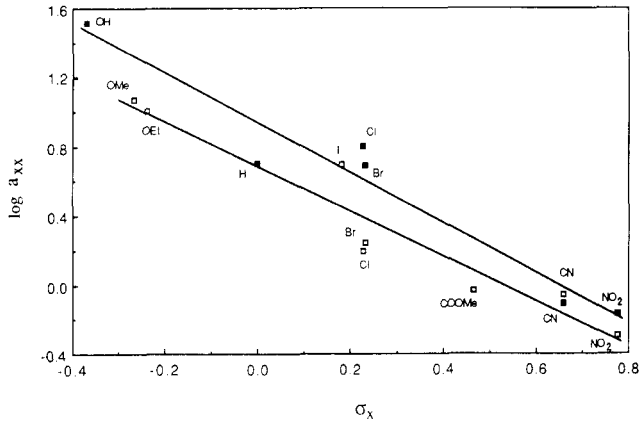

Figure 5. Hammett plot of log a_{XX} vs substituent constant for sym-4,4'-disubstituted biphenyls (solid symbols) and sym-1,4-disubstituted benzenes (open symbols). The benzene data are from ref 2.

Figure 5 is a plot of log a_{XX} against the Hammett substituent constant σ_X, for both the benzene series and the biphenyl series. The equations of the lines in Figure 5 are

$$\log a_{XX} = -1.45\sigma_X + 0.94 \text{ (biphenyls)} \quad (9)$$

$$\log a_{XX} = -1.29\sigma_X + 0.68 \text{ (benzenes)} \quad (10)$$

The standard deviations of the slopes are about 0.17 and of the intercepts about 0.07; hence the slopes are not significantly different whereas the intercepts are.

The dicarboxy member of the benzene series, terephthalic acid, is a serious negative deviator and is not included in the plot. In the biphenyl series, dimethylbiphenyl is a serious negative deviator, and dicarboxybiphenyl is an outstanding serious positive deviator (since the 1:1 complex cannot be detected). Indeed, the log a_{XX} vs σ_X correlation for the biphenyls is not, by itself, very convincing; its acceptability comes largely from the consistency of most of the points with the benzene data. The negative deviation of terephthalic acid was taken[2] as evidence of a large repositioning effect on a_{XX}, signifying that the COOH binding site is very deeply inserted in the cavity in the 1:1 complex. The positive deviation by dicarboxybiphenyl was not predicted, but it can be rationalized in a consistent manner. If, as the terephthalic acid result suggests, the carboxy group is deeply inserted in the 1:1 complex, presumably it occupies a similar position in the dicarboxybiphenyl complex. Addition of a second ligand to terephthalic acid required displacement of the first, giving a low a_{XX} value; but in the dicarboxybiphenyl case, addition of the second ligand must be highly favorable, so much so that the 1:2 complex forms with the virtually complete extinction of the 1:1 complex. It may be inferred that the spacing between sites in the biphenyl complex is optimal for avoiding the repositioning effect and for bringing the ligand–ligand interaction effect into play.

The dimethylbiphenyl behavior is anomalous. Since this compound nicely follows the correlation of log K_{11} against $-\log S_0$ (Figure 4), evidently K_{11} is normal, and so the negative deviation in a_{XX} must be a consequence of an abnormally small K_{12} value. This suggests a reduction in a_{XX} via the repositioning effect and, therefore, deep insertion of the methyl group into the cyclodextrin cavity.

Acknowledgment is made to the donors of the Petroleum Research Fund, administered by the American Chemical Society, for the partial support of this work.

Registry No. 4,4'-$HOC_6H_4C_6H_4OH$, 92-88-6; 4,4'-$MeC_6H_4C_6H_4Me$, 613-33-2; Ph_2, 92-52-4; 4,4'-$ClC_6H_4C_6H_4Cl$, 2050-68-2; 4,4'-$BrC_6H_4C_6H_4Br$, 92-86-4; 4,4'-$NCC_6H_4C_6H_4CN$, 1591-30-6; 4,4'-$O_2NC_6H_4C_6H_4NO_2$, 1528-74-1; 4,4'-$HOOCC_6H_4C_6H_4COOH$, 787-70-2; α-cyclodextrin, 10016-20-3.

