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(36) Our preliminary report indicated that 9-BBN exhibits high selectivity in olefin hydroborations. A more detailed study revealed that the regioselectivity is higher than that originally observed, and even higher than that recently obtained in hydroborations with chloroborane.[37]
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(38) A detailed study of the kinetics of hydroboration with 9-BBN is now underway. A report of this work will be submitted in the near future.
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(42) Detailed procedures for handling boranes are described by G. W. Kramer, A. B. Levy, and M. M. Midland in H. C. Brown, "Organic Syntheses via Boranes," H. C. Brown, Ed., Wiley, New York, N.Y., in print.
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(46) For a discussion of the precautions necessary for the glpc analysis of organoborane derivatives, see ref 22.

Chemistry of Benzenesulfinyl Azides. Reactions with Sulfoxides[1]

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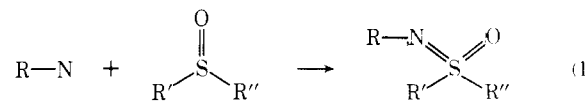
Abstract: The preparation and decomposition of some benzenesulfinyl azides are reported. They undergo ready first-order decomposition with loss of nitrogen to give products which generally are consistent with a dipolar sulfinylnitrene intermediate. Unlike carbonyl and sulfonyl azides, the benzenesulfinyl azides do not undergo the Curtius rearrangement or react with C–H bonds. In unreactive solvents like 1,2-dimethoxyethane and acetonitrile, the sulfinyl azide reacts with itself. Sulfinyl azides react with dipolar and nucleophilic compounds to give products which are quite unlike those obtained from carbonyl and sulfonyl azides. The reactions of benzenesulfinyl and *p*-toluenesulfinyl azides with dimethyl, diphenyl, methyl phenyl, and methyl *p*-tolyl sulfoxides yield sulfimide products rather than sulfoximides. The stereochemistry of the reaction was investigated with optically active methyl *p*-tolyl sulfoxide to give a sulfimide possessing a high degree of retention of configuration. Sulfinylsulfoximides were excluded as intermediates in the reaction. The evidence supports a mechanism where a delocalized sulfinylnitrene intermediate combines with sulfoxide *via* a 1,2-dipolar cycloaddition.

The organic chemistry of the azido group has been reviewed extensively in recent years,[2-5] and, with the exception of sulfonyl azides, very little has been reported on the chemistry of the azido group bonded to sulfur. Attempts to isolate sulfenyl azides have been unsuccessful.[6] Benzenesulfinyl azide was first proposed as an intermediate in the deoxygenation reaction of benzenesulfonyl azide by triphenylphosphine in acetonitrile or chloroform.[7] Purrington[8] and Kobayashi and Yamamoto[9] independently attempted the preparation of *p*-toluenesulfinyl azide but were not able to isolate it without decomposition.

Furthermore, nitrene and nitrenoid intermediates have often been proposed for azide decomposition reactions, for which sulfoxides have been perhaps the most effective of trapping reagents. In every case, the sulfoxide adduct has been a sulfoximide. Photolysis or thermolysis of acyl[10-12] or sulfonyl azides[10,11] and azidoformates[13] normally gives low yields of sulfoximides, and probably involves free nitrenes. The copper-catalyzed reaction of sulfonyl azides with sulfoxides proceeds in high yields but involves complexation of the reactants.[14,15]

Other important routes to sulfoximides include reactions of sulfoxides with (1) *N*-aminolactams[16,17] or sulfonamides[18] and lead tetraacetate, (2) sulfonoxy sulfonamides and triethylamine,[19] (3) chloramine-T[20] at 140° or chloramine-B[21] and copper at 80°, (4) hydrazoic acid and sulfuric acid in a Schmidt reaction,[22,23] (5) 3-substituted 1,4,2-dioxazolidin-5-ones[24] at 150°, or (6) trityl thionitrite by deoxygenation with triphenylphosphine.[25] The general reaction illustrated in eq 1 depicts a nitrene mechanism as a unifying scheme; however, no statement regarding the exact mechanism is intended.



(1)

Previously, no sulfinyl azide had been isolated. Therefore, our objectives in this study were to prepare them and determine how they compared with other acyl azides. Particular objectives were to determine whether thermal decomposition of sulfinyl azides led to a Curtius rearrangement or intermolecular nitrene reactions. Sulfoxides were chosen as trapping reagents because of their prior effectiveness with other nitrenes.

Results

Preparation of Sulfinyl Azides. Sulfinyl azides were pre-

pared from sulfinyl chlorides and sodium azide in anhydrous acetonitrile or 1,2-dimethoxyethane at low temperatures (eq 2). The best results were obtained from carefully

$$ArSCl + NaN_3 \longrightarrow ArSN_3 \quad (2)$$

1a, Ar = C_6H_5; **1b**, Ar = p-$CH_3C_6H_4$; **1c**, Ar = p-$NO_2C_6H_4$

purified reagents and solvents and from a properly preconditioned reaction vessel. Even so, an occasional reaction did not proceed normally (low conversion), especially for *p*-toluenesulfinyl azide (**1b**). Reaction times of up to 3 hr were usually allowed. Benzenesulfinyl azide (**1a**) was prepared at about −25° in about 85% yield, based upon nitrogen evolution obtained on decomposition. *p*-Toluenesulfinyl azide (**1b**) and *p*-nitrobenzenesulfinyl azide (**1c**) were prepared in comparable yields at about −25 and −20°, respectively. Reactions with these azides were normally carried out in the solvent of their preparation after low-temperature filtration.

The azide solutions were pale yellow and evolved nitrogen gas smoothly on warming to −5°. Neat, solid samples of **1a** and **1b** were obtained at −40° by high vacuum removal of the solvent. These samples could be safely stored at Dry Ice temperature. The azides sometimes exploded violently upon warming when neat or in high concentration. Small, neat test samples were deliberately warmed to determine their explosion points. Azides **1a** and **1b** detonated at about 11 and 8°, respectively.

Infrared analysis at −30° of a neat sample of **1a** showed absorption at 2100 (asym N_3), 1177 (sym N_3), and 1129 cm^{-1} (SO), plus other bands typical of monosulfur-substituted benzene. The azide bands disappeared when **1a** was warmed either neat or in chloroform solution.

Because of their instability, elemental analyses were not feasible; however, the kinetic results may serve as a criterion of purity.

Kinetics of Sulfinyl Azide Decomposition. Kinetics of the decomposition of sulfinyl azides **1a, 1b,** and **1c** were determined by following the rate of nitrogen evolution at 0° in acetonitrile or 1,2-dimethoxyethane solution. Good first-order kinetic data were obtained (>90% reaction, Table I).

Table I. Kinetics of Sulfinyl Azide Decomposition at 0°

Azide[a]	Solvent[b]	Added substrate (equiv)	10^4k,[c] sec^{-1}	Correlation coefficient
1a	A	None	3.5[d]	0.9991[d]
1a	B	None	3.1	0.9998
1a	A	Dimethyl sulfoxide (2.0)	2.0[e]	0.9994[e]
1a	A	Methyl phenyl sulfoxide (1.5)	2.2	0.9995
1b	B	None	2.4	0.9972
1c	A	None	2.6	0.9997
1c	A	Pyridine[f] (0.3)	3.6	0.9991

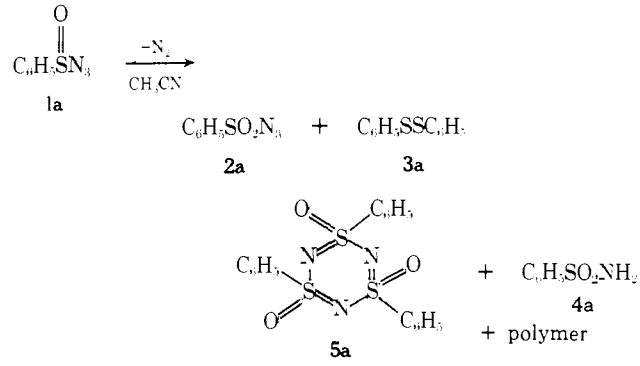
[a] The concentration of the azide in solution based upon sulfinyl chloride varied from 0.5 to 1.2 *M*. [b] Acetonitrile = A, 1,2-dimethoxyethane = B. [c] First-order rate constants for nitrogen evolution. [d] Average of three runs. [e] Average of two runs. [f] Added during preparation of the azide.

Decomposition of the azides in the presence of up to 2 equiv of dimethyl sulfoxide (DMSO) or methyl phenyl sulfoxide had no effect on the order and minor effects on the rate constants.

Sulfinyl Azide Decomposition Products. Decomposition of benzenesulfinyl azide (**1a**) in either acetonitrile or 1,2-dimethoxyethane showed no detectable reaction with either solvent. By various combinations of gas and liquid chromatography, trituration, and fractional crystallization, several products were isolated in up to 10% yield. The yields varied from run to run and according to the work-up procedure. Among the products were benzenesulfonyl azide (**2a**), phenyl disulfide (**3a**), benzenesulfonamide (**4a**),[26] and polymer.

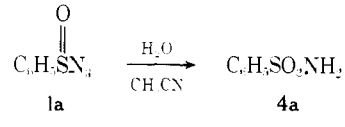
A trithiatriazine of formula $(C_6H_5NOS)_3$ (**5a**) was isolated from some reactions of **1a** in up to 9% yield. The structure of **5a** is well supported by the analytical data. Its melting point and infrared spectrum agree with previously published data for the same compound prepared by an independent method.[27]

We did not examine the direct decomposition products of **1b** and **1c** in detail. However, while others[8,9] did not isolate **1b,** they apparently generated it as an intermediate. Their decomposition products **2b, 3b,** and **4b** were analogous to some of the compounds we obtained from **1a.**

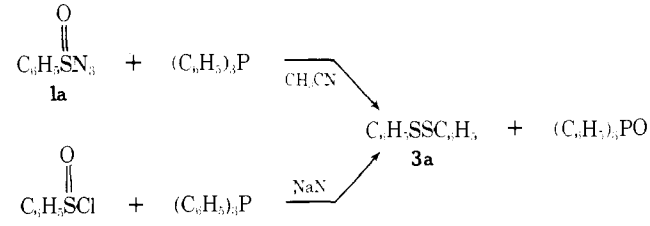


Sulfinyl Azide Reactions. Benzenesulfinyl azides (**1**) were observed to react with a variety of substrates. The substrate was usually dissolved in the solvent (acetonitrile or 1,2-dimethoxyethane) containing the azide and warmed. In each case, some polymer and other decomposition products were obtained as before, but in reduced amounts. The yields of reactions with various substrates were improved by adding the cold azide solution dropwise to a warm (*ca.* 45°) solution of the substrate. The reactions studied here were not optimized for yield.

