more effective than other mineral acids by a factor of at least 10.[122] For three of the acids studied, moderately concentrated sulfuric acid,[147] phosphoric acid,[148] and trichloroacetic acid,[149] a



Scheme 11.

111

sulfur radical cation **111** is probably involved. It is clear that one must be cautious in interpreting all hydrogen chloride catalyzed racemizations in terms of the mechanism shown in Scheme 11, for the reduction of thianthrene sulfoxide[112] with hydrogen chloride produces an intermediate which gives a five-line EPR spectrum characteristic of the thianthrene radical cation.[150]

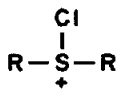
It is interesting that even in halocarbon solvents, the reaction of water with a chlorosulfonium salt must be faster than α-proton removal by the halide ion; for if water is removed from the reaction in which a sulfoxide is treated with hydrogen chloride, and if an α-hydrogen atom is present, the chlorosulfonium salt formed decomposes *via* the Pummerer pathway. Thus, Rynbrandt[63] observed that treatment of a number of sulfoxides with dry hydrogen chloride in methylene chloride using molecular sieves as a water trap led to the formation of α-halosulfides **32** in good yield.

7. SULFOXIDE FORMATION VIA HALOSULFONIUM SALTS

Sulfides can be oxidized to sulfoxides through the intermediacy of halosulfonium salts. Early work on this well-known halogen oxidation has been reviewed.[151,152] By appropriate choice of conditions one can control the reaction to eliminate most overoxidation to sulfones and the competing Pummerer reaction. For example, chlorination of dimethyl sulfide in aqueous hydrochloric acid was shown to produce a mixture of products including dimethyl sulfone, mesyl chloride, halogenated methanes, and formaldehyde when high chlorine/sulfide ratios were used but only DMSO when the ratio was 1:1 and $DMSO_2$ when the ratio was 2:1.[153] The recent work has centered on attempts to increase the selectivity of the oxidation using a variety of reagents and on efforts to establish the mechanisms of the oxidations.

Oae *et al.*[154] found that the complex of bromine with 1,4-diazabicyclo[2.2.2]octane could cleanly oxidize some sulfides to sulfoxides in 70% aqueous acetic acid without overoxidation. This reagent avoided the cleavage of dialkyl, aryl–alkyl, and alkyl–benzyl sulfides observed with NBS/methanol,[79] and aromatic ring bromination observed with molecular bromine. The authors also observed that incorporation of ^{18}O from $H_2{}^{18}O$ was virtually complete thus implying that scrambling of ^{18}O with the acetic acid is not important.

Oxidation of a variety of sulfides with t-butyl hypochlorite in methanol leads cleanly to sulfoxides.[154,155] Propargyl sulfides, however, were found to provide α-methoxysulfides.[155] Oxidation of diphenyl sulfide with equimolar quantities of t-butyl hypochlorite in dioxane containing two equivalents of $H_2{}^{18}O$ gave only sulfoxide in which 60% of the oxygen came from the water.[156] The possibility of ^{18}O incorporation by HCl-catalyzed exchange of the product sulfoxide was excluded by experiment. Oae *et al.* concluded that either the chlorosulfonium salt **112** or the mixed sulfurane **113** were the most likely intermediates.



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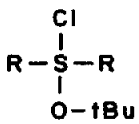


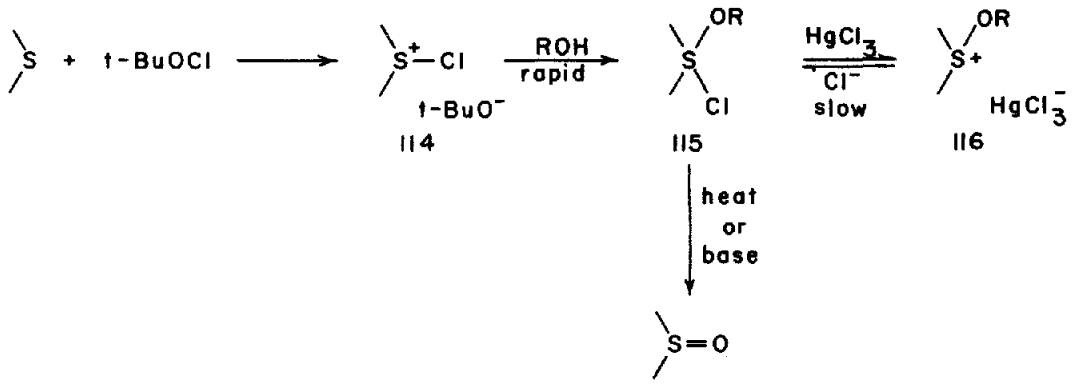
113

Johnson and Rigau[157] provided clever and convincing evidence for a tetrahedral intermediate in the reaction carried out in methylene chloride and formulated the reaction Scheme 12 below. The intermediacy of only **114** could be excluded because alkoxide interchange was not observed in the trapped trichloromercurate **116** in the absence of HCl to catalyze rapid exchange between **114** and **115**.

