variation in intensity was noted in these standards but no systematic trends were evident. Scattered intensity in a scan was assumed significant at the $3\sigma$ level. No absorption corrections were applied and the data were converted to structure amplitudes in the usual way.

**Structure Determination and Refinement.** For **5**, the positions of the two sulfur atoms were found from a sharpened three-dimensional Patterson function and the structure solved by the heavy atom method. Compound **7** is isostructural with **5** and parameters for the atoms of **5** were used to phase the reflections of **7**. The additional oxygen atom was found from a difference map. The program MULTAN[19] was used to solve the structure of **6** in a routine way.

Hydrogen atoms were located in all cases from difference electron-density maps and included in the block-diagonal least-squares refinement. A conventional weighting scheme was used,[20] and anisotropic thermal parameters were assigned to S, O, and C atoms, isotropic $B$ values to H. Damping factors were applied to assure smooth convergence and refinement continued until no calculated shift in any parameter exceeded one-tenth of the corresponding esd. The final conventional unweighted and weighted residuals were 0.044 and 0.040 for **5**, 0.045 and 0.032 for **6**, and 0.047 and 0.036 for **7**. The scattering curves used for S, O, and C were taken from Hanson et al.[21] and for hydrogen from Stewart et al.[22] Programs used, other than MULTAN and ORTEP, were written in this laboratory for the XDS Sigma 2 computer.

**Registry No.**—**4**, 5425-44-5; **5**, 60349-76-0; **6**, 60349-79-3; **7**, 61158-78-9.

**Supplementary Material Available.** Listings of observed and calculated structure amplitudes, complete bond length and angle calculations, and information on least-squares mean planes of interest and on intermolecular contacts (35 pages). Ordering information is given on any current masthead page.

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# Chemistry of the Sulfur–Nitrogen Bond. 12.[1] Metal-Assisted Synthesis of Sulfenamide Derivatives from Aliphatic and Aromatic Disulfides


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The metal-assisted synthesis of sulfenamide derivatives 1 and 2 from aliphatic and aromatic disulfides and amines was explored. This method is more convenient and results in higher yields and a less reactive product than sulfenamides prepared from sulfenyl chlorides. Sulfenamides containing reactive functional groups, not accessible from sulfenyl chlorides, can be prepared using this procedure. With ammonia and aromatic disulfides this method yields bis(arenesulfen)imides **4** when the groups attached to sulfur are more electron donating than a 3,4-dichlorophenyl group. Alkanesulfenamides of ammonia ($RSNH_2$) cannot be isolated, but are trapped with aromatic aldehydes and ketones to yield $N$-alkylidenealkanesulfenamides **2**.


Sulfenamides **1** and $N$-alkylidenesulfenamides **2** are important intermediates in organic synthesis and have proven useful in investigations of lone pair interactions ("$\alpha$ effect"), bond polarization effects, and (p–d) $\pi$ conjugation.[2] Sulfenamides have also found important industrial applications.

R–S–NR′R″ — **1a**, R = alkyl; **b**, R = aryl

R–S–N=CR′R″ — **2**, R′, R″ = alkyl, aryl

Sulfenamides (1) are used as sulfenyl-transfer reagents in the synthesis of sulfides,[3] disulfides,[4] trisulfides,[4b] sulfenate esters,[5] sulfenamides,[6] alkyl (aryl) dialkylaminosuccinimidosulfonium salts,[7] and aminecarbotrithioates.[8] $N$-Alkylidenearenesulfenamides, **2b**, can be oxidized to 2-arenesulfonyl-3-phenyloxaziridines[9a] and sulfinamides.[9b] The latter compounds are useful in the synthesis of sulfenic acids.[9b,10]

The possibility that interactions between the lone pairs of electrons on sulfur and nitrogen may destabilize the S–N