Reaction of **1a** with water in acetonitrile gave benzenesulfonamide (**4a**) in 20–29% yield.

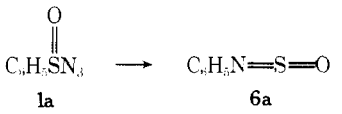


Reaction of **1a** with triphenylphosphine in acetonitrile gave phenyl disulfide (**3a,** 80%) and triphenylphosphine oxide (75%). When benzenesulfinyl chloride was treated first with triphenylphosphine, then with sodium azide, the same products were obtained (89 and 68%, respectively).



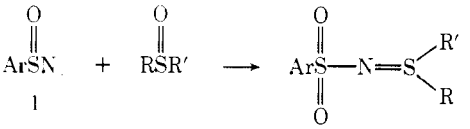
Effort was made to detect a possible Curtius rearrangement product, *N*-sulfinylaniline (**6a**), from **1a,** but it could not be detected. *N*-Sulfinylaniline was stable to the reaction conditions and could have been isolated if present. Ko-

bayashi and Yamamoto[9] likewise could not detect the rearrangement product **6b** from their decompositions of **1b**.



1a **6a**

Reactions with Sulfoxides. In a preliminary study, one of us[1a] reported the failure to isolate an adduct between benzenesulfinyl azide (**1a**) and dimethyl sulfoxide.[28] A careful work-up of the same reaction has now provided *N*-benzenesulfonyldimethylsulfimide (**7a**) in 20% yield. In these experiments, the unstable azide was prepared at low temperature (below −20°) in acetonitrile and transferred cold to a flask containing the sulfoxide or a solution of sulfoxide in acetonitrile. The reaction proceeded with nitrogen evolution on warming to room temperature. A significant improvement in the yields of the sulfimides was obtained by adding the cold azide solution dropwise to a warm (40–50°), concentrated solution of sulfoxide. The reaction is general, occurring with dialkyl, diaryl, and alkyl aryl sulfoxides and two differently substituted benzenesulfinyl azides. The data for these reactions are summarized in Table II.



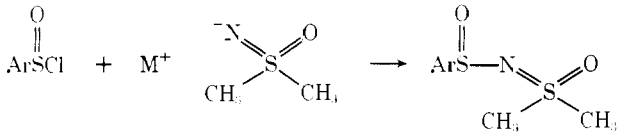
1 7

Table II. *N*-Benzenesulfonylsulfimides (**7**)

Compd no.	Ar	R	R′	% yield	Mp, °C Found (Reported)
7a	C_6H_5	CH_3	CH_3	20	126–127 (131)[29]
7b	*p*-$CH_3C_6H_4$	CH_3	CH_3	73[b]	154–156 (158–159)[10,29]
7c	C_6H_5	C_6H_5	C_6H_5	26[b]	118–120
7d	*p*-$CH_3C_6H_4$	CH_3	*p*-$CH_3C_6H_4$	16[b]	122–124 (125–126)[30]
(+)-**7d**[a]	*p*-$CH_3C_6H_4$	CH_3	*p*-$CH_3C_6H_4$	42[b]	121.8–124 (124–125)[31]

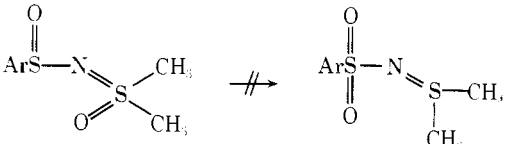
[a] Optically active (+)-(*R*)-**7d**. [b] From dropwise addition of azide.

The observation that **7** was obtained from these reactions and not the sulfoximide (**8**) required the synthesis of **8**, which had not previously been reported. The *N*-benzenesulfinyl- and *N*-*p*-toluenesulfinyldimethylsulfoximides (**8a, b**) were prepared from the appropriate sulfinyl chloride and the lithium or sodium dimethylsulfoximide. Buchholt[32] has reported an independent synthesis of **8a**.



8a, Ar = C_6H_5,
b, Ar = *p*-$CH_3C_6H_4$

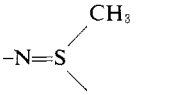
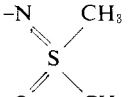
While the spectra and melting points of compounds **7** and **8** are consistent with their structures and agree with the data reported in the literature, we felt that chemical confirmation by degradation was desirable. The possibility of ambiguity in the structures of **7** and **8** due to interconversion by a rearrangement justified this precaution. The compound presumed to be **7a** was treated with lithium aluminum hydride to give the expected benzenesulfonamide (65%) and dimethyl sulfide. Further supporting evidence for the correct assignment of the structures of **7** and **8** was found in an nmr study of the sulfinyl sulfoximides (**8a, b**). Diastereotopic nonequivalence (by 6 Hz) of the two sulfoximide methyl groups was observed in $CDCl_3$, but equivalence was noted in D_2O. The nonequivalence in $CDCl_3$ might be explained by proximity of the asymmetric sulfinyl group. The asymmetry effect becomes negligible in D_2O, perhaps because of insulative solvation. Diastereotopic nonequivalence is not possible for compounds **7**, and none was found.



8 **7**

To determine whether **8** was formed first from the azide–sulfoxide reaction and rearranged to **7**, we investigated the stability of **8** to the reaction and work-up conditions. Decomposition of **1a** in the presence of **8b** and dimethyl sulfoxide gave a mixture of **7a** and unchanged **8b**. No **7b** or **8a** was detected. The analysis procedure involved isolation of a mixture of compounds **7** and **8** from the remainder of the reaction mixture by successive extractions with water and chloroform. No further separation was feasible without disturbing the integrity of the sample mixture. This was analyzed directly by nmr and compared with the spectra of all of the possible products. The nmr spectrum (Table III) of the reaction mixture showed absorption at δ 2.4, 2.7, and 3.25–3.40 in the relative ratios of 1:1:2, respectively. All of the absorption at δ 3.25–3.40 is assigned to **8b**, since no **8a** was ever isolated from the reaction of **1a** with dimethyl sulfoxide. The 1:2 ratio of the absorptions at δ 2.4 and 3.25–3.40 is exactly that required for **8b** alone, so no **7b** can be present in any significant amount. All of the absorption at 2.7 must be attributed to **7a**. Thus, the sulfoximide **8** does not rearrange under azide–sulfoxide reaction conditions to give **7**. In fact, this rearrangement was not observed under vigorous conditions with or without acid present. Only decomposition resulted.

Table III. Nmr Spectra of Sulfimides and Sulfoximides

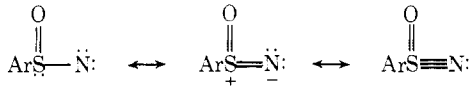
Compd no.	Chemical shifts (δ, ppm from TMS) in $CDCl_3$		
			*p*-CH_3-
7a	2.7 (6)		
7b	2.7 (6)		2.4 (3)
8a		3.25, 3.40 (3, 3)	
8b		3.25, 3.40 (3, 3)	2.4 (3)

Stereochemistry of Sulfinylnitrene–Sulfoxide Reaction. Treatment of (+)-(*R*)-methyl *p*-tolyl sulfoxide ((+)-**9**) of 99% optical purity with *p*-toluenesulfinyl azide (**1b**) in acetonitrile at 50° gave a 42% yield of nonfractionally crystallized (+)-(*R*)-*N*-(*p*-tosyl)methyl-*p*-tolylsulfimide ((+)-**7d**) of 92.1% optical purity ($[\alpha]^{25}D$ +247.6°, *c* 1.68, acetone).[33] Corrected for the purity of the sulfoxide, this indicates that the reaction proceeded with 96.5% retention of configuration. *p*-Toluenesulfonamide (15.2%) and methyl

p-tolyl sulfide (2.8%) were also isolated in addition to polymeric material and other minor components normally found in the absence of sulfoxide. In a related reaction, **1a** and diphenyl sulfoxide gave **7c** (26%), benzenesulfonamide (27%), and diphenyl sulfide (7%).

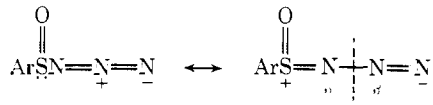
Discussion

Nature of Reactive Intermediate. An examination of the information available for sulfinyl azide reactions reveals: (1) unusually low stability of the azide, (2) no Curtius rearrangement, (3) failure to react with C–H bonds, (4) abnormal reaction with water, and (5) unprecedented products from an azide–sulfoxide reaction. A delocalized, dipolar sulfinylnitrene intermediate (**10**) is compatible with these results, including the stereochemistry (discussed below).

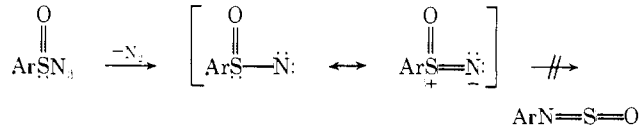


10

Thus, benzenesulfinyl azides represent an entirely new class of acyl azides. Not only are they structurally different, but their chemistry also differs dramatically from that of the carbonyl and sulfonyl azides.[2-5,34,35] Their instability and anomalous reactivity may be explained by the effect of the nonbonded electron pair on sulfinyl sulfur. Delocalization of the nonbonded sulfinyl electrons into the azide group might be expected to decrease the bond order between the α- and β-nitrogen atoms, facilitating cleavage. This hypothesis may be used to explain the very low stability of a number of other azides, including a postulated sulfenyl azide,[6] phosphinic azides,[36] and amino azides.[37] The chemical behavior of these azides is also anomalous.