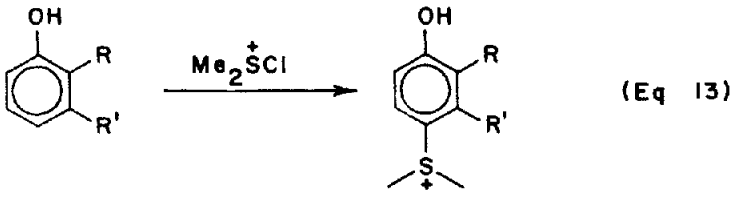
Detailed kinetic studies of the oxidation of sulfides by iodine[158–160] and by bromine[161] have been published but are outside the scope of this review.

8. MISCELLANEOUS REACTIONS OF HALOSULFONIUM SALTS

Halosulfonium salts may act as electrophiles, forming bonds at the sulfur atom. Additon to phenols occurs at the p-position if possible,[162–164] but o-substitution is observed when the p-position is blocked

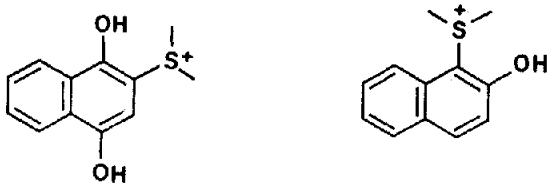


Scheme 12.



R = R' = H
R = H, R' = Me
R = Me, R' = H

(eqn 13). It is necessary to have a highly activated aromatic since neither anisole nor toluene react,[162] but both α- and β-naphthol react with the intermediate generated from NCS and dimethyl sulfide to provide **117** and **118** respectively.[165]



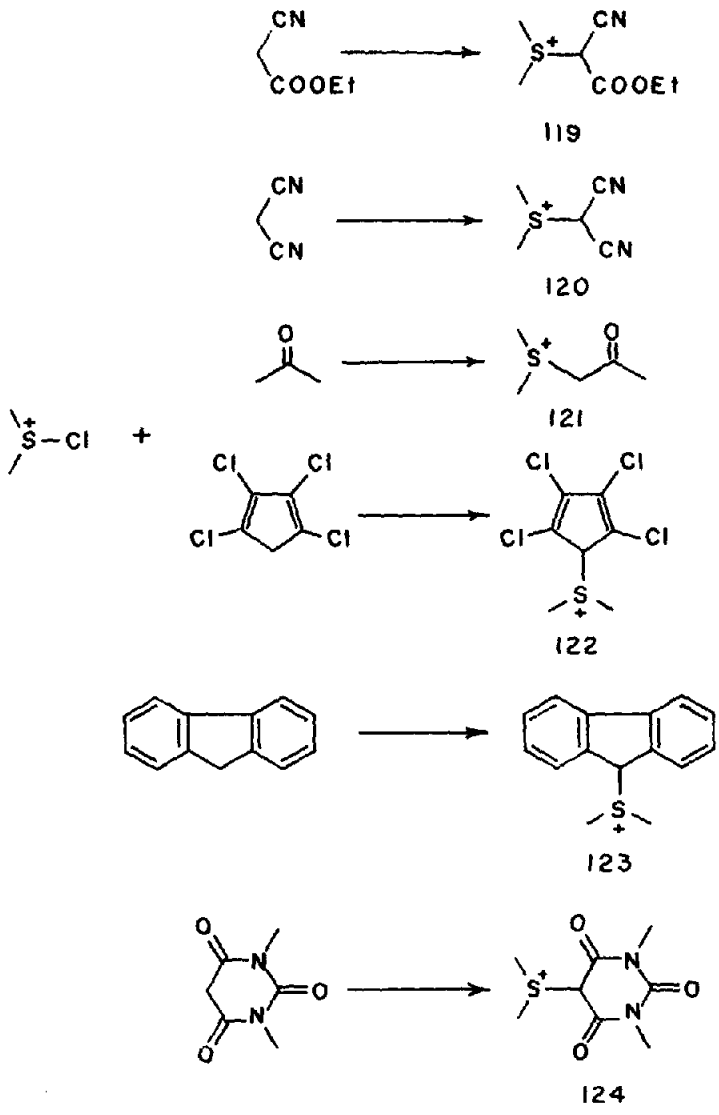
117 118

Chlorodimethylsulfonium hexachloroantimonate[164] and fluoborate[47] have been found to react with a number of substrates **119–124** by displacement on sulfur to produce sulfonium salts (Scheme 13).