**Table I. Sulfenamides from Aromatic Disulfides**

| Entry | Disulfide | Registry no. | Amine | Registry no. | Conditions | Sulfenamide % yield | Registry no. | Bp (mp), °C (mm) | NMR, δ ($CDCl_3$) |
|---|---|---|---|---|---|---|---|---|---|
| 1 | *p*-Tolyl | 103-19-5 | Piperidine | 110-89-4 | $AgNO_3$–MeOH | 60 | 18511-53-0 | 78–79 (0.005 | 1.6 (m, 6), 2.4 (s, 3, Me), 2.9 (t, 4), 7.2 (q, 4) |
| 2 | | | Aniline | 62-53-3 | | 35 | | *a* | |
| 3 | Phenyl | 882-33-7 | Ethylamine | 75-04-7 | | 75 | 24380-80-1 | 54–57 (0.0.04) | 1.2 (t, 3, $J$ = 7 Hz), 2.9 (dt, NH, $CH_2$ 7.2 (s, 5) |
| 3 | | | Isopropylamine | 75-31-0 | | 76 | 34690-94-3 | 61–62 (0.4) | 1.1 (d, 6, $J$ = 7 Hz), 2.8 (b, 4, NH), 3.1 (m, 1), 7.26 (m, 5) |
| 4 | | | *tert*-Butylamine | 75-64-9 | | 70 | 19117-31-8 | 57–60 (0.3) | 1.1 (s, 9), 2.7 (b s, 1), 6.9–7.4 (m, 5) |
| 5 | | | Allylamine | 107-11-9 | | 88 | 61076-24-2 | 61–64 (0.15) | 2.85 (b, 1, NH), 3.5 (t, 2, $J$ = 5 Hz), 5.1 (m, 1), 5.8 (m, 1), 7.3 (s, 5) |
| 6 | | | 2-Aminoethanol | 141-43-5 | | 70 | 61076-25-3 | 124 (0.05) | 3.0 (b t, 2 H), 3.3 (b, 2 H, OH, NH), 3.6 (m, 2 H), 7.25 (s, 5) |
| 7 | | | Aniline | | | 75–80 | | *a* | |
| 8 | | | Diethylamine | 109-89-7 | | 55 | 6667-19-2 | 60–65 (0.65) | 1.13 (t, 6, $J$ = 8 Hz), 2.96 (g 4, $J$ = 8 Hz), 7.26 (m, 5) |
| 9 | | | Diisopropylamine | 108-18-9 | | 73 | 19117-30-7 | 71–73 (0.4) | 1.17 (d, 12, $J$ = 7 Hz), 3.4 (m, 2), 7.25 (m, 5) |
| 10 | 4-Chlorophenyl | 1142-19-4 | Aniline | | | 75 | | *b* | |
| 11 | 4-Bromophenyl | 5335-84-2 | Aniline | | | 70 | 32338-03-7 | 85–89 | 5.05 (bs, 1, NH), 6.8–7.5 (m, 9) |
| 12 | 3-Nitrophenyl | 537-91-7 | Ethylamine | | | 90 | 34879-73-7 | *c* | 1.2 (t, 3, $J$ = 6 Hz), 3.0 (q, 2), 7.2–8.4 m, 4) |
| 13 | | | | | $HgCl_2$–MeOH | 61 | | | |
| 14 | | | Allylamine | | $AgNO_3$–MeOH | 75 | 61076-26-4 | 128–130 (0.05) | 3.0 (b, 1, NH), 3.6 (t, 2, $J$ = 5 Hz), 5.2 (m, 1), 5.8 (m, 1), 7.3–8.0 (m, 4) |
| 15 | | | 2-Aminoethanol | | | 75 | 61076-27-5 | Oil | 2.4 (s, 1, OH) 3.1 (t, 2, $J$ = 5 Hz), 3.4 (b, 1, NH), 3.8 (t, 2, $J$ = 5 Hz), 7.5–8.5 (m, 4) |
| 16 | | | Aniline | | | 82 | | *d* | |
| 17 | | | Dimethylamine | 124-40-3 | | 60 | 61076-28-6 | 82 (0.015) | 2.9 (s, 6), 7.3–8.1 (m, 4) |
| 18 | | | | | $HgCl_2$–MeOH | 60 | | | |
| 19 | | | Bis(2-chloroethyl)amine | 334-22-5 | | 23 | 61076-29-7 | Oil[e] | 3.6 (m, 8), 7.1–8.5 (m, 4) |
| 20 | | | Diethylamine | | $AgNO_3$–MeOH | 86 | 61076-30-0 | 109 (0.05) | 1.2 (t, 6, $J$ = 7 Hz), 3.1 (q, 4, $J$ = 7 Hz), 7.3–8.2 (m,4) |
| 21 | | | 2,2-Dimethylaziridine | 2658-24-4 | | 45 | 61076-31-1 | 123 (0.2) | 1.4 (s, 6), 2.0 (s, 2), 7.4–8.4 (m, 4) |
| 22 | | | Di-*sec*-butylamine | 626-23-3 | | 70 | 61076-32-2 | 134 (0.13) | 0.9 (t, 6, $J$ = 7 Hz), 1.2 (d, 3, $J$ = 7 Hz), 1.5 (m, 4), 3.0 (hep, 2), 7.2–8.3 (m, 4) |
| 23 | 2-Nitrophenyl | 1155-00-6 | Ethylamine | | | 87[a] | 24398-42-3 | 118 (0.75) | 1.2 (t, 3, $J$ = 7 Hz), 2.4 (q, 2, $J$ = 7 Hz), 2.4 (b, 1, NH) |
| 24 | 4-Nitrophenyl | 100-32-3 | Aniline | | | 60 | | *a* | |
| 25 | 2-Benzothiazolyl | 120-78-5 | Isopropylamine | | | 90 | | *f* | |
| 26 | | | Aniline | | | 90 | | *g* | |
| 27 | | | Piperidine | | | 90 | | *h* | |