Failure of the sulfinyl azides to undergo the Curtius rearrangement may also be explained as a result of sulfinyl electron pair delocalization. The delocalization makes the α-nitrogen atom electron rich, even after cleavage. However, Curtius rearrangement reactions require migration of a group to an electron-deficient α-nitrogen atom.

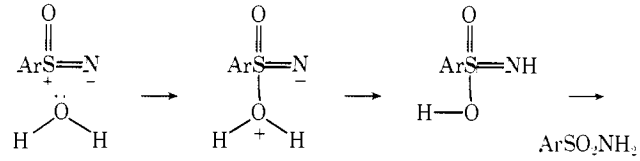


The first-order kinetics of sulfinyl azide decompositions in acetonitrile or 1,2-dimethoxyethane with or without the presence of added sulfoxides argue for a simple unimolecular azide fragmentation without complexation with the substrate.[38] The slight differences in rate constants are compatible with solvent effects. The apparent lack of a substituent effect on para benzene substitution emphasizes the insulating ability of the sulfinyl group. A more detailed kinetic study of a wider range of sulfinyl azides and substrates is planned. A study of activation parameters for these reactions should be quite informative.

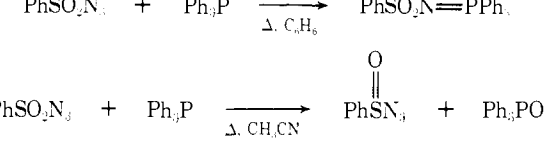
The combined results of kinetics and product studies are indicative of a sulfinylnitrene intermediate from decomposition of **1**. However, the lack of typical nitrene reactivity must be explained. The presence of an electron-rich sulfur atom adjacent to an electron-deficient nitrogen suggests that delocalization of the sulfinyl nonbonded electron pair would complete the "octet" of nitrogen and produce a dipolar sulfinylnitrene species. Some back-bonding of the nitrogen electrons with sulfur d orbitals could also contribute to decrease the charge separation. Such dipolar character has been invoked before to explain the failure of "nucleophilic" carbenes[39] and the nitrenes like aminonitrenes (1,1-diazenes)[40] to insert into C–H bonds.

Rationale for Reaction Products. The formation of the trithiatriazine (**5a**) may proceed by trimerization of the dipolar sulfinylnitrene (**10a**). There are some parallels to this mechanism in inorganic trithiatriazine chemistry.[41-43] The other azide decomposition products can be rationalized by disproportionation and condensation processes.

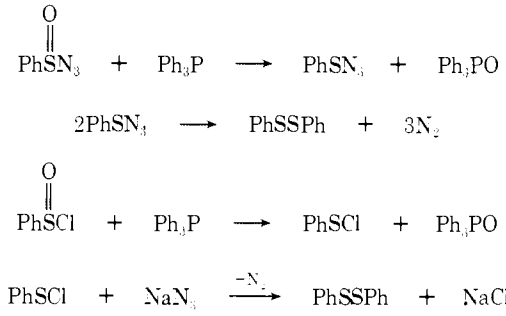
The reaction of sulfinyl azides with water is readily explained by nucleophilic attack of the hydroxyl oxygen on the electrophilic sulfinyl sulfur of the intermediate sulfinylnitrene. Tautomerization would give initially the sulfonimidic acid, then sulfonamide.[44]



Franz and Osuch[46] found that the reaction of benzenesulfonyl azide with triphenylphosphine in hot benzene gave the iminophosphorane, but, in hot acetonitrile, phenyl disulfide and triphenylphosphine oxide were the main products. Benzenesulfinyl azide (**1a**) was proposed as an intermediate from deoxygenation of the sulfonyl azide by the phosphine. The sulfinyl azide in turn was postulated to be further deoxygenated to sulfenyl azide, which decomposed to disulfide.



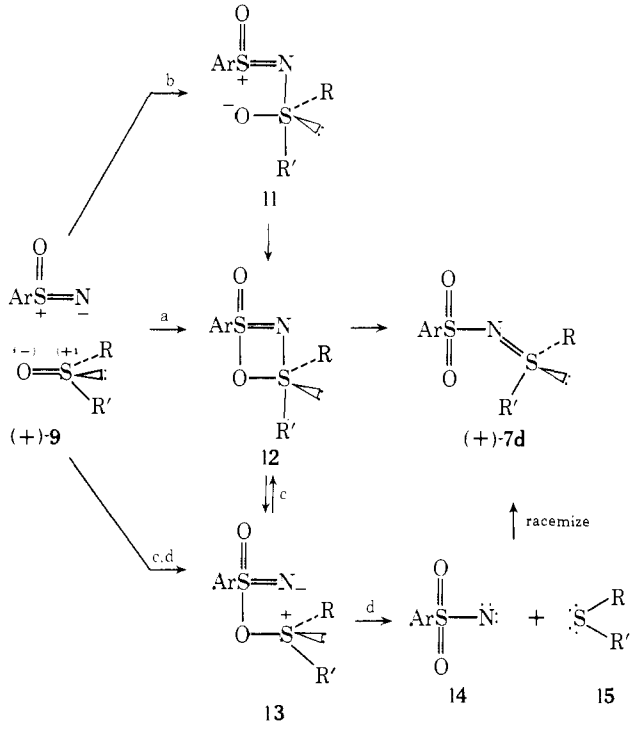
Our observations with benzenesulfinyl azide and triphenylphosphine are compatible with this mechanism. However, this reaction is a prime candidate for a kinetic study to determine the exact nature of the involvement of the phosphine. The formation of the same products from sequential reaction of sulfinyl chloride with phosphine followed by sodium azide suggests that the phosphine probably deoxygenated the sulfinyl chloride to sulfenyl chloride. This could then have reacted with sodium azide to give the unstable sulfenyl azide and finally to decompose to disulfide.



Mechanism of Sulfinylnitrene–Sulfoxide Reaction. If we consider the possible reaction mechanisms for a delocalized, dipolar sulfinylnitrene reacting with a sulfoxide, several possibilities become apparent. We can discount direct attack by the azide on the sulfoxide because the rate of azide decomposition was essentially independent of the presence of sulfoxide. Furthermore, attack by an electrophilic nitrene on the sulfoxide sulfur lone electron pair is ruled unlikely because sulfoximides were not formed in this reaction. The

remaining possibilities include (Scheme I): (a) concerted 1,2-dipolar cycloaddition leading to a four-membered cyclic sulfurane intermediate (**12**), followed by ring opening to **7**; (b) stepwise cycloaddition with the first step being nucleophilic attack of nitrogen on sulfur, followed by cyclization and alternate ring opening; (c) stepwise electrophilic attack of the positive sulfinyl sulfur on the sulfoxide oxygen, followed again by cyclization and ring opening; and (d) deoxygenation of the sulfoxide by the sulfinylnitrene to give a sulfonylnitrene and sulfide, which can recombine directly to the sulfimide (**7**).

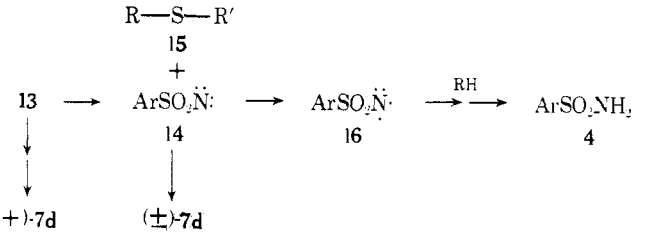
Scheme I



From our stereochemical results (if R = CH_3, R′ = *p*-Tol), path d must be excluded as a major process because racemization of the sulfimide (**7d**) would be expected. Even if recombination of a sulfonylnitrene and sulfide were very rapid, a high value for retention of configuration would not be expected because only a minor rotational motion of the free sulfide would be required for inversion of configuration. Path b is unlikely because unassisted nucleophilic attack on sulfoxides is unprecedented. This mechanism does not explain the formation of the sulfonamide and sulfide side-products.[47] Furthermore, if this betaine adduct (**11**) were formed, it might be expected to collapse into the structure of the sulfoximide (**8**). Path a is consistent with the high degree of retention of configuration but does not directly account for the side-products and the small amount of racemization. Either **12** is formed by path a and equilibrates with **13** or path c predominates. In either case, some small contribution from path d must be assumed to account for the reduced optical purity of **7d** and formation of sulfonamide (**4**) and sulfide (**15**). The formation of **4** most likely occurs from triplet sulfonylnitrene (**16**) by hydrogen abstraction from the medium (Scheme II). The formation of benzenesulfonamide and diphenyl sulfide from diphenyl sulfoxide may be explained in the same way.