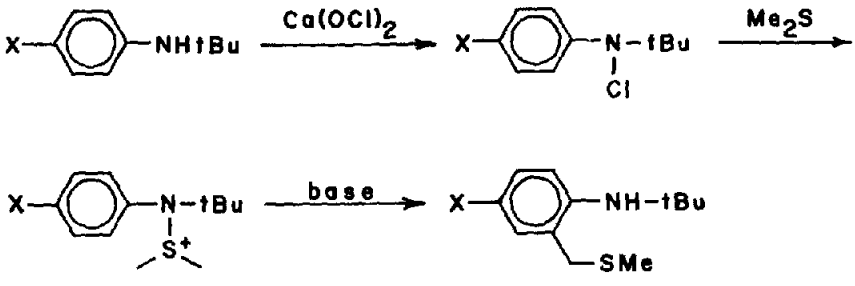
Halosulfonium salts are probably intermediates in a novel method for functionalization of the ortho-position of anilines.[166,167] The requisite intermediate azasulfonium salt can be generated by the reaction of an N-chloroamine with a sulfide[167] (Scheme 14) or by displacement of halide ion from a halosulfonium salt by an amine (Scheme 15). In both cases the azasulfonium salt undergoes a Stevens rearrangement to produce the product. This sequence has been used in an elegant synthesis of the indole nucleus[168] (Scheme 16).

Other recent efforts have been directed toward the use of halosulfonium salts for the selective oxidation of alcohols to aldehydes and ketones[169–171] and thiols to disulfides[172] under mild conditions. Particularly interesting in this regard is a polymeric reagent generated from p-methylmercaptostyrene.[173] These reactions rely on the intervention of the same alkoxysulfonium salt[171] generated in the familiar Moffatt oxidation of alcohols (Scheme 17).

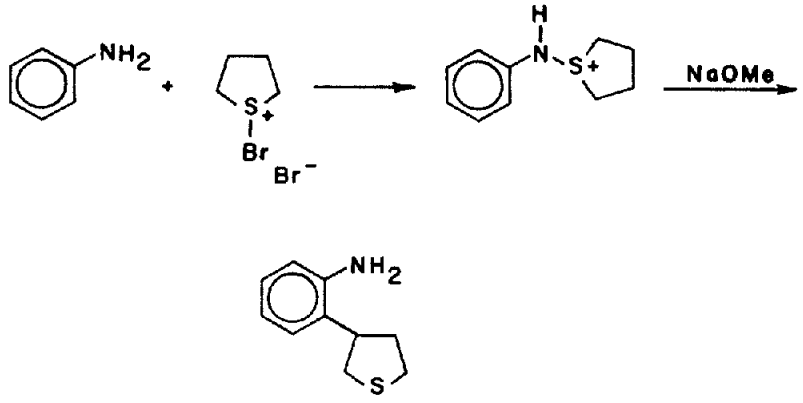
Epoxides and enamines can be oxidized by preformed halosulfonium salts to produce α-haloketones[174] (Scheme 18).



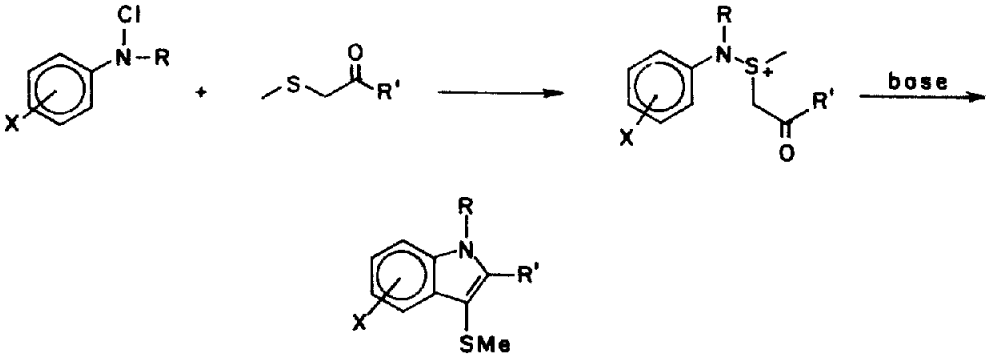
Scheme 13.