S-Alkyl Alkanesulfonothioates and *S*-1-Chloroalkyl Alkanesulfonothioates from Linear Alkanesulfinyl Chlorides[1]

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Treatment of linear alkanesulfinyl chlorides **1** with dry *N*,*N*-dimethylmethanamide (DMF), *N*,*N*-dimethylethanamide (DMA), or 1-methyl-2-pyrrolidone (NMP) in an inert atmosphere, with or without added solvent, gives *S*-alkyl alkanesulfonothioates **4** (minor products) and *S*-1-chloroalkyl alkanesulfonothioates **5**. The yield of **4** is decreased in the presence of the radical inhibitor 1,4-dihydroxybenzene. Evidence has been obtained for the formation and trapping of sulfines (including methanethial *S*-oxide) and for formation of sulfinyl radicals, *vic*-disulfoxides (α-disulfoxides), and *O*,*S*-sulfenyl sulfinates as reaction intermediates. *S*-Phenyl benzenesulfonothioate is a major product from the reaction of alkanesulfinyl chlorides and benzenesulfinyl chloride in the presence of DMF.

Although several routes have been developed for the synthesis of *S*-monooxides of thiocarbonyl compounds (sulfines), the 1,2-dehydrochlorination of alkanesulfinyl chlorides **1** containing an α-hydrogen atom with triethylamine is one of the most widely used methods for the preparation of aliphatic sulfines (eq 1).[2-8] Despite numerous attempts, none of the routes generally used for the

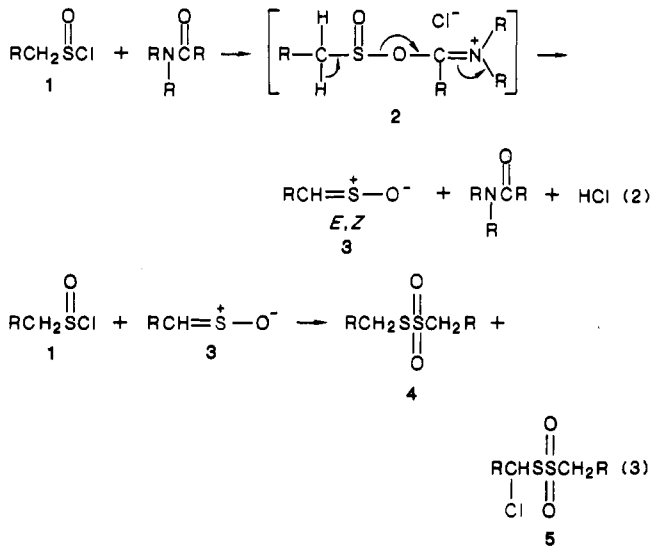
$$\underset{\mathbf{1}}{RCH_2\overset{\overset{O}{\|}}{S}Cl} + (C_2H_5)_3N \longrightarrow \underset{E,Z}{RCH{=}\overset{+}{S}{-}O^-} + (C_2H_5)_3NHCl \quad (1)$$

(1) Presented in part at the 186th National Meeting of the American Chemical Society, Washington, DC, September 1, 1983, ORGN 242, and the 1983 Pacific Conference on Chemistry and Spectroscopy, Pasadena, CA, October 28, 1983.

(2) Block, E. *Org. Sulfur Chem., Invited Lect. Int. Symp., 9th 1980* 1981, 15; *Chem. Abstr.* **1981**, *95*, 96267c.

0022-3263/88/1953-2026$01.50/0

preparation of sulfines has yielded the parent sulfine, methanethial S-oxide (thioformaldehyde S-oxide (3, R = H) in solution.[9-14] However, Freeman and Keindl[13,14] proposed methanethial S-oxide (3, R = H) as an intermediate during the treatment of methanesulfinyl chloride (1, R = H) with N,N-dimethylmethanamide (DMF, eq 2 and 3), which affords S-methyl methanesulfonothioate (4,



R = H) and S-chloromethyl methanesulfonothioate (5, R = H). More recently, Block and Wall[11,12] reported that fluorodesilylation of (trimethylsilyl)methanesulfinyl chloride also affords methanethial S-oxide (3, R = H), which can be trapped with cyclopentadiene.