Mechanistic Implications of Stereochemistry. The conclusion that paths a and c are consistent with a retention mechanism may not be obvious. Therefore, we shall discuss the steps leading from **13** to **12** to (+)-**7d** in more detail. Involvement of the betaine intermediate **13** in a retention

Scheme II



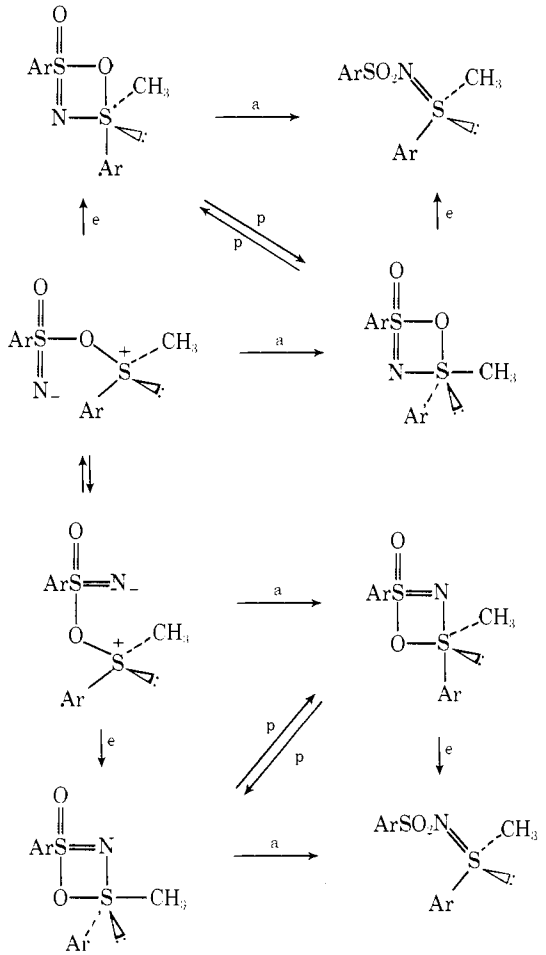
mechanism is reasonable because sulfonium ions would be configurationally stable under the reaction conditions.[48] The proposed intermediacy of a cyclic sulfurane, **12**, is supported by numerous analogies in phosphorane and sulfurane chemistry. Stable trigonal bipyramidal sulfuranes have been prepared,[49] and cyclic four-membered sulfurane intermediates have been implicated in some reactions.[50] Very recently the four-membered oxaphosphetane intermediate of the Wittig reaction was established by nmr.[51] The composite results of these and other workers[31,49-56] indicate that **12** is a reasonable structure to propose in this instance. Intermediate, **12**, should also possess trigonal bipyramidal geometry, and the ring should occupy one axial and equatorial position with the electron pair in an equatorial position. Axial attack by the entering nitrogen (**13** → **12**) and axial expulsion of the leaving oxygen group (**12** → (+)-**7d**) would be favored for electronic reasons. Alternative directions of ring closure and ring opening are discussed below.

Ring closure of **13** to **12** may occur in principle by attack of the negative nitrogen group at either a face (axial) or edge (equatorial) of the tetrahedron described by the asymmetric sulfonium ion (Figure 1). Certain faces and edges may be excluded for steric or electronic reasons. Attack on the face opposite (perpendicular to) the S–O bond would place two of the ring bonds in highly strained diaxial positions. Attack on the face opposite the S lone pair orbital would place the lone pair in a less stable axial position. Attack on any of the three edges between the CH_3, Ar, and lone pair functions can be excluded because the ring would be forced to occupy the strained diequatorial positions. Attack on the edge between O and the lone pair is disfavored again because the lone pair would occupy an axial position. Thus, only the faces behind the S–CH_3 and S–Ar bonds and the edges joining O with CH_3 and O with Ar are available for attack. Axial expulsion of the oxygen group will reform similar faces and equatorial expulsion will give similar edges to a tetrahedron in which nitrogen occupies the same relative position as oxygen did in the sulfoxide.

The possible combinations of axial attack with equatorial expulsion (ae), equatorial attack with axial expulsion (ea), and axial attack with axial expulsion (apa) are outlined in Scheme III. For electronic reasons, axial attack and expulsion are considered to be more energetically favorable than equatorial attack and expulsion. However, the apa mechanism (or epe) requires pseudorotation[54,55,57] to complete the process. Since the barriers for pseudorotation of sulfuranes having similar structures to **12** are unknown and may be high,[55,58] a compromise ae or ea path may be required. The question of whether violation of the principle of microscopic reversibility might occur in this case is discussed in the Appendix.

In each of the mechanistic paths for the reaction described in Scheme III, the same product is obtained with retention of configuration. We are aware of no experiment at this time which will distinguish between these paths, nevertheless we tend to prefer the apa mechanism with pseudorotation. One experiment reported in the literature[58] has led some investigators to become skeptical about pseudorotation in sulfuranes. The reaction of ethoxy-3-methylthietan-

Scheme III



ium salts with *external* nucleophiles occurs with *inversion* of configuration about sulfur.[58] This is insufficient reason to exclude consideration of pseudorotation processes for reactions of *internal* nucleophiles at chiral sulfur—especially when they occur with *retention* of configuration. Other results which are compatible with these contentions are those of Oae[59] and Christensen,[60] and more recently of Cram and coworkers.[61]

Experimental Section

General Procedures. Chemicals and solvents were reagent grade unless otherwise specified. Dry solvents were obtained by usual procedures. Infrared (ir) spectra were obtained on a Perkin-Elmer Model 137 spectrophotometer. Liquid samples were analyzed neat between sodium chloride plates, and solid samples were analyzed in pressed potassium bromide disks. Nuclear magnetic resonance (nmr) spectra were taken in chloroform-*d* (unless otherwise noted) on a Varian Associates Model A-60A spectrometer. Chemical shifts are reported in parts per million (δ) downfield from internal tetramethylsilane. Specific rotations were taken on a Franz, Schmidt, and Haensch polarimeter using the sodium D line at 20° in a 2-dm cell. Melting points were taken on a Thomas-Hoover Uni-Melt apparatus and are uncorrected. Either Baker Analyzed silica gel or Woelm neutral alumina was used for chromatography; for thin-layer chromatography (tlc) Eastman Chromagram thin-layer plates coated with silica gel containing a fluorescent indicator were used. Gas liquid chromatography (glc) was performed on a Varian Model A-700 gas chromatograph with a hot wire thermal detector and disk integrator. Fractions were collected manually in 3-mm glass tubes immersed in liquid nitrogen. All determinations were made isothermally on a 10 ft × ⅜ in. column of 30% SE-30 on 80/100 Chromosorb P with helium as the carrier gas. Quantitative data were obtained by using an internal glc standard. A Kewaunee drybox under a nitrogen atmosphere with phosphorus pentoxide as a desiccant was used. Gas evolution from reactions

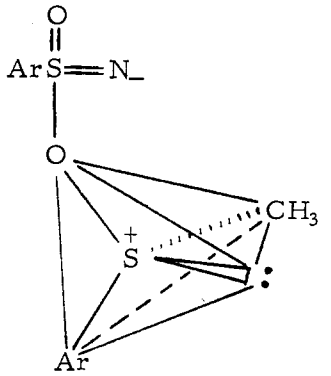


Figure 1.

was measured on a Precision "wet-test" gas meter. For kinetic studies this meter was modified to provide continuous output on a strip chart.

Phenyl disulfide (mp 59-60.5°) and *p*-tolyl disulfide (mp 44.5-46.5°) were recrystallized from methanol. Sodium hydride, obtained as a 50% oil dispersion, was washed twice with ether before use. *N*-Butyllithium was used as a 12.90% solution in pentane, as supplied by Foote Mineral Co.

The yields of products obtained from sulfinyl azide reactions are based upon the amount of sulfinyl chloride used, because the per cent conversions to sulfinyl azide are difficult to determine.

Preparation of Sulfinyl Chlorides. The sulfinyl chlorides were prepared by some of the following procedures: (A) reaction of sodium sulfinate salt with thionyl chloride;[62] (B) reaction of a thiol with chlorine and glacial acetic acid in methylene chloride by a modification of the procedure of Douglass, Farah, and Thomas;[63] (C) reaction of disulfide with chlorine and acetic anhydride by the procedure of Douglass and Norton[64] but with methylene chloride as solvent. Procedure C is the method of choice for disulfides which do not readily dissolve in acetic anhydride. The methylene chloride helped to strip-off the acetyl chloride by-product. Residual acetyl chloride was removed by adding more methylene chloride to the reaction concentrate and evaporating *in vacuo*.

Liquid sulfinyl chlorides were purified by vacuum distillation (0.05 Torr) in a "Kontes" falling film molecular still. These distillations proceeded smoothly without complication or significant decomposition of the sulfinyl chloride. The sulfinyl chlorides are very moisture sensitive.

Preparation of Benzenesulfinyl Chloride. Methods A, B, and C were used, but C gave the best product and the best yield after molecular distillation (>90%). The sulfinyl chloride was degassed at room temperature by evacuation (0.02 Torr) until bubbling ceased before distillation was started. This helped to prevent splattering. Distillation progressed well at the temperature of refluxing methanol. The product was a lemon yellow oil, which did not crystallize in a refrigerator. Slow decomposition occurs on prolonged storage in the refrigerator.

Preparation of *p*-Toluenesulfinyl Chloride. Method C was used to give a lemon yellow oil after molecular distillation (>90%) under the same conditions as with benzenesulfinyl chloride. *p*-Toluenesulfinyl chloride crystallized after standing in the refrigerator at about 0°. Prolonged storage in the refrigerator results in some decomposition.

Preparation of *p*-Nitrobenzenesulfinyl Chloride. Method C was employed as follows. A mixture of bis(*p*-nitrophenyl) disulfide (15.4 g, 0.050 mol; recrystallized from chloroform) and acetic anhydride (10.21 g, 0.10 mol) in methylene chloride (*ca.* 100 ml) was cooled to −5° and chlorinated. Chlorination was stopped when chlorine was no longer absorbed in the reaction mixture. The reaction mixture was rotary evaporated *in vacuo* to give a light yellow solid. This was treated several times with methylene chloride and reconcentrated to remove the last traces of acetyl chloride. This gave 17.6 g (86%) of product (mp 65-67°). Recrystallization from methylene chloride-hexane lowered the melting point to 60-64°. Thus, the crude product was used directly, after acetyl chloride was removed. While moisture sensitive, this sulfinyl chloride is thermally stable: ir (KBr, cm^{-1}) 1505 (s), 1325 (s), 1140 (s), 850 (s), 735 (s), 719 (s).