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**Table II. Sulfenamides from Aliphatic Disulfides**

| Entry | Disulfide | Registry no. | Amine | Conditions | Sulfenamide % yield | Registry no. | Bp, °C (mm) | NMR, δ |
|---|---|---|---|---|---|---|---|---|
| 1 | Methyl | 624-92-0 | Piperidine | AgOAc–EtOAc | 43 | 7257-48-9 | 58 (10) | 2.92 (t, 4, $J$ = 6 Hz), 2.2 (s, 3, Me), 1.48 (m, 6) |
| 2 | | | Aniline | | Trace[a] | | | |
| 3 | | | Isopropylamine | | Trace[a] | | | |
| 4 | Ethyl | 110-81-6 | Piperidine | | 30 | 25116-55-6 | 37–38 (0.32) | 1.2 (t, 3, $J$ = 7 Hz), 1.5 (m, 6), 2.65 (q, 2, $J$ = 7 Hz), 3.0 (m, 4) |
| 5 | | | Piperidine | $AgNO_3$–MeOH | 0 | | | |
| 6 | | | Allylamine | AgOAc–EtOAc | Trace[a] | | | |
| 7 | *n*-Butyl | 629-45-8 | Piperidine | | 40 | 25116-56-7 | 76 (0.7) | 0.93 (t, 3, $J$ = 6 Hz), 1.5 (m, 10), 2.6–3.2 (m, 6) |
| 8 | Isopropyl | 4253-89-8 | Piperidine | | 45 | 61076-33-3 | 36.7 (0.35) | 1.3 (d, 6, $J$ = 6 Hz), 1.4 (m, 6), 2.1 (m, 1), 2.8 (m, 4) |
| 9 | Benzyl | 150-60-7 | Isopropylamine | | 97 | 59004-78-3 | *b* | 1.1 (d, 6), 2.33 (broad s, 1), 3.0 (m, 1), 3.75 (s, 2), 7.25 (s, 5) |
| 10 | | | Diethylamine | | 58 | 34879-74-8 | 79–82 (0.07) | 1.1 (t, 6, $J$ = 7 Hz), 2.9 (q, 4, $J$ = 7 Hz), 3.77 (s, 2), 7.3 (m, 5) |
| 11 | | | Di-*n*-butylamine[c] | | 53 | 61076-34-4 | 80–81 (0.007) | 0.9 (t, 6), 1.4 (m, 8), 2.81 (t, 4, $J$ = 7 Hz), 3.8 (s, 2), 7.27 (m, 5) |

[a] As indicated by NMR. [b] Decomposes on heating. [c] Registry no., 111-92-2.

bond[2] and increase the nucleophilicity of the sulfenamide nitrogen has recently been discussed.[11] Bond polarization effects resulting from the difference in electronegativity between sulfur and nitrogen in 1 activate the S–N bond for attack by both nucleophiles and electrophiles and appear to be the factor primarily responsible for the chemistry of these compounds. Recent reports suggest that there is little, if any, (p–d) $\pi$ conjugation between sulfur and nitrogen when sulfur is attached to an $sp^3$-hybridized nitrogen.[12,13] Localized (p–d) $\pi$ bonding exists when sulfur is attachd to an $sp^2$-hybridized nitrogen, i.e., **2**.[13,14]

Industrial applications of sulfenamide derivatives include use as accelerators in rubber vulcanization, pesticides and fungicides, radioprotective agents, and in polymerization reactions.[15]