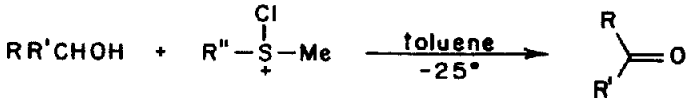
Scheme 14.



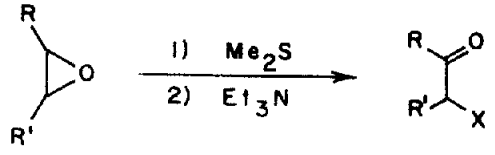
Scheme 15.



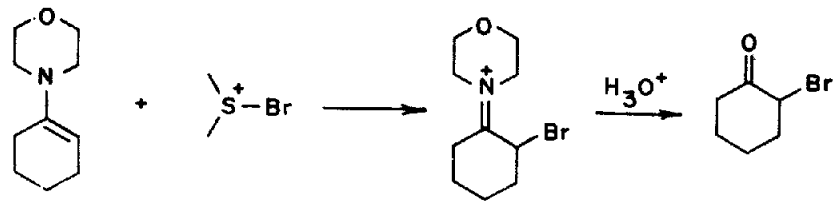
Scheme 16.



Scheme 17.



X = Br, Cl



Scheme 18.

REFERENCES

[1]G. E. Wilson, Jr and M. M. Y. Chang, *Tetrahedron Lett.* 875, (1971).
[2]G. E. Wilson, Jr and M. M. Y. Chang, *J. Am. Chem. Soc.* **96**, 7533 (1974).
[3]K. Kimura and S. H. Bauer, *J. Chem. Phys.* **39**, 3172 (1963).
[4]R. G. Stone, H. L. Tigelaar, and W. H. Flygare, *Ibid.* **53**, 3947 (1970).
[5]W. M. Tolles and W. D. Gwinn, *Ibid.* **36**, 1119 (1962).
[6]V. C. Ewing and L. E. Sutton, *Trans. Faraday Soc.* **59**, 1241 (1963).
[7]R. J. Gillespie, *J. Chem. Ed.* **40**, 295 (1963).
[8]R. J. Gillespie, *Angew. Chem. Int. Ed.* **6**, 819 (1967).
[9]W. G. Klemperer, J. K. Krieger, M. D. McCreary, E. L. Muetterties, D. D. Traficante and G. M. Whitesides, *J. Am. Chem. Soc.*, **97**, 7023 (1975).
[10]R. S. Berry, *J. Chem. Phys.* **32**, 933 (1960).
[11]W. A. Sheppard and D. W. Ovenall, *Org. Magn. Resonance* **4**, 695 (1972).
[12]P. Meakin, D. W. Ovenall, W. A. Sheppard and J. P. Jesson, *J. Am. Chem. Soc.* **97**, 522 (1975).
[13]D. G. Ibbott and A. F. Janzen, *Can. J. Chem.* **50**, 2428 (1972).
[14]G. C. Demitras and A. G. MacDiarmid, *Inorg. Chem.* **6**, 1903 (1967).
[15]S. P. Von Halasz and O. Glemser, *Chem. Ber.* **103**, 594 (1970).
[16]D. B. Denney, D. Z. Denney and Y. F. Hsu, *J. Am. Chem. Soc.* **95**, 4064 (1973).
[17]L. D. Martin, E. F. Perozzi and J. C. Martin, *Ibid.* **101**, 3595 (1979).
[18]C. Roemming, *Acta. Chem. Scand.* **14**, 2145 (1960).
[19]N. C. Baenziger, R. E. Buckles, R. J. Maner and T. D. Simpson, *J. Am. Chem. Soc.* **91**, 5749 (1969).
[20]G. Allegra, G. E. Wilson, Jr., E. Benedetti, C. Pedone and R. Albert, *J. Am. Chem. Soc.* **92**, 4002 (1970).
[21]K. C. Hodges, D. Schomburg, J. V. Wiess and R. Schmutzler, *Ibid.* **99**, 6096 (1977).
[22]I. C. Paul, J. C. Martin and E. F. Perozzi, *Ibid.* **94**, 5010 (1972).
[23]I. C. Paul, J. C. Martin and E. F. Perozzi, *Ibid.* **93**, 6674 (1971).
[24]E. F. Perozzi, J. C. Martin and I. C. Paul, *Ibid.* **96**, 6735 (1974).
[25]O. Ruff, *Chem. Ber.*, **37**, 4513 (1904).
[26]O. Ruff and G. Fisher, *Chem. Ber.* **36**, 418 (1903).
[27]A. J. Edwards, *J. Chem. Soc. Dalton*, 1723 (1978).
[28]I. B. Douglass, K. R. Brower and F. T. Martin, *J. Am. Chem. Soc.* **74**, 5770 (1952).
[29]K. R. Brower and I. B. Douglass, *Ibid.* **73**, 5787 (1951).
[30]G. E. Wilson, Jr. and R. Albert, *J. Org. Chem.* **38**, 2156 (1973).
[31]J. B. Lambert, *J. Am. Chem. Soc.* **89**, 1836 (1967).
[32]J. B. Lambert, *Accounts Chem. Res.* **4**, 87 (1971).
[33]J. B. Lambert, D. H. Johnson, R. G. Keske and C. E. Mixan, *J. Am. Chem. Soc.* **94**, 8172 (1972).
[34]J. D. McCullough and R. E. Marsh, *Acta Cryst.* **3**, 41 (1950).