Oae, Ikura, and Shimano[65] used a variation of the procedure of

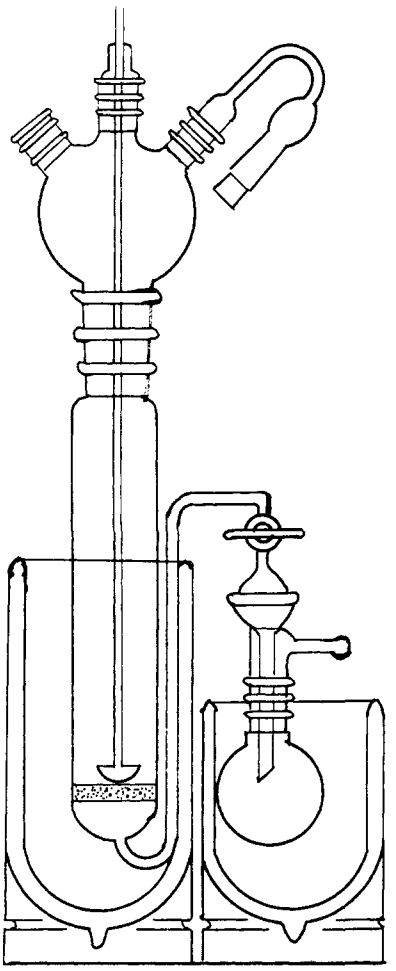


Figure 2. Azide preparation and reaction apparatus.

Douglass, Farah, and Thomas[63] to prepare the same product in 82.5-94.4% yield (mp 58-60°).

Preparation of Benzenesulfinyl Azides (General). The benzenesulfinyl azides were prepared in 0.5-0.9 *M* concentrations in quantities ranging from 0.03 to 0.09 mol per reaction. Yields ranged up to 90% (typically 80-85%) based on the volume of gas evolved upon decomposition.

The use of high quality starting materials was extremely important. Significant reductions in yields were observed when the liquid sulfinyl chlorides were stored for more than a month before use or if they had not been carefully distilled.

Treatment of the reaction vessel (Figure 2) prior to its use had an important effect on the reaction. This aspect is discussed below. Water must be rigorously excluded from the system since it can reduce the yield of azide and react with the decomposing azide.

Preparation of Benzenesulfinyl Azide (1a). The azide reaction vessel (Figure 2) was charged with 60 ml of acetonitrile or 1,2-dimethoxyethane and 5.58 g (0.086 mol) of sodium azide and allowed to stir at room temperature for 15 min while 12.52 g of benzenesulfinyl chloride (0.076 mol) was weighed into an addition funnel in a drybox. The solvent-sodium azide mixture was cooled to −40° and the sulfinyl chloride added as rapidly as the addition funnel would allow. After stirring for 3 hr at from −20 to −30°, the azide solution was filtered through the frit at the bottom of the vessel, with the aid of N_2 pressure, into a cold receiver. Throughout the reaction the flask was swept with a slow stream of dry nitrogen to prevent moisture condensation in the cold solution. The reaction produced a clear, light yellow azide solution. The Ir spectrum (Figure 3) of **1a** was obtained with a low temperature infrared cell. The outer cell windows were cesium bromide, the inner Irtran-2 (polyzinc sulfide). A neat film of **1a** was used to obtain the spectrum at −30°.

Preparation of *p*-Toluene- and *p*-Nitrobenzenesulfinyl Azide (1b, c). These azides were prepared in the same manner as benzenesulfinyl azide except that the temperature of each reaction was changed somewhat to increase yields. The optimum temperature range for the preparation of *p*-toluenesulfinyl azide was from −30 to −20° and for *p*-nitrobenzenesulfinyl azide ranged from −25 to −15°.

Preconditioning of the Azide Reaction Vessel. The procedure used for washing and handling the reaction vessel had a pronounced effect on the preparation of the sulfinyl azides.

The procedure which gave the most reproducible results consisted of rinsing the flask in turn with chloroform and acetone followed by a quick detergent wash and a thorough rinsing with distilled water. The flask was dried at 120° for at least 12 hr before use and assembled hot and flushed with dry nitrogen while it cooled to prevent moisture contamination. When the glass frit at the bottom of the flask was cleaned with chromic acid or by prolonged soaking in detergent, preconditioning was required before the flask could be used for the next azide preparation.

Preconditioning was accomplished by stirring excess sodium azide and 2 or 3 g of a sulfinyl chloride in the flask for 2-3 hr at −30°. The flask was then emptied and subjected to the usual washing procedure to complete the preconditioning process.

Even with these precautions, an occasional run would proceed with only low conversion to the azide. The preparation of **1b** was most fickle in this respect.

The addition of 5-10% of pyridine or sodium iodide facilitated the progress of some of the sluggish runs. Ordinarily, such additions were unnecessary.

Explosion Temperatures of Sulfinyl Azides. Small quantities of the azides were obtained by evacuating approximately 1-ml quantities of the appropriate azide solution at −30° and 0.030 Torr for 5-6 hr.

The leads of a small iron-constantan thermocouple were connected to a 0-1 mV strip chart recorder, and the output trace was calibrated by immersing the thermocouple into solutions of known temperature. Decomposition points for **1a** and **1b** were determined by placing the thermocouple into a drop of cold azide contained in a small flask. The flask was allowed to warm. At the point when the azide exploded the recorder pen was driven off scale, thus giving a graphic indication of the explosion temperature. By this method benzenesulfinyl azide (**1a**) was found to explode at 11° and *p*-toluenesulfinyl azide (**1b**) at 8°.

Kinetics of Sulfinyl Azide Decomposition. For kinetic studies the filtered sulfinyl azide solutions were decomposed at 0°. Reaction progress was followed by measuring the volume of gas evolved as a function of time. Decomposition of the sulfinyl azides in the presence of added reagents was accomplished by adding the reagents to the cold azide solutions prior to warming.

The decompositions were carried out in a flat-bottomed cylindrical glass tube (3.5 cm diameter by 40 cm long) with a 24/40 joint at the top and an 8-mm gas outlet tube 2 cm below the bottom of the joint.

The stoppered decomposition tube containing cold sulfinyl azide, a small magnetic stirring bar, and any other desired reagents were placed in a Forma constant-temperature bath through a hole cut into the lid. A water driven magnetic stirrer powered by the temperature bath's external circulation pump stirred the decomposing sulfinyl azide solution and provided additional circulation within the bath.

Gas evolution was measured by means of a Precision wet test meter modified to give a continuous record on a strip chart recorder and connected to the gas outlet of the decomposition tube. Figure 4 shows the modified gas meter. The modification being the attachment of a circular slide wire, salvaged from a discarded Leeds and Northrup "Minimax" recorder, to the gas meter pointer shaft. A very fine insulated copper wire provided one electrical connection to the slide wire and an insulated brass contact arm pivoting on a screw attached to the gas meter provided the second contact. The slide wire served as a variable leg of the resistive Wheatstone bridge circuit shown in Figure 5. A 0-1 mV strip chart recorder was used to measure the degree of imbalance in the bridge circuit. This arrangement provided a linear pen displacement on the recorder which was proportional to the amount of gas passed through the gas meter.

After allowing the sulfinyl azide to decompose overnight the maximum displacement on the strip chart recorder was used to give the first approximation of the displacement at infinite time.

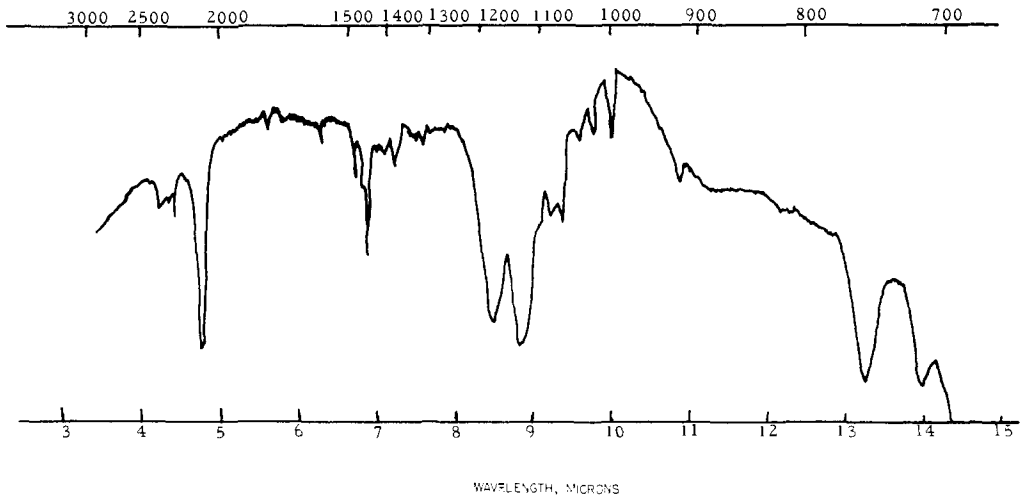


Figure 3. Ir spectrum of benzenesulfinyl azide (**1a**).

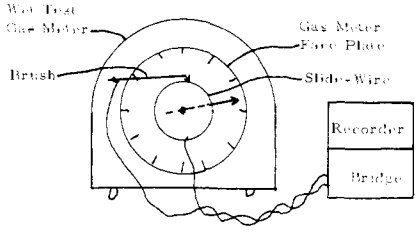


Figure 4. Recording gas meter.

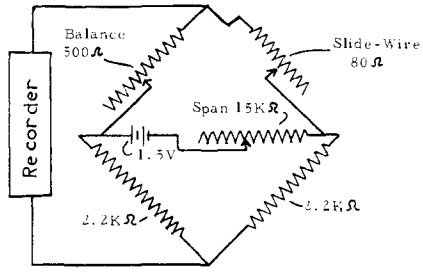


Figure 5. Electronic circuit for recording gas meter.

First-order rate constants were calculated from a plot of ln (infinity displacement − displacement at any time) *vs.* time. A least-squares computer program was used to obtain the best fit of data points for a straight line plot to greater than 90% reaction. The infinity values were adjusted to optimize the correlation coefficients. The results are tabulated in Table I.

Decomposition of Benzenesulfinyl Azide (1a) in Acetonitrile. Benzenesulfinyl azide (**1a**) was allowed to decompose in acetonitrile solution either with or without prior filtering of the inorganic salt. No significant difference was observed in the product mixture. The azide decomposed as the mixture was slowly warmed to 0° or room temperature. If the reaction mixture was brought to room temperature rapidly, then the mixture would exotherm to a higher temperature with a very rapid evolution of gas.