Tertiary amides such as DMF, N,N-dimethylethanamide (DMA), and 1-methyl-2-pyrrolidone (NMP) are aprotic solvents of high polarity, low nucleophilicity, and relatively low basicity. Although these amides are considered to be relatively inert and stable, they may be used as regenerable dehydrohalogenating agents. Since alkanesulfinyl chlorides 1 may react with alkanethial S-oxides (sulfines, 3) to afford S-alkyl and S-1-chloroalkyl alkanesulfonothioates (thiosulfonates, 4 and 5),[3,13,14] we have investigated the feasibility of a one-step one-flask synthesis of 4 and/or of 5 from 1 and in situ generated sulfine (3, eq 2 and 3). Thiosulfonates are valuable precursors and halogenated thiosulfonates possess bactericidal, fungicidal, herbicidal, and pesticidal properties.[3,15]

Table I. Yields of S-Alkyl and S-1-Chloroalkyl Alkanesulfonothioates 4 and 5 from Linear Alkanesulfinyl Chlorides[a]

$RCH_2S(O)Cl$ R	amide[b] or amine	added solvent	yield,[c] % RCH_2SSCH_2R (O) 4	$RCHSSCH_2R$ (Cl, O) 5	overall
H	$N(C_2H_5)_3$[d,e]	Et_2O	6	27	33
H	pyridine[d,f]	Et_2O	11	68	79
H	pyridine	Et_2O	57	43	100
H	H_2NCHO[g]		32	0	32
H	CH_3NHCHO[h]				
H	$CH_3NHCOCH_3$[i]	Et_2O	22	26	48
H	2-pyrrolidone[j]				
H	DMF		11	63	74
H	DMF	Et_2O	18	65	83
H	DMF	C_6H_6	13	60	73
H	DMA[k]		18	72	90
CH_3	H_2NCHO[l]		58	0	58
CH_3	DMF[d]		18	82	100
CH_3	DMF		7	67	74
CH_3	DMF	$CHCl_3$	12	82	94
C_2H_5	H_2NCHO[l]		54	16	70
C_2H_5	DMF		13	87	100
C_2H_5	DMF[i]	Et_2O	7	87	94
C_2H_5	DMF[m]	c-C_6H_{12}	13	87	100
C_2H_5	DMF	C_6H_6	13	74	87
C_2H_5	DMF[g]	CCl_4	10	72	82
C_2H_5	DMF[m,n]	$CFCl_3$	8	65	73
C_2H_5	DMF[g,m]	CH_2Cl_2	14	86	100
C_2H_5	DMF[k]	CH_3CN	14	82	96
C_2H_5	DMF	$(CH_3OCH_2)_2$	9	91	100
C_2H_5	NMP		17	83	100
C_3H_7	H_2NCHO[l]		54	16	70
C_3H_7	DMF		15	85	100
C_4H_9	DMF		14	81	95
C_7H_{15}	DMF		5	90	95

[a] Neat, reaction time 24 h at 22–24 °C; 1 equiv of sulfinyl chloride:3 equiv of amide or amine. [b] DMF is N,N-dimethylmethanamide; DMA is N,N-dimethylethanamide; NMP is 1-methyl-2-pyrrolidone. [c] Isolated and/or ^1H NMR yields. [d] Ratio sulfinyl chloride:amine or amide = 1.65. [e] 67% conversion. [f] 72% conversion. [g] Reaction time 48 h. [h] Complex product mixture after 168 h. [i] Reaction time 60 h. [j] Complex product mixture from −70 °C to 24 °C during 24 h. [k] Reaction time 12 h. [l] Reaction time 96 h. [m] Initial heterogeneous reaction medium owing to limited solubility of substrates. [n] Reaction incomplete after 5 days; propanesulfinic acid (11%) was also obtained.

Table I shows the yields of products from treatment of alkanesulfinyl chlorides with primary, secondary, and tertiary amides. It is seen that tertiary amides (DMA, DMF, NMP) gave the highest overall yields of products (4, 5) with S-1-chloroalkyl alkanesulfonothioates 5 as the major products.[16] The secondary amides gave complex product mixtures and/or low yields of products. The primary amide (methanamide), which reacted slower than the tertiary amides, gave low to acceptable overall yields of products (4, 5) with the S-alkyl alkanesulfonothioate 4 as the major product.[16]

The absence of a significant solvent effect, except for trichlorofluoromethane (Freon 11), in the reaction of propanesulfinyl chloride and DMF is seen in Table I. The reaction appears to be slowest in Freon 11 and fastest in ethanenitrile. Although the limited solubility of the substrates in benzene and trichlorofluoromethane may par-