The condensation of an aryl or alkyl sulfenyl chloride with an amine has been the only general synthetic route to sulfenamides (eq 1).[2,16,17]

$$R\text{–}S\text{–}Cl + 2R_2NH \rightarrow R\text{–}S\text{–}NR_2 + R_2NH_2{}^+Cl^- \quad (1)$$

Other less satisfactory methods for the synthesis of sulfenamides include the reaction of metal mercaptides with chloro amines,[18] oxidative condensation of thiols with amines,[19] and the displacement of amines on alkylsulfenyl thiocyanates[20] or alkyl thiolsulfonates.[21] A potentially useful synthesis of alkyl and aryl sulfenamides is the substitution of alkyl- and arylamines on thiophthalimides;[6] however, this procedure requires the synthesis of the intermediate thiophthalimide from the sulfenyl chloride and phthalimide.[22]

There are a number of disadvantages in using the sulfenyl chloride method to prepare sulfenamides (eq 1). While the chlorination of a disulfide usually produces the sulfenyl chloride in good yield, side reactions often occur;[16,17] this is particularly true of the lower molecular weight aliphatic disulfides. Sulfenyl chlorides are also thermally unstable, easily hydrolyzed, and react with hydroxyl groups, active methylene groups, and multiple bonds.[17] Sulfenamides containing these functional groups cannot be prepared from the sulfenyl chloride and amine.

Another limitation of the synthesis of sulfenamides from sulfenyl chlorides, which has only recently been recognized, is the difficulty in removing trace amounts of amine hydrochlorides, a by-product in this synthetic procedure (eq 1), which activates the S–N bond toward attack by nucleophiles,[23] markedly lowers the storage lifetime of sulfenamides, and alters the thermal chemistry of arenesulfenanilides.[24]

An important alternative to the synthesis of sulfenamides from amines and sulfenyl chlorides is the metal-assisted synthesis of sulfenamides from disulfides and amines (eq 2).[25] Many of the disadvantages associated with the synthesis of sulfenamides from amines and sulfenyl chloride can be avoided using this procedure (eq 2).

$$R\text{–}S\text{–}S\text{–}R + MX \xrightarrow{2R_2NH} MS\text{–}R + R\text{–}SNR_2 + R_2NH_2{}^+X^- \quad (2)$$

R = alkyl, aryl
MX = $AgNO_3$, AgOAc, $HgCl_2$

In this paper we report on the scope of this method (eq 2) for sulfenamide synthesis.

## Results and Discussion

The metal-assisted synthesis of sulfenamides from alkyl and aryl disulfides is a convenient "one-pot" reaction. The metal salt is dissolved in methanol or ethyl acetate followed by addition of the disulfide and an excess of the amine. Removal of the precipitated metal mercaptide yields the sulfenamide. Disulfides can be obtained in high yield (ca. 90%) by oxidation of the thiol with 15% hydrogen peroxide.

Good to excellent yields of sulfenamides from aromatic disulfides (Table I) and moderate yields of sulfenamides from aliphatic disulfides (Table II) were obtained. The sulfenamides were identified by their IR and NMR spectra, comparison with literature values, and elemental analysis where stability of the sulfenamide permitted. The infrared spectra of sulfenamides from primary amines showed a single absorption at 3320–3330 $cm^{-1}$ and sulfenamides of ammonia ($RSNH_2$) absorption at 3280 and 3380 $cm^{-1}$.

The metal-assisted synthesis of sulfenamides does not require the separate preparation of an unstable intermediate (i.e., sulfenyl chloride) and yields via this method were better than those reported for the sulfenyl chloride method. Furthermore, the sulfenamides obtained by this method (eq 2) were less reactive as indicated by their longer storage time and increased thermal stability.[24] Apparently the amine hydronitrate and -acetate (eq 2) are more easily removed than the corresponding amine hydrochlorides (eq 1).

Using this procedure, sulfenamides containing reactive functional groups such as hydroxyl and double bonds, not accessible from the sulfenyl chloride, can be prepared. Good yields of sulfenamides were obtained from allylamine and 2-aminoethanol and aromatic disulfides (Table I, entries 5, 6, 14, 15), but the procedure failed with aliphatic disulfides.

A disadvantage of the metal-assisted synthesis of sulfenamides is the use of relatively expensive silver salts. This can be overcome to a large extent if the silver is recovered from the silver mercaptide and converted to silver nitrate. This was accomplished with an overall yield of about 70% (see Experimental Section).