Analysis of the decomposition products was carried out on a number of separate runs by a variety of methods. Each product isolated and identified was not necessarily isolated in every run. Because of the complexity of the mixtures and the difficulty of relating yields from one run and one separation procedure to another, only approximate yields of products can be given.

The filtered azide decomposition mixture was concentrated by rotary evaporation to give a yellow, gummy material. Trituration with ether in a drybox gave a white solid (*1*) on filtration. Exposure of 1 to the air caused it to turn gummy. Product 1 melted with decomposition and gas evolution at 90–97°. It appeared to be a polymeric mixture. Elemental analysis gave: C, 52.5; H, 4.3; N, 8.1; S, 18.7. When this material (1) was washed with ethanol a small amount (0–5%) of solid (mp 176–177°) was isolated. This was identified as the trithiatriazine (**5a**), which will be described in detail below. Analysis of the ether triturate solution by gas chromatography on a 6 ft × ¼ in. silicone column with temperature programing from *ca.* 150–230° gave benzenesulfonyl azide (**2a**) and phenyl disulfide (**3a**) in less than 10% yield each. Their ir spectra were identical with those of authentic samples. Nmr analysis of the gummy concentrate of the reaction mixture from acetonitrile solution showed no methyl group protons, indicating lack of reaction with the solvent. Likewise, no nmr absorptions derived from 1,2-dimethoxyethane were observed in reaction mixtures obtained in that solvent.

Column chromatography of decomposition mixtures of **1a** through alumina or silica gel did not provide good separations of products. Most of the fractions were contaminated with other components.

Benzenesulfonamide (**4a**) was isolated in *ca.* 2–15% yield by triturating the reaction concentrates with 1–2 *N* sodium hydroxide solution, followed by extraction of the aqueous base solution with chloroform. Acidification and filtration gave the sulfonamide, which was recrystallized from methylene chloride.

Isolation of 1,3,5-Triphenyl-1,3,5,2,4,6-trithiatriazine 1,3,5-Trioxide (5a). The trithiatriazine (**5a**) was isolated in variably low yields by trituration and fractional crystallization of the azide (**1a**) decomposition mixtures. Trituration of the decomposition mixture with dry pentane, then dry ether gave a very thick, gummy mass. Trituration with a minimum amount of ethanol gave a mixture of white crystals and some brown oil. Finally, trituration with a minimum amount of methylene chloride dissolved the brown oil to give the white, crystalline trithiatriazine (**5a**) in up to 5% yield. This technique was more effective with decomposition mixtures that had been allowed to stand for a prolonged period of time.

In another case, **5a** was isolated by chromatography from a reaction mixture containing styrene oxide. Benzenesulfinyl azide (**1a**), prepared from 0.033 mol of benzenesulfinyl chloride in 60 ml of 1,2-dimethoxyethane, was allowed to decompose by dropwise addition at room temperature into 7.92 g (0.066 mol) of styrene oxide. After gas evolution was complete, the solvent was removed *in vacuo*. The viscous, brown oily concentrate was diluted with 5 ml of methylene chloride to reduce its viscosity. This solution was slowly added to 250 ml of rapidly stirred diethyl ether. The ether solution was decanted from the insoluble tacky solid and concentrated to give 2.37 g of light brown oil. This oil was mixed with a very small amount of Woelm alumina and introduced onto a 50 × 200 mm column of alumina. Fractions of *ca.* 30 ml each were collected upon elution by a 25:75 hexane:benzene mixture. The first fraction eluted contained a brown oil, followed by two more fractions, each containing a mixture of oil and a white solid. The fourth and fifth fractions contained 157 and 272 mg, respectively, of **5a**. The yield was 9.3% based upon sulfinyl chloride. The infrared spectrum and melting point were essentially the same as reported previously:[27] mp 176–177°; ir (KBr) 1468, 1441, 1255 (s), 1180, 1135 (s), 1115 (s), 1084, 1021, 994, 826, 757, 746, 707, and

682 cm^{-1}. *Anal.* Calcd for $C_{18}H_{15}N_3O_3S_3$: C, 51.8; H, 3.6; N, 10.1; S, 23.0. Found: C, 51.7; H, 3.6; N, 10.1; S, 22.6. High resolution mass spectral analysis showed that the molecular ion has the empirical formula $C_{18}H_{15}N_3O_3S_3$ (error: found − calcd = 1.11 millimass units) and was quite intense. The principal ions in the spectrum were determined with an error of ≤1.00 millimass units: $C_6H_5O_3N_2S_3$, C_6H_5ONS, C_6H_4ONS, C_6H_5SO (most intense), C_6H_4SO (very intense) C_6H_5, C_6H_4, HSON. A mixture of perfluorokerosene and n-$C_{30}H_{62}$ was used to establish the mass scale.

The trithiatriazine **5a** is a very stable compound. It remelted sharply at the same melting point after two heating cycles to 300°.

Decomposition of 1a in the Presence of *N*-Sulfinylaniline (6a). By the usual procedure 6.5 g (0.10 mol) of sodium azide in 50 ml of acetonitrile was treated with 5.98 g (0.027 mol) of benzenesulfinyl chloride. An attempt to accelerate the reaction by adding *ca.* 0.05 g of iodine was unsuccessful. However, the addition of 0.2 ml of pyridine appeared to be quite beneficial. During the 3-hr period for the preparation of benzenesulfinyl azide (**1a**), 0.07 l. of gas was evolved.

After 2.20 g of *N*-sulfinylaniline was added at −20°, the mixture was allowed to warm to room temperature. After 20 min the volume of gas evolved was 0.54 l. The total was 0.80 l. (96.5% of theory) after standing at room temperature overnight. The reaction mixture was filtered, concentrated *in vacuo*, and dispersed in rapidly stirred ether. Filtration of the ether mixture was followed by concentration and short path vacuum distillation to give 1.01 g (46% recovery) of distillate, which was 96% pure unreacted *N*-sulfinylaniline by glc and ir.

Reaction of 1a with Triphenylphosphine. Benzenesulfinyl azide (**1a**) was prepared as usual from 6.5 g (0.10 mol) of sodium azide and 8.22 g (0.51 mol) of benzenesulfinyl chloride. A solution of 13.37 g (0.51 mol) of triphenylphosphine in a mixture of 50 ml of dry acetonitrile and 50 ml of dry methylene chloride was added at −20° during 10 min. The reaction mixture was allowed to warm to room temperature and stand overnight. Gas evolution was rapid during the warm-up period and the color changed from bright to pale yellow.

The mixture was filtered by suction to remove 6.10 g of salt. Concentrating the filtrate *in vacuo* gave a solid, which was washed with ether and filtered to give 11.5 g of solid. Most of the solid dissolved in benzene, was filtered and concentrated to yield 9.45 g of triphenylphosphine oxide, mp 149–153°. The concentrate of the ether filtrate solution was recrystallized from ethanol-water to give 4.34 g of phenyl disulfide, mp 56–57°. An additional 0.87 g of triphenylphosphine oxide and 0.07 g of phenyl disulfide were obtained by extracting the ethanol-water mother liquor with methylene chloride, concentrating, and working up as before. The products were identified by comparing their ir spectra with those of authentic samples. The total yield of triphenylphosphine oxide was 10.32 g (74.5%) and the yield of phenyl disulfide was 4.41 g (79.3%).

Reaction of Benzenesulfinyl Chloride with Triphenylphosphine and Sodium Azide. To a solution of 12.67 g (0.0483 mol) of triphenylphosphine in 150 ml of dry acetonitrile was added slowly with stirring 7.75 g (0.0483 mol) of benzenesulfinyl chloride. Since the reaction was exothermic, the solution was held at room temperature with an ice bath. No gas was evolved. The reaction mixture was pale yellow. Then, 6.5 g (0.10 mol) of sodium azide was added slowly during 20 min, while cooling to control the rapid gas evolution. About 80% of the gas was evolved during the first 30 min. After standing for several hours gas evolution ceased at a volume of 1.27 l. (59% of theory). The reaction mixture was worked up as in the preceding experiment to give 9.10 g (67.5%) of triphenylphosphine oxide and 4.7 g (89.0%) of phenyl disulfide, as identified by ir.

Reaction of Benzenesulfinyl Azide (1a) with Water. Prepared by the usual procedure from 6.80 g (0.0423 mol) of benzenesulfinyl chloride and 6.5 g (0.10 mol) of sodium azide, benzenesulfinyl azide was allowed to decompose in the presence of 1.8 g (0.10 mol) of water. After standing overnight, the gas evolution measured 1.06 l (112%) at standard temperature and pressure. Suction filtration gave 6.15 g of water soluble salt. Concentration of the filtrate *in vacuo*, treatment with methylene chloride-hexane, and filtration gave 1.35 g (20.2%) of benzenesulfonamide (by ir). Concentration of this filtrate *in vacuo* gave 3.37 g of an oily mixture, from which no identifiable product could be isolated.

In another run of the same reaction (0.05 mol scale), benzenesulfonamide (29% yield) was obtained from the reaction concentrate by washing with chloroform. Washing the chloroform concentrate with ethanol gave a trace of phenyl disulfide (identified by ir). The ethanol filtrate was concentrated, triturated with ether, filtered, and concentrated again. The ether concentrate was eluted with benzene-hexane (5 to 1 volume) through silica gel. The first fraction (an oil) weighed 0.43 g and consisted mostly of phenyl disulfide (**3a**) with some benzenesulfonyl azide (**2a**). This oil crystallized overnight. Recrystallization from cold hexane gave pure **3a** (by ir). The second fraction weighed 1.22 g and was a mixture of **2a** and **3a** and other material.