[35]J. D. McCullough and G. Hamburger, *J. Am. Chem. Soc.* **63**, 803 (1941).
[36]L. Battelle, C. Knobler and J. D. McCullough, *Inorg. Chem.* **6**, 958 (1967).
[37]G. Y. Chao and J. D. McCullough, *Acta Cryst.* **13**, 727 (1960).
[38]E. L. Muetterties and W. D. Phillips, *J. Am. Chem. Soc.* **81**, 1084 (1959).
[39]F. A. Cotton, J. W. George and J. S. Waugh, *J. Chem. Phys.* **28**, 994 (1958).
[40]E. L. Muetterties and W. D. Phillips, *Ibid.* **46**, 2861 (1967).
[41]R. L. Redington and C. V. Berney, *Ibid.* **46**, 2862 (1967).
[42]R. A. Frey, R. L. Redington and A. L. K. Aljibury, *Ibid.* **54**, 344 (1971).
[43]J. A. Gibson, D. G. Ibbott and A. F. Janzen, *Can. J. Chem.* **51**, 3203 (1973).
[44]M. Zupan and B. Zajc, *J. Chem. Soc. Perkin I*, 965 (1978).
[45]C. G. Kruse, E. K. Poels, F. L. Jonkers and A. van der Gen, *J. Org. Chem.* **43**, 3548 (1978).
[46]H. Boehme and E. Boll, *Z. Anorg. Allgem. Chem.* **290**, 17 (1957).
[47]H. Meerwein, K. F. Zenner and R. Gipp, *Liebigs Ann.* **688**, 67 (1965).
[48]E. Vilsmaier and W. Spruegel, *Liebigs Ann.*, **747**, 151 (1971).
[49]M. A. Riche, *Ann. Chim. Phys.* **43**, 283 (1855).
[50]I. G. Arzamanova and E. N. Guryanova, *Akad. Nauk, SSSR*, **7**, 76 (1964).
[51]G. Barbieri, M. Cinquini, S. Colonna and F. Montanari, *J. Chem. Soc. C* 659 (1968).
[52]H. Richtzenhain and B. Alfredsson, *Chem. Ber.* **86**, 142 (1953).
[53]W. D. Kingsbury and C. R. Johnson, *J. Chem. Soc. D. Chem. Commun.*, 365 (1969).
[54]S. Oae, Y. Ohnishi, S. Kozuka and W. Tagaki, *Bull. Chem. Soc. (Japan)*, **39**, 364 (1966).
[55]D. L. Tuleen and T. B. Stephens, *J. Org. Chem.* **34**, 31 (1969).
[56]K. Hartke and E. Akguen, *Chem. Ber.* **112**, 2436 (1979).
[57]R. A. Olofson and D. W. Hansen, Jr. *Tetrahedron* **27**, 4209 (1971).
[58]J. von Braun and P. Engelbertz, *Chem. Ber.* **56**, 1573 (1923).
[59]E. Gross and B. Witkop, *J. Am. Chem. Soc.* **83**, 1510 (1961).
[60]R. G. Hiskey and D. N. Harpp, *Ibid.* **87**, 3965 (1965).
[61]R. Pummerer, *Ber.* **42**, 2282 (1909).
[62]C. R. Johnson and W. G. Phillips, *J. Am. Chem. Soc.* **91**, 682 (1969).
[63]R. H. Rynbrandt, *Tetrahedron Letters* 3553 (1971).
[64]H. D. Becker, *J. Org. Chem.* **29**, 1358 (1964).
[65]H. D. Becker and G. A. Russell, *J. Org. Chem.* **28**, 1896 (1963).
[66]R. H. Rynbrandt, F. E. Dutton and C. G. Chidester, *J. Am. Chem. Soc.* **98**, 4882 (1976).
[67]F. G. Bordwell and B. M. Pitt, *Ibid.* **77**, 572 (1955).
[68]T. L. Ho, *Synthetic Commun.* **9**, 267 (1979).
[69]W. E. Lawson and T. P. Dawson, *J. Am. Chem. Soc.* **49**, 3119 (1927).
[70]H. Bohme, H. Fischer and R. Frank, *Liebigs Ann.* **563**, 54 (1949).
[71]W.E. Truce, G. H. Birum and E. T. McBee, *J. Am. Chem. Soc.* **74**, 3594 (1952).
[72]D. L. Tuleen and V. C. Marcum, *J. Org. Chem.* **32**, 204 (1967).