Mercuric chloride in methanol gave results similar to silver nitrate–methanol (Table I, entries 13, 18). With mercuric chloride yields were somewhat lower and the thermal stability of the sulfenamide was reduced. No reaction between aliphatic disulfides, amines, and mercuric chloride was detected. Mercuric chloride can also be used in place of silver nitrate where the latter reagent would react with the amine. For example a low yield of bis(2-chloroethyl)-3-nitrobenzenesulfenamide (Table I, entry 19) was obtained using mercuric chloride. This sulfenamide was only moderately stable, decomposing after several weeks at room temperature. Although bis(2-chloroethyl)benzenesulfenamide was apparently formed, it could not be isolated. The reactivity of this sulfenamide may be due to the increased nucleophilicity of the sulfenamide nitrogen (vide infra).

The mechanism for the metal-assisted synthesis of sulfenamides probably involves the complexation of the metal ion with one of the lone pairs of electrons of the disulfide bond. This orientates the S–S bond toward nucleophilic attact by the amine. A similar mechanism has been proposed for the formation of **2** from silver nitrate, disulfides, ammonia, and aldehydes or ketones.[26]

**Aromatic Disulfides.** Good yields of sulfenamides from aromatic disulfides and a wide variety of aliphatic amines and aniline were obtained using the metal-assisted procedure (eq 2). Hindered amines such as diisopropyl- and di-*sec*-butylamine also gave good yields of the corresponding sulfenamides (Table I, entries 9, 22). Sulfenamides from aliphatic amines were sufficiently stable to be purified by distillation. Sulfenamides from primary aliphatic amines appeared to be less stable than those from secondary amines, the former decomposing over a period of months to yield the disulfide and amine. Since arenesulfenanilides decompose on heating,[2] excess aniline was removed by column chromatography. These results are summarized in Table I.

Amines less basic than aniline failed to yield sulfenamides using this procedure. Disulfides such as 4-hydroxyphenyl disulfide, 2-aminophenyl disulfide, and *N,N'*-piperidinyl disulfide also failed using this procedure.

**Aliphatic Disulfides.** The metal-assisted synthesis of sulfenamides from aliphatic disulfides and amines required the use of an excess of silver acetate in ethyl acetate. Aliphatic sulfenamides were observed to decompose to disulfide in the presence of silver nitrate–methanol.

The synthesis of aliphatic sulfenamides **1a** using this procedure succeeded with a variety of aliphatic disulfides and amines, but failed with aniline and allylamine. Benzyl disulfide also gave good yields of alkylbenzylsulfenamides with a range of amines using silver acetate–ethyl acetate. These results are summarized in Table II.

Moderate to low yields of aliphatic sulfenamides were obtained from disulfides and aliphatic amines using this method. However, considering the instability of aliphatic sulfenyl chlorides and the inaccessibility of benzylsulfenyl chloride,[27] this method (eq 2) is superior to the sulfenyl chloride method (eq 1).

There appears to be general agreement, but little quantitative evidence, that aryl sulfenamides are more stable than alkyl sulfenamides.[2] A number of workers[28,19] have noted that the thermal stability of alkyl sulfenamides decreases as the basicity of the sulfenamide nitrogen increases, as the electron-donating ability of the group attached to sulfur increases, and when the number of groups attached to the sulfenamide nitrogen decreases. These trends are in the correct order for stabilization of the sulfenyl and amino radicals. Alternatively, increased electron density on nitrogen and sulfur may destabilize the S–N bond and/or increase the nucleophilicity of the sulfenamide nitrogen (vide infra).

The metal-assisted synthesis of alkyl and aryl sulfenamides (Tables I and II) reflects these trends; aromatic sulfenamides were less reactive than aliphatic sulfenamides with the latter obtained in lower yields. Aromatic sulfenamides prepared from primary aliphatic amines were more reactive than those from dialkylamines. With the exception of isopropylbenzylsulfenamide (Table II, entry 9), all attempts to prepare alkanesulfenamides from primary amines failed (see Table II, entry 3).

**Disulfides and Ammonia.** Sulfenamides of ammonia, **3,** are intermediates in the synthesis of *N*-alkylidenesulfenamides, **2,** from aromatic disulfides, silver nitrate, ammonia, and aldehydes and ketones.[26]

| $YY\text{-}C_6H_3S\text{-}NH_2$ | $(XY\text{-}C_6H_3S)_2NH$ |
|---|---|
| **3a,** X = Y = 3,4-$Cl_2$ | **4a,** X = Y = H |
| **b,** X = H; Y = 3-$NO_2$ | **b,** X = H; Y = 4-Cl |
| **c,** X = H; Y = 4-$NO_2$ | **c,** X = H; Y = 3-$NO_2$ |

This provides an alternative synthesis of **2** which avoids an excess of ammonia.