Reaction of Benzenesulfinyl Azide (1a) with Dimethyl Sulfoxide (DMSO). A cold azide solution (below −23°), prepared from 6.65 g (0.042 mol) of benzenesulfinyl chloride in acetonitrile, was combined with 5.88 ml (0.083 mol) of DMSO and warmed (40–50°). On decomposition 0.969 l. of gas was evolved at 742 Torr and 25° (93.5% of theory). The solvent (acetonitrile) was removed by rotary evaporation and the resultant brown oil extracted with 50 ml of water. The water extract was extracted with two 25-ml portions of chloroform. An oily yellow solid was produced when the combined chloroform extracts were concentrated after drying with magnesium sulfate. Recrystallization of the solid from chloroform–hexane gave 1.8 g (20%) of *N*-(benzenesulfonyl)-*S,S*-dimethylsulfimide (**7a**), mp 126–127°, lit.[29] mp 131°.

Reaction of *p*-Toluenesulfinyl Azide (1b) with DMSO. A cold acetonitrile solution of azide (**1b**, prepared from 17.46 g (0.1 mol) of *p*-tolucnesulfinyl chloride was added dropwise to a warm (40–50°) solution of DMSO (15.5 g, 0.2 mol) in acetonitrile (10 ml). After gas evolution ceased, the reaction mixture was worked up in the same way as in the reaction of **1a** with DMSO. Recrystallization from chloroform–hexane produced 16.78 g (73%) of *N*-(*p*-toluenesulfonyl)-*S,S*-dimethylsulfimide (**7b**), mp 154–156°, lit[10,29] mp 158–159°.

Reaction of Benzenesulfinyl Azide (1a) with Diphenyl Sulfoxide. A cold acetonitrile solution of azide (**1a**), prepared from 4.82 g (0.03 mol) of benzenesulfinyl chloride was added dropwise to a warm (50°), saturated solution of 6.06 g (0.03 mol) of diphenyl sulfoxide in acetonitrile. After decomposition was complete, the solvent was removed by rotary evaporation and the residue was dissolved in ethanol. A mixture of benzenesulfonamide and *N*-(benzenesulfonyl)-*S,S*-diphenylsulfimide (**7c**) crystallized upon cooling with Dry Ice. Recrystallization of **7c** from ethanol produced 2.65 g of a white solid (26%), mp 118–120°.

Ethanol was removed *in vacuo* from the **7c** recrystallization mother liquor to produce a sticky yellow solid. The solid was washed with small quantities of cold ether to give 1.27 g (27%) of benzenesulfonamide (identified by ir).

Concentration of the original ethanolic solution after removal of **7c** and benzenesulfonamide gave a dark brown, viscous oil. This oil was chromatographed on a 5 × 40 cm silica gel column with toluene. Concentration of the first 100 ml of eluent produced a colorless oil. Gas chromatographic separation of this oil (⅜ in. by 10 ft column of 30% SE-30 on Chromosorb P) gave diphenyl sulfide (identical by ir and retention time with an authentic sample) in 7% yield.

Reaction of *p*-Toluenesulfinyl Azide (1b) with Methyl *p*-Tolyl Sulfoxide. The azide (**1b**) solution in acetonitrile prepared from 8.73 g (0.05 mol) of *p*-toluenesulfinyl chloride was added dropwise into 6.62 g (0.0477 mol) of methyl *p*-tolyl sulfoxide at 50°. After decomposition the solvent was removed by rotary evaporation and 10 ml of dichloromethane was added to the viscous, oily residue. The dichloromethane solution was added slowly into 250 ml of vigorously stirred ether. A precipitate was filtered and the filtrate was concentrated to give a viscous brown oil. Trituration of the oil with pentane produced a sticky yellow solid which was separated from the triturate by filtration. This solid was recrystallized from ethanol to give *N*-(*p*-toluenesulfonyl)-*S*-methyl-*S*-*p*-tolylsulfimide (**7d**) in 16% yield (based upon sulfoxide used), mp 122–124°, lit.[30] mp 125–126°.

Reaction of *p*-Toluenesulfinyl Azide with Methyl *p*-Tolyl Sulfoxide ((+)-9). One-sixth of the azide solution prepared from 10.47 g (0.06 mol) of *p*-toluenesulfinyl chloride was added dropwise at 50° to a solution containing 1.4 g (0.0092 mol) of (+)-(*R*)-methyl *p*-tolyl sulfoxide ((+)-**9**) (99% optical purity) and 10 ml of acetonitrile. After decomposition, the mixture was concentrated *in*

vacuo, dissolved in 10 ml of dichloromethane, and added slowly to 250 ml of ether, as in the previous reaction. Concentration of the ether filtrate produced 3.085 g of light yellow oil, which was triturated with 15 ml of ether to give 2.838 g of a sticky white solid and a light brown solution. Dichloromethane was added to just dissolve the white solid and the solution was added dropwise into 200 ml of a vigorously stirred pentane–ether solution. Filtration of the pentane–ether solution produced 1.4894 g of crude product, mp 113–116°, $[\alpha]^{20}D$ +211.7° (*c* 1.68, acetone). Ir analysis showed it to be **7d**. All other fractions were combined and concentrated to a brown oil. Next, 1.069 g of the solid identified as **7d** was chromatographed on 100 g of silica gel in a 3.5-cm diameter column with acetonitrile as eluent. The fractions collected from the column were analyzed by tlc, and those containing only **7d** were combined. Removal of the solvent yielded 0.8391 g of optically active (+)-**7d**, mp 121.8–124°, $[\alpha]^{20}D$ +247.6° (*c* 1.68, acetone), lit.[31] mp 124–125°, $[\alpha]^{20}D$ +269° (optically pure (+)-**7d**). Based upon starting sulfoxide, (+)-**7d** was obtained in 42% yield.

The combined residues resulting from the isolation of **7d** were dissolved in warm dichloromethane followed by the addition of pentane to a cloud point. Upon cooling 0.216 g (15.2%, based upon sulfoxide) of *p*-toluenesulfonamide (identified by ir) was isolated.

Solvent was removed from the remaining residue and the resultant oil was molecularly distilled at 90° (0.5 Torr), giving a yellow oil distillate (0.2883 g). Gas chromatographic separation on a ¼ in. × 6 ft 15% SE-30 column gave methyl *p*-tolyl sulfide (by ir and retention time) in 2.8% yield.

Reaction of Benzenesulfinyl Azide (1a) with DMSO in the Presence of *N*-(*p*-Toluenesulfonyl)-*S,S*-dimethylsulfoximide (8b). One-half of a cold benzenesulfinyl azide (**1a**) solution in acetonitrile, prepared from 4.82 g of benzenesulfinyl chloride (0.030 mol), was combined with a solution containing 2.96 g (0.012 mol) of *N*-(*p*-toluenesulfinyl)-*S,S*-dimethylsulfoximide (**8b**) in 1.67 g (0.0214 mol) of DMSO and warmed to room temperature. When the decomposition was complete, the solvent was evaporated and the residue was extracted with two 50-ml portions of water. The water extracts were extracted with three 50-ml portions of chloroform. The chloroform extracts were combined, dried with magnesium sulfate, and concentrated to give 3.868 g of a colorless oil.

Nmr analysis showed that the colorless oil contained a sulfimide-methyl peak (singlet δ 2.7), a sulfoximide-methyl peak (doublet δ 3.25–3.4), and a tolyl-methyl peak (singlet δ 2.4). The ratio of sulfoximide peak integral to the tolyl-methyl peak integral was 2:1. Independent studies showed that a mixture of *N*-(benzenesulfonyl)-*S,S*-dimethylsulfimide and *N*-(*p*-toluenesulfinyl)-*S,S*-dimethylsulfoximide could be quantitatively extracted from a water solution with chloroform. An nmr analysis of **9b** showed an integral ratio of 2:1 for the sulfoximide-methyls to tolyl-methyl nmr peaks when analyzed alone or in the presence of *N*-(benzenesulfonyl)-*S,S*-dimethylsulfimide (**7a**).

Preparation of *N*-(Benzenesulfonyl)-*S,S*-dimethylsulfimide (7a). The sulfimide (**7a**) was prepared from benzenesulfonamide and dimethyl sulfide using a general procedure reported by Kucsman and coworkers.[66] The sulfimide (**7a**) was recrystallized from chloroform–hexane, mp 127.5–127.7°, lit.[29] mp 131°. The ir spectrum and melting point of this product were identical with those of the product isolated from the reaction of **1a** with DMSO. Their mixture melting points showed no depression.

Preparation of *N*-(*p*-Toluenesulfonyl)-*S,S*-dimethylsulfimide (7b). The sulfimide (**7b**) was prepared from chloramine T and dimethyl sulfide using the general procedure of Leandri and Spinelli.[67] Recrystallization from chloroform–hexane gave **7b** in 30.8% yield, mp 158–159°, lit.[10,29] mp 158–159°. The ir spectrum of this product was identical with that obtained from the reaction of **1b** with DMSO.

Preparation of *N*-(Benzenesulfonyl)-*S,S*-diphenylsulfimide (7c). The sulfimide (**7c**) was prepared from benzenesulfonamide and diphenyl sulfide by the general procedure of Kucsman and coworkers[66] in low yield (*ca.* 20%). It was recrystallized from ethanol–diethyl ether, mp 122–124°. The ir of this compound was identical with that of **7c** isolated from the reaction of **1a** with diphenyl sulfoxide. The mixture melting point of these two products was not depressed. *Anal.* Calcd for $C_{18}H_{15}NO_2S_2$: C, 63.31; H, 4.43; N, 4.10. Found: C, 63.43; H, 4.21; N, 4.08.

Preparation of *N*-(*p*-Toluenesulfonyl)-*S*-methyl-*S*-*p*-tolylsulfimide (7d). Sulfimide **7d** was prepared from chloramine T and methyl *p*-tolyl sulfide by the same procedure used to prepare **7b** in 43% yield. It was recrystallized from chloroform–hexane, mp 122–124°, lit.[30] mp 125–126°. The ir spectrum of this compound was identical with that of **7d** isolated from the reaction of **1b** with methyl *p*-tolyl sulfoxide (both optically active and racemic).