(3) Block, E.; Bazzi, A. A. *Tetrahedron Lett.* **1982**, *23*, 4569.
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(8) Sheppard, W. A.; Diekmann, J. *J. Am. Chem. Soc.* **1964**, *86*, 1891.
(9) (a) It may be possible that a complex is formed between triethylamine and methanesulfinyl chloride and/or methanethial S-oxide (3, R = H). Methanethial S-oxide can be generated from methanesulfinyl chloride, dimethyl sulfoxide, 1,3-dithietane 1-oxide, allyl methyl sulfoxide, and other precursors via the flash vacuum pyrolysis (FVP) technique.[10] (b) Tertiary amines react reversibly with aryl thiosulfonates under anhydrous conditions: Wevers, J. H.; Kloosterziel, H. *J. Chem. Soc., Chem. Commun.* **1975**, 13.
(10) (a) Powers, D. E.; Arrington, C. A.; Harris, W. C.; Block, E.; Kalasinsky, V. F. *J. Phys. Chem.* **1979**, *83*, 1890 and references cited therein. (b) Block, E.; Penn, R. E.; Olsen, R. J.; Sherwin, P. F. *J. Am. Chem. Soc.* **1976**, *98*, 1264. (c) Block, E.; Bock, H.; Mohmand, S.; Rosmus, P.; Solovki, B. *Angew. Chem., Int. Ed. Engl.* **1976**, *15*, 383.
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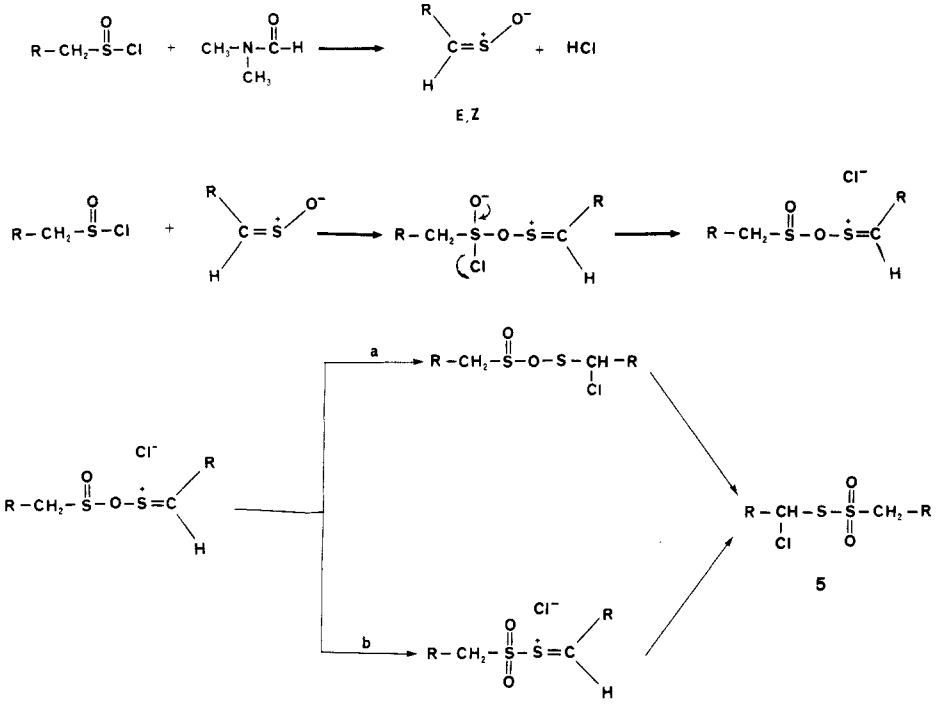
(14) Freeman, F.; Keindl, M. C. *Synthesis* **1984**, 500.
(15) (a) Block, S. S.; Weidner, J. P. *J. Med. Chem.* **1967**, *10*, 1167. (b) Phillips, W. G. U.S. Pat. 3798254, 1974; *Chem. Abstr.* **1974**, *80*, 145787y.

(16) The amides (DMF, DMA, NMP) appear to be regenerated and strictly speaking are not reagents. The reaction did not go to completion when a 1:1 ratio of sulfinyl chloride:amide was used. The isolation of ammonium chloride from the reactions with methanamide may suggest it reacts differently than the tertiary amides. This reversal of product distribution with methanamide is under investigation.