Good yields of arenesulfenamides **3** were obtained from silver nitrate, aromatic disulfides, and ammonia when the disulfide contained electron-attracting groups more powerful than a 4-chlorophenyl group. Both phenyl and 4-chlorophenyl gave the corresponding bis(arenesulfen) imide **4a,b b** as the only isolated product. Ethyl disulfide was recovered when this disulfide was subjected to the reaction conditions. These results are summarized in Table III.

Benzenesulfenyl chloride and *p*-tolylsulfenyl chloride are reported to yield the imide **4** in low yield on reaction with ammonia[16,29] Zincke obtained the sulfenamides **3** from 4- and 2-nitrobenzenesulfenyl chloride and ammonia.[30] When these compounds were heated with dilute acetic acid, imides **4** were obtained in good yield.

We have found that boron trifluoride etherate in ether also effects the rearrangement of 3-nitrobenzenesulfenamide **3c** to **4c** in 70% yield. In attempts to extend this reaction to sulfenamides **5a** and **5b** either boron trifluoride or 20% acetic acid resulted in mixtures of the corresponding disulfide and the imide **6**. The formation of the imide **6** was indicated by the appearance of new methylene absorptions in the NMR at 3.5 and 3.6 ppm, respectively. The imide **6** could not be satisfactorily separated from the disulfide.

$$\underset{\mathbf{5}}{X\text{-}C_6H_4S\text{-}NHC_2H_5} \rightarrow (X\text{-}C_6H_4S)_2 + \underset{\mathbf{6}}{(X\text{-}C_6H_4S)_2NC_2H_5}$$

**a,** X = H
**b,** X = 3-$NO_2$

The mechanism for the formation of the bis(sulfen)imides

**Table III. Sulfenamides from Disulfides and Ammonia**

| Entry | Disulfide | Conditions[e] | Product[f] (% yield) | Mp, °C | NMR, δ |
|---|---|---|---|---|---|
| 1 | Ethyl | $AgNO_3$–MeOH | No reaction | | |
| 2 | Phenyl | $AgNO_3$–MeOH | **4a** (20) | 133–134 (129)[a] | 4.7 (bs, 1), 7.35 (s, 10) |
| 3 | 4-Chlorophenyl | | **4b** (50) | 138–140 | 4.6 (bs, 1), 7.3 (s, 8) |
| 4 | | AgOAc–EtOAc | No reaction | | |
| | | $HgCl_2$–MeOH | No reaction | | |
| 5 | 3,4-Dichlorophenyl[d] | $AgNO_3$–MeOH | **3a** (62) | 38–40 | 2.8 (bs, 2, $NH_2$), 7.0–7.5 (m, 3) |
| 6 | 3-Nitrophenyl | | **3b** (72) | *b* | |
| 7 | 4-Nitrophenyl | | **3c** (84) | *c* | |

[a] H. Lecher, F. Holschneider, K. Koberle, W. Speer, and P. Stocklin, *Ber.*, **58**, 409 (1925). [b] Reference 26. [c] T. Zincke and S. Lenhardt, *Justus Liebigs Ann. Chem.*, **400**, 1 (1913). [d] Registry no., 4235-78-3. [e] Registry no.: $AgNO_3$, 7761-88-8; AgOAc, 563-63-3, $HgCl_2$, 7487-94-7. [f] Registry no.: **4a**, 24364-84-9; **4b**, 34583-74-9; **3a**, 61076-35-5.