[73]D. L. Tuleen, *Ibid.* **32**, 4006 (1967).
[74]D. L. Tuleen and R. H. Bennett, *J. Heterocyclic Chem.* **6**, 115 (1969).
[75]D. L. Tuleen and D. N. Buchanan, *J. Org. Chem.* **32**, 495 (1967).
[76]G. E. Wilson, Jr. and R. Albert, *Ibid.* **38**, 2160 (1973).
[77]G. E. Wilson Jr. and R. Albert, *Tetrahedron Letters* 6271 (1968).
[78]G. E. Wilson Jr. and M. G Huang, *J. Org. Chem.* **35**, 3002 (1970).
[79]W. Tagaki, K. Kikukawa, K. Ando and S. Oae, *Chem. Ind. (London)*, 1624 (1964).
[80]W. Groebel, *Chem. Ber.* **92**, 2887 (1959).
[81]A. Arcorio and G. Scarlata, *Ann. Chim. (Rome)* **54**, 139 (1954).
[82]N. P. Buu-Hoi, *Liebigs Ann.* **556**, 1 (1944).
[83]M. Zupan, *J. Fluorine Chem.* **8**, 305 (1976).
[84]S. Wolfe and P. M. Kazmaier, *Can . J. Chem.* **57**, 2388 (1979).
[85]W. G. Phillips and K. W. Ratts, *J. Org. Chem.* **36**, 3145 (1971).
[86]W. R. Hardstaff, R. F. Langler, J. Leahy and M. J. Newman, *Can. J. Chem.* **53**, 2664 (1975).
[87]L. A. Paquette, L. S. Wittenbrook and K. Schreiber, *J. Org. Chem.* **33**, 1080 (1968).
[88]T. P. Ahren, D. G. Kay and R. F. Langler, *Can. J. Chem.* **56**, 2422 (1978).
[89]L. A. Paquette, L. S. Wittenbrook and V. V. Kane, *J. Am. Chem. Soc.* **89**, 4487 (1967).
[90]L. A. Paquette, *J. Am. Chem. Soc.* **86**, 4089 (1964).
[91]C. G. Kruse, N. L. J. M. Broeckhof, A. Wijsman and A. van der Gen, *Tetrahedron Letters* 885 (1977).
[92]F. Bernadi, I. G. Csizmadia, H. B. Schlegel and S. Wolfe *Can. J. Chem.* **53**, 1144 (1975).
[93]J. L. Kice and G. Guaraldi, *J. Am. Chem. Soc.* **90**, 4076 (1968).
[94]J. L. Kice and G. Guaraldi, *Tetrahedron Letters* 6135 (1966).
[95]G. Chassaing, R. Lett and A. Marquet, *Tetrahedron Letters* 471 (1978).
[96]D. M. Roush and C. H. Heathcock, *J. Am. Chem. Soc.* **99**, 2337 (1977).
[97]N. J. Leonard and G. E. Wilson, Jr., *Tetrahedron Letters* 1471 (1964).
[98]N. J. Leonard and G. E. Wilson, Jr., *J. Am. Chem. Soc.* **86**, 5307 (1964).
[99]G. E. Wilson, Jr. and F. Davidson, Unpublished results.
[100]D. S. Tarbell and D. P. Harnish, *J. Am. Chem. Soc.* **74**, 1862 (1952).
[101]K. C. Schreiber and V. P. Fernandez, *J. Org. Chem.* **26**, 2478 (1961).
[102]W. A. Bonner, *J. Am. Chem. Soc.* **70**, 3491 (1948).
[103]W. A. Bonner, *Ibid.* **70**, 770 (1948).
[104]M. L. Wolfrom and W. Groebke, *J. Org. Chem.* **28**, 2986 (1963).
[105]M. L. Wolfrom, H. G. Garg and D. Horton, *Ibid* **28**, 2989 (1963).
[106]J. M. Stewart and C. H. Burnside, *J. Am. Chem. Soc.* **75**, 243 (1953).
[107]N. V. Schwartz, *J. Org. Chem.* **33**, 2895 (1968).
[108]J. M. Stewart and H. P. Cordts, *J. Am. Chem. Soc.*, **74**, 5880 (1952).