Preparation of *N*-(Benzenesulfinyl)-*S,S*-dimethylsulfoximide (8a). Under a stream of dry nitrogen, 9.1 ml (0.0118 mol) of a 1.3 *M* solution of *n*-butyllithium was added to 10 ml of a benzene solution containing 1.099 g (0.0118 mol) of dimethyl sulfoximide. After stirring for 1.75 hr, 1.89 g (0.0118 mol) of benzenesulfinyl chloride was added at such a rate that the temperature never exceeded 35°. The benzene was removed by rotary evaporation and the resultant white solid was extracted with two 25-ml portions of dichloromethane. Removal of the solvent produced a brown oil which was crystallized first from benzene–hexane and then recrystallized from dichloromethane–hexane to give 1.158 g (41%) of **8a** as a white solid, mp 86.5–88°, lit.[32] mp 84–85.5°. The yield of this reaction was increased to *ca.* 70% by substituting sodium hydride for *n*-butyllithium in the procedure; however, conditions were not optimized in either case.

Preparation of *N*-(*p*-Toluenesulfinyl)-*S,S*-dimethylsulfoximide (8b). The procedure described for the preparation of **8a** was employed to prepare **8b** in *ca.* 70% yield as a white solid, mp 108–109°, from *N*-sodiodimethylsulfoximide[68] and *p*-toluenesulfinyl chloride. The nmr was especially definitive for the identification of compounds **8a** and **8b** because the sulfoximide-methyl groups of both compounds show a doublet when the spectrum is taken in chloroform-*d* and a singlet in deuterium oxide (see Table III).

Preparation of Dimethyl Sulfoximide. Dimethyl sulfoximide was prepared by modification of a procedure described by Bentley and coworkers.[69] In a 500-ml three-necked flask fitted with a condenser, powder addition funnel, and thermometer, a heterogeneous mixture consisting of 50 ml (0.89 mol) of concentrated sulfuric acid (specific gravity 1.84), 20 ml (0.26 mol) of dry DMSO, and 200 ml of dry chloroform was prepared. To this magnetically stirred mixture was added 20 g (0.31 mol) of sodium azide at such a rate as to maintain the temperature at 45–50°. After stirring overnight the mixture was poured over ice and the acid neutralized with solid sodium bicarbonate. Excess water was removed by distillation at aspirator pressure, and 100 ml of absolute ethanol was added to the resultant slurry. The insoluble sodium sulfate was filtered off and the solution concentrated to 60 ml by rotary evaporation. After standing overnight, precipitated salts were again filtered off, and the remaining solution was distilled *via* a short path distillation apparatus. All materials which distilled at a pot temperature of 50° (0.025 Torr) were discarded. Sublimation of the viscous, brown pot residue at 70–75° (0.025 Torr) produced a hygroscopic light yellow solid. Resublimation gave 16.5 g (63.5%) of the white, hygroscopic sulfoximide, mp 56.5–58°, lit.[69b] mp 57–58°.

Preparation of Methyl *p*-Tolyl Sulfoxide. Methyl *p*-tolyl sulfide[70] was oxidized with sodium *m*-periodate by the method of Leonard and Johnson.[71] In a typical reaction, 12 g (0.087 mol) of methyl *p*-tolyl sulfide was oxidized to produce 13 g (97%) of the sulfoxide, mp 52–54°.

Preparation of (+)-(*R*)-Methyl *p*-Tolyl Sulfoxide ((+)-9). (+)-(*R*)-Methyl *p*-tolyl sulfoxide ((+)-**9**) was prepared from (*l*)-menthyl *p*-toluenesulfinate[72] and methylmagnesium iodide by the method of Andersen,[73] mp 73.4–75.0°, $[\alpha]^{20}D$ +144.0° (*c* 0.790, acetone), lit.[31,74] mp 74.5–75.5°, $[\alpha]^{20}D$ +145.5° (*c* 0.795, acetone) for optically pure (+)-**9**.

Acknowledgment. Financial support for this research was provided in part by grants from the National Cancer Institute (CA-13201) and from Research Corporation. We also wish to thank Jill Armbrust, Victor Munson, and Roy Wong for their assistance in preparing some compounds and Dr. Robert Koob for helpful discussions.

Appendix

Microscopic Reversibility and Substitution *via* Trigonal Bipyramidal Intermediates. In considering possible mechanistic pathways for substitution at phosphorus involving trigonal bipyramidal intermediates, Westheimer[54] has suggested an "expanded principle of microscopic reversibility

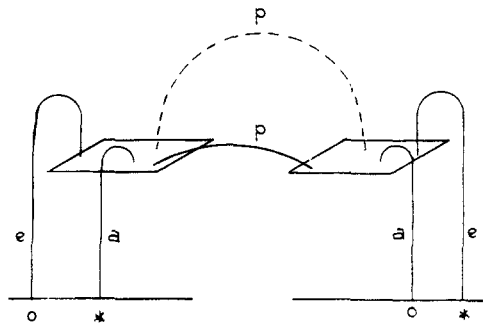


Figure 6. Energy surface for substitution *via* trigonal bipyramidal intermediates: *, labeled group; O, unlabeled group.

(PMR), which has been rephrased by Mislow[55] as an "extended" PMR. This principle states that the stereochemistry (axial *vs.* equatorial) of entry and departure must be the same. However, Mislow[55] points out that, in fact, this rule is *not* required according to Burwell and Pearson's[75] analysis of the PMR. Rather, from past experiments, certain kinetic preference rules have been established which indicate that ae and ea mechanisms are normally energetically unfavorable compared with an apa (axial entry, pseudorotation, axial departure) mechanism.[54,55] Thus, ea and ae mechanisms are reasonable and would be expected if the barrier to pseudorotation should become excessive. Even if the entering and leaving groups are the same, the ae and ea mechanisms do not violate the PMR.

If a reaction is to be described in which the reactants and products are equivalent, and the entering and leaving groups the same, then one of the groups must be labeled and traced through each step or no reaction occurs. Thus, for analysis purposes the groups are distinguished from each other. Examination of Figure 6 demonstrates that entrance of the labeled group by one path (a) and departure of the unlabeled group by another (e) from the same intermediate does not violate the PMR, because the reverse process must retrace the same paths (if p is large). When p is small, the apa mechanism will dominate, again without violation of the PMR. None of these mechanisms requires formation of the intermediate by one energy path and return to the same labeled starting point by another energy path. Only a mechanism like ape (when p is small) would violate the PMR.

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The Stereospecific Total Synthesis of Haemanthidine and Tazettine[1]

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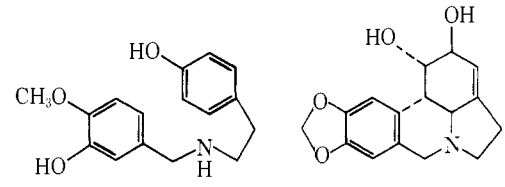
Abstract: Synthesis design principles are discussed for the crinane skeleton family of amaryllidaceous alkaloids, and a prime synthetic sequence so derived is realized in a stereospecific total synthesis of the functionally and stereochemically most complex member, haemanthidine, as well as the closely related tazettine.

Most of the structures of alkaloids can be grouped into a few large families of common skeleton and/or common biosynthesis. Of these, the large family (over 70 structures) of alkaloids of the *Amaryllidaceae* are a single biosynthetic family containing three main skeletal variants from oxidative coupling of the norbelladine (**1**) precursor;[2] the three are represented by their ubiquitous members, lycorine (**2**), galanthamine (**3**), and crinine (**4d**). At the time we initiated this work, galanthamine had been synthesized by a biomimetic route[3] and the other two had not. Natural alkaloids of the lycorine family have not yet been synthesized despite a number of efforts,[4] and two syntheses of crinine have since appeared.[5]

We elected to examine the most complex of the crinine family, *i.e.*, haemanthidine (**4a**), as the most challenging. The crinine family consists of a variety of alkaloids differing in functionality at positions 3, 6, and 11 as summarized in **4**; a parallel set exists with an added methoxyl group on the aromatic ring. In selecting haemanthidine as the primary target, we should create the most functionalized member, from which selective removal or alteration of the functional groups could lead to the other members (*cf.* **4a** → **b** → **c** → **d**). Such a route would then constitute a more general synthesis of the whole family, whereas a primary target of less functionality would require functionalization of unactivated sites (a much more difficult synthetic direction) in order to achieve the same generality. Indeed, at least in the dihydro series, such functionality removal had already been achieved by Wildman[6] during degradative studies.

The synthetic challenge is manifest both in the stereochemistry of haemanthidine and in its sensitivity to acid and base. The stereochemistry is depicted in **5**; there are five asymmetric centers marked, four centered on ring C, and the fifth, at C-6, which is selfequilibrating *via* the amino–aldehyde tautomer.[7] From a synthetic viewpoint, the axial carbon-11 mounted on a rigid *trans*-decalin skeleton affords a functional site for stereocontrol, particularly of the introduction of the less stable axial methoxyl group at C-3, equilibration of which to the more stable allylic ether should provide a route to the crinamine epimers (**4a,b**). The hydroxyl group at C-11, however, is the opposite epimer to



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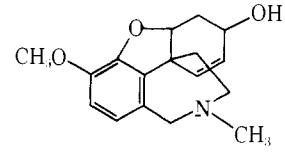

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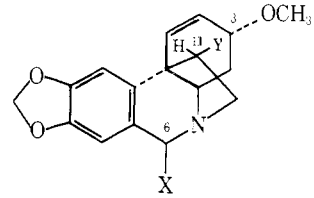
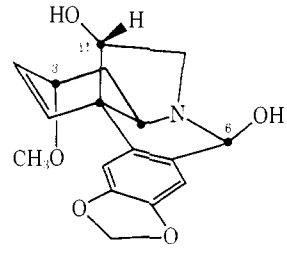


		6-X	11-Y	3-epimer
4a,	haemanthidine	OH	OH	6-hydroxy-crinamine
b,	haemanthamine	H	OH	crinamine
c,	buphanisine	H	H	
d,	crinine(3-OH)	H	H	epicrinine



5

that obtained on hydride reductions of ketone in the natural series.[8,9] The sensitivity of haemanthidine to acid and base also puts severe synthetic strictures on the choice of the