**Table IV. *N*-Alkylidenealkylsulfenamides**

| Entry | Disulfide | Aldehyde/ ketone | Registry no. | Conditions | $RSN{=}CR_2$ % yield | Registry no. | Bp, °C (mm) | NMR, δ |
|---|---|---|---|---|---|---|---|---|
| 1 | Methyl | Benzaldehyde | 100-52-7 | $AgNO_3$–MeOH | 33 | 61076-36-5 | 71–72 (0.11) | 2.72 (s, 3, Me), 7.55 (m, 5), 8.35 (s, 1) |
| 2 | | | | AgOAc–EtOAc | 35 | | | |
| 3 | | Salicylaldehyde | 90-02-8 | $AgNO_3$–MeOH | 30 | | *a* | |
| 4 | | Acetaldehyde | 75-07-0 | | No reaction | | | |
| 5 | | Acetone | 67-64-1 | | No reaction | | | |
| 6 | Ethyl | Benzaldehyde | | | 24 | 61076-37-7 | 77–78 (0.1) | 1.4 (t, 3, $J$ = 7 Hz), 3.2 (q, 2, $J$ = 7 Hz), 7.5 (m, 5), 8.5 (s, 1) |
| 7 | *n*-Propyl[b] | Benzaldehyde | | | 30 | 61076-38-8 | 79–80 (0.08) | 1.1 (t, 3, $J$ = 6 Hz), 1.9 (m, 2), 3.1 (t, 2), 7.5 (m, 5), 8.5 (s, 1) |
| 8 | | | | $HgCl_2$–MeOH | No reaction | | | |
| 9 | | Salicylaldehyde | | $AgNO_3$–MeOH | 33 | 61076-39-9 | 88–90 (0.08) | 1.1 (t, 3, $J$ = 6 Hz), 1.8 (m, 2), 3.1 (t, 2), 6.97 (m, 4), 8.6 (s, 1), 11.0 (s, 1) |
| 10 | | Acetophenone | 98-86-2 | | 26 | 61076-40-2 | 103 (0.7) | 1.1 (t, 3, $J$ = 6 Hz), 1.9 (m, 2), 2.3 (s, 3, Me), 3.1 (t, 2), 7.5 (m, 5) |
| 11 | *n*-Butyl | Salicycaldehyde | | | 17 | 61076-41-3 | 137 (0.14) | 0.9 (t, 3, $J$ = 6 Hz), 1.6 (m, 4), 2.7 (t, 2, $J$ = 6 Hz), 7.1 (m, 2), 7.6 (m, 2), 10.0 (s, 1), 11.0 (s, 1) |
| 12 | Isopropyl | Benzaldehyde | | | No reaction | | | |
| 13 | | Benzaldehyde | | AgOAc–EtOAc | No reaction | | | |
| 14 | *tert*-butyl[c] | Benzaldehyde | | $AgNO_3$–MeOH | No reaction | | | |

[a] Reference 13. [b] Registry no., 629-19-6. [c] Registry no., 110-06-5.

undoubtedly involves a nucleophilic attack by the sulfenamide nitrogen at the S–N bond of another sulfenamide unit with elimination of an amine (eq 3). Sulfenic acids (RSOH) undergo a similar reaction with formation of a thiolsulfinite [RS(O)SR] and elimination of water.[10]

$$R\text{–}S\text{–}NH_2 + R\text{–}S\text{–}NH_2 \rightarrow (R\text{–}S)_2NH + NH_3 \quad (3)$$

Sulfenamides meet the requirements for "α-effect" nucleophiles in that the nucleophilic atom (nitrogen) is adjacent to a heteroatom (sulfur) containing lone pairs of electrons.[31] In certain cases such nucleophiles display greater nucleophilicity than the parent nucleophile.

As the electronegativity of groups attached to sulfur increases the electron density on sulfur in **3** should decrease. This should reduce the magnitude of the "α effect" and the nucleophilicity of the sulfenamide nitrogen. As reflected in Table III, bis(sulfen)imides **4** were obtained only when the group attached to sulfur was more electron donating than a 3,4-dichlorophenyl group. Similar results have recently been reported by Welch, who observed a regular decrease in the formation of bis(arenesulfen)imides of 6-aminopenicillanic acid as the electronegativity of the group attached to the sulfenyl chloride increased.[11]

The "α effect" could well explain the difference in reactivity between aliphatic and aromatic sulfenamides. However, other factors such as leaving group ability and the effect of electrophiles are also important in determining the reactivity of these compounds.

***N*-Alkylidenealkylsulfenamides.** In a previous paper we reported on the metal-assisted synthesis of *N*-alkylidenear-

enesulfenamides **2** from aromatic disulfides, silver nitrate, ammonia, and aldehydes and ketones,[26] and reported that this procedure failed with benzyl and ethyl disulfide using acetone as the carbonyl compound. We report here that *N*-alkylidenealkylsulfenamides **2** (R = alkyl) can be prepared in certain cases using this method.

*N*-Alkylidenealkylsulfenamides can only be prepared from aliphatic disulfides using the metal-assisted procedure when the disulfide is straight chain and an aromatic group is attached to the carbonyl carbon. Yields of **2** prepared in this way were generally low, 17–30%. Similar yields of *N*-benzylidenemethylsulfenamides were obtained using silver nitrate–methanol or silver acetate–ethyl acetate. Table IV summarizes these results.