[109]G. E. Wilson, Jr., *Ibid.* **87**, 3785 (1965).
[110]G. E. Wilson, Jr. and M. G. Huang, *J. Org. Chem.* **41**, 966 (1976).
[111]H. Kwart and R. K. Miller, *J. Am. Chem. Soc.*, **78**, 5008 (1956).
[112]H. Kwart and L. J. Miller, *J. Am. Chem. Soc.* **80**, 884 (1958).
[113]H. Kwart and R. W. Body, *J. Org. Chem.*, **30**, 1188 (1965).
[114]D. S. Tarbell and D. P. Harnish, *Chem. Revs.* **49**, 1 (1951).
[115]H. Kwart and P. S. Strilko, *Chem. Commun.* 767 (1967).
[116]H. Kwart, R. W. Body and D. M. Hoffman, *Chem. Commun.* 765 (1967).
[117]J. von Braun and P. Engelbertz, *Chem. Ber.* **56**, 1573 (1923).
[118]J. von Braun and R. Murjahn, *Chem. Ber.* **59**, 1203 (1926).
[119]E. Gross and B. Witkop, *J. Am. Chem. Soc.* **83**, 1510 (1961).
[120]E. Gross and B. Witkop, *J. Biol. Chem.* **237**, 1856 (1962).
[121]T. F. Spande, B. Witkop, Y. Degani and A. Patchornik, *Advan. Protein Chem.* **24**, 97 (1970).
[122]I. Ookuni and A. Fry, *J. Org. Chem.* **36**, 4097 (1971).
[123]K. Mislow, T. Simmons, J. T. Melillo, A. L. Ternay Jr. *J. Am. Chem. Soc.* **86**, 1452 (1964).
[124]D. Landini, G. Modena, F. Montanari and G. Scorrano, *J. Am. Chem. Soc.* **92**, 7168 (1970).
[125]S. Allenmark and C. Hagberg, *Acta Chem. Scand.* **22**, 1461 (1968).
[126]E. N. Karaulova and G. D. Galpern, *Zh. Obsch. Khim.*, **29**, 3033 (1959).
[127]S. Oae, *Quart. Rep. Sulfur Chem.* **5**, 53 (1970).
[128]H. Yoshida, T. Numata and S. Oae, *Bull. Chem. Soc. (Japan)*, **44**, 2875 (1971).
[129]J. H. Krueger, *Inorg. Chem.* **5**, 132 (1966).
[130]D. Landini, F. Montanari, H. Hogeveen and G. Maccagnani *Tetrahedron Letters* 2691 (1964).
[131]G. Modena, F. G. Scorrano, D. Landini and F. Montanari, *Tetrahedron Letters* 3309 (1966).
[132]S. Allenmark and H. Johnsson, *Acta Chem. Scand.* **21**, 1672 (1967).
[133]S. Allenmark, *Ark. Kemi*, **26**, 37 (1966).
[134]R. A. Strecker and K. K. Andersen, *J. Org. Chem.* **33**, 2234 (1968).
[135]A. Bovio and U. Miotti, *J. Chem. Soc. Perkin II* 172 (1978).
[136]S. Allenmark and C. Hagberg, *Acta Chem. Scand.* **22**, 1694 (1968).
[137]S. Allenmark, *Ibid.* **15**, 928 (1961).
[138]S. Allenmark, *Ibid.* **17**, 2715 (1963).
[139]S. Allenmark, *Ibid.* **19**, 1 (1965).
[140]S. Allenmark, *Ibid.* **19**, 1667 (1965).
[141]S. Allenmark, *Ibid.* **19**, 2075 (1965).
[142]S. Allenmark and G. Oequist, *Ibid.* **19**, 277 (1965).
[143]J. H. Krueger, *J. Am. Chem. Soc.* **91**, 4974 (1969).
[144]C. M. Hull and T. W. Bargar, *J. Org. Chem.* **40**, 3152 (1975).
[145]W. E. Savige and A. Fontana, *J. Chem. Soc. Chem. Commun.* 599 (1976).
[146]G. Scorrano, *Accnts. Chem. Res.* **6**, 132 (1973).