Assuming that an alkylsulfenamide ($RSNH_2$) is an intermediate in the formation of **2**, the low yields of *N*-alkylidenealkylsulfenamides and the inability to prepare **2** from branched-chain disulfides is readily explained. For the reasons discussed above, an alkanesulfenamide of ammonia ($RSNH_2$) should be very unstable with the instability increasing as the degree of branching of the disulfide increases. Furthermore, steric hindrance to attack by ammonia on the silver–disulfide complex would be anticipated to be greater for the branched-chain disulfides.

## Experimental Section

Melting points were measured on a Mel-Temp apparatus. $^1H$ NMR spectra were obtained on a Varian A-60A spectrometer and IR spectra on a Perkin-Elmer 457 spectrometer. Disulfides obtained commercially were used without further purification. Solvents were purified by standard methods. *N*-Alkylidenealkanesulfenamides **2** were prepared as described previously for *N*-alkylidenearenesulfenamides.[26]

**Oxidation of Thiols to Disulfides.** The thiol was dissolved in 70% ethanol containing 1 equiv of NaOH. The solution was cooled and an equivalent amount of 15% hydrogen peroxide added dropwise. The precipitated disulfide was collected and crystallized from ethanol.

**General Synthesis of Sulfenamides from Aromatic Disulfides.** In a 1000-ml three-necked flask equipped with overhead stirrer was placed 7.8 g (0.045 mol) of silver nitrate in 400 ml of methanol. After solution had taken place an equivalent amount of disulfide was added and the reaction mixture cooled in an ice bath. An excess of the appropriate amine (usually 5 equiv) was added and the reaction mixture allowed to stir overnight. The silver mercaptide was filtered and the solvent removed at reduced pressure, at a temperature of 35–40 °C. The resulting residue was dissolved in ether, washed with water (4 × 100 ml), and dried over $MgSO_4$. Removal of the ether solvent gave the sulfenamide which was distilled or crystallized. Sulfenanilides were purified prior to crystallization by chromatography on Florisil. This same procedure was used with mercuric chloride. To prepare sulfenamides of ammonia, dry ammonia gas was passed through the metal–disulfide solution for 10–15 min at 0 °C.

**General Synthesis of Sulfenamides from Aliphatic Disulfide.** In a 1000-ml three-necked flask equipped with overhead stirrer were placed 8.38 g (0.05 mol) of silver acetate and 0.025 mol of the appropriate alkyl disulfide in 300 ml of ethyl acetate. The solution was cooled, an excess of the appropriate amine (5 equiv) was added, and the reaction mixture was stirred for 23 h at room temperature in the dark. The silver mercaptide was removed by filtration and the filtrate evaporated under reduced pressure at 40 °C. The residue was extracted with ether, washed with water (3 × 100 ml), and dried over $MgSO_4$. Evaporation of the ether yielded a yellow oil which was distilled.

**Bis(3-nitrobenzenesulfen)imide (4c).** In a 50-ml round-bottom flask equipped with magnetic stirring bar was placed 0.5 g (0.00294 mol) of 3-nitrobenzenesulfenamide **3b** in 25 ml of water or 35 ml of ethyl ether. Acetic acid (5 ml), or 0.417 g (0.00294 mol) of boron trifluoride etherate (Aldrich) was added and the reaction mixture allowed to stir for 12 h at room temperature. The precipitated solid was removed by filtration, washed with water, dried, and crystallized from chloroform to yield 0.35–0.4 g (72–84%) of orange needles; mp 166–168 °C; IR (KBr) 3230 $cm^{-1}$ (NH); NMR ($CDCl_3$) $\delta$ 2.7 (broad s, 1), 7.4–8.3 (m, 8)

Anal. Calcd for $C_{12}H_9N_3O_4S$: C, 44.58; N, 2.79. Found: C, 44.44; H, 2.82.

**Silver Recovery.** The silver mercaptide was burned to yield a dark ash which was further combusted to silver metal using an oxygen-gas torch. The silver metal was dissolved in concentrated nitric acid and filtered. The filtrate was concentrated by boiling and on cooling yielded crystals of silver nitrate. Additional silver nitrate can be obtained by further concentration of the filtrate. Overall recovery of silver nitrate by this method is 65–75%.

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**Registry No.**—**3b,** 40576-93-0; **4c,** 61076-42-4; ammonia, 7664-41-7.

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