[147]S. Oae and N. Kunieda, *Bull. Soc. Chem. (Japan)* **41**, 696 (1968).
[148]N. Kunieda and S. Oae, *Ibid.* **41**, 1025 (1968).
[149]S. Oae, M. Yokoyama and M. Kise, *Ibid.* **41**, 1221 (1968).
[150]H. J. Shine and C. F. Dais, *J. Org. Chem.* **30**, 2145 (1965).
[151]H. Szmant, *Organic Sulfur Compounds* (Edited by N. Kharasch), Vol. 1, p. 154. Pergamon Press, Oxford (1961).
[152]W. Ranky and D. Nelson, *Organic Sulfur Compounds* (Edited by N. Kharasch), Vol. 1, p. 170. Pergamon Press, Oxford (1961).
[153]C. F. Bennett, D. W. Goheen and W. S. MacGregor, *J. Org. Chem.* **28**, 2485 (1963).
[154]P. S. Skell and M. F. Epstein *Abstracts*, p. 26N. 147th National Meeting of the American Chemical Society, Philadelphia, April (1964).
[155]L. Skattebol, B. Boulette and S. Solomon, *J. Org. Chem.* **32**, 3111 (1967).
[156]K. Kikukawa, W. Tagaki, N. Kunieda and S. Oae, *Bull. Chem. Soc. (Japan)* **42**, 831 (1969).
[157]C. R. Johnson and J. J. Rigau, *J. Am. Chem. Soc.* **91**, 5398 (1969).
[158]T. Higuchi and K. H. Gensch, *Ibid.* **88**, 5486 (1966).
[159]K. H. Gensch, I. H. Pitman and T. Higuchi, *Ibid.* **90**, 2096 (1968).
[160]T. Higuchi and K. H. Gensch, *J. Am. Chem. Soc.* **88**, 3874 (1966).
[161]U. Miotti, G. Modena and L. Sedea, *J. Chem. Soc. B*, 802 (1970).
[162]E. Goethals and P. de Radzitzky, *Bull. Soc. Chim. Belges*, **73**, 546 (1964).
[163]M. E. Cisney, *Fr. Pat.* 1377019 (1964).
[164]R. Neidlein and B. Stackebrandt, *Liebigs. Ann.* 914 (1977).
[165]E. Vilsmaier and W. Sprugel, *Tetrahedron Letters* 625 (1972).
[166]P. G. Gassman, G. Gruetzmacher and T. J. van Bergen, *J. Am. Chem. Soc.* **96**, 5512 (1974).
[167]P. G. Gassman and G. D. Gruetzmacher, *Ibid.* **96**, 5487 (1974).
[168]P. G. Gassman, T. J. van Bergen and G. Gruetzmacher, *Ibid.* **95**, 6508 (1973).
[169]E. J. Corey and C. U. Kim, *Ibid.* **94**, 7586 (1972).
[170]E. J. Corey and C. U. Kim, *J. Org. Chem.* **38**, 1233 (1973).
[171]J. P. McCormick, *Tetrahedron Letters* 1701 (1974).
[172]G. A. Olah, M. Arvanaghi and Y. D. Vankar, *Synthesis* 721 (1979).
[173]G. A. Crosby, N. M. Weinshenker and H. S. Uh, *J. Am. Chem. Soc.* **97**, 2232 (1975).
[174]G. A. Olah, Y. D. Vankar and M. Arvanaghi, *Tetrahedron Letters* 3653 (1979).