Scheme I



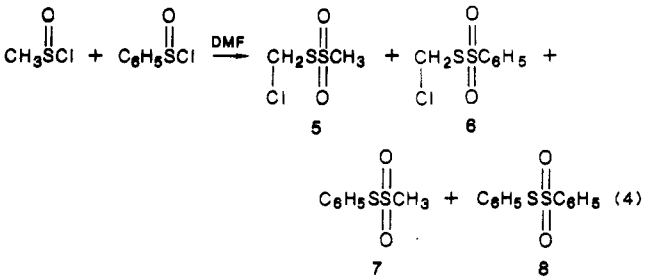
tially account for the observed low reactivity, other solvent effects are also operative since the homogeneous reaction medium in diethyl ether required 60 h for completion.

Table I also shows the product distribution from the reaction of methanesulfinyl chloride with pyridine and with triethylamine. The higher conversions were obtained with pyridine at a 1:3 molar ratio of base to substrate. Block and Bazzi[3] reported *S*-1-chloroalkyl alkanesulfonothiates **5**, but no *S*-alkyl alkanesulfonothioates **4**, from the reaction of 1 equiv of triethylamine and 2 equiv of ethane-, propane-, and dodecanesulfinyl chloride, respectively.

The formation of *S*-1-chloroalkyl alkanesulfonothioates **5** probably involves *S*-monooxides of thiocarbonyl compounds **3** (eq 3, Scheme I).[3,11-14] Nucleophilic attack by sulfine oxygen at the sulfinyl sulfur of the sulfinyl chloride could lead to a chloro derivative of the long sought elusive *O,S*-sulfenyl sulfinate (path a in Scheme I) which can rearrange to *S*-1-chloroalkyl alkanesulfonothioate **5**.[3,11-14,17-24] Thus, treatment of methanesulfinyl chloride with DMF leads to methanethial *S*-oxide (**3**) which reacts with methanesulfinyl chloride to give *S*-chloromethyl methanesulfonothioate.[3,11-14,17]

Although tertiary amides (DMF, DMA, NMP) may not be sufficiently basic to remove a proton from the α-carbon atom of the alkanesulfinyl chloride **1** in an E2-type process (1,2-dehydrochlorination) to generate alkanethial *S*-oxides (sulfines, **3**; eq 1), their oxygen atoms are sufficiently nucleophilic to attack the sulfinyl sulfur atom (O-sulfination) to yield imminium salts **2** (eq 2).[17,25-29] Elimination of hydrogen chloride and amide from imminium salts **2** affords the corresponding alkanethial *S*-oxides (sulfines, **3**; eq 1).

Benzenesulfinyl chloride, which does not have an α-hydrogen and cannot form a sulfine, did not react with DMF during 48 h at 22–24 °C. However, a reaction mixture of methanesulfinyl chloride, benzenesulfinyl chloride, and DMF at 22 to 24 °C for 48 h gave *S*-chloromethyl methanesulfonothioate (**5**, R = H, 17%), *S*-chloromethyl benzenesulfonothioate (**6**, 30%), *S*-phenyl methanesulfonothioate (**7**, 4.5%),[30] and *S*-phenyl benzenesulfonothioate (**8**, 41%, eq 4).[31] No *S*-methyl methanesulfonothioate (**4**, R = H) was observed in the product mixture, although Table I suggests that a small amount should be formed (vide infra).



Formation of *S*-chloromethyl methanesulfonothioate (**5**, R = H) and *S*-chloromethyl benzenesulfonothioate (**6**, eq 4) is consistent with the mechanism shown in Scheme I and demonstrates the intermolecularity of the reaction.

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(18) Freeman, F. *Chem. Rev.* **1984**, *84*, 117.
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(26) (a) Heller, M.; Lenhard, R. H.; Bernstein, S. *J. Am. Chem. Soc.* **1964**, *86*, 2309. (b) Grimshaw, J.; Grimshaw, J. T.; Juneja, H. R. *J. Chem. Soc., Perkin Trans. 1* **1972**, 50.
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(28) Arrieta, A., Aizpurua, J. M., Palomao, C. *Tetrahedron Lett.* **1984**, *25*, 3365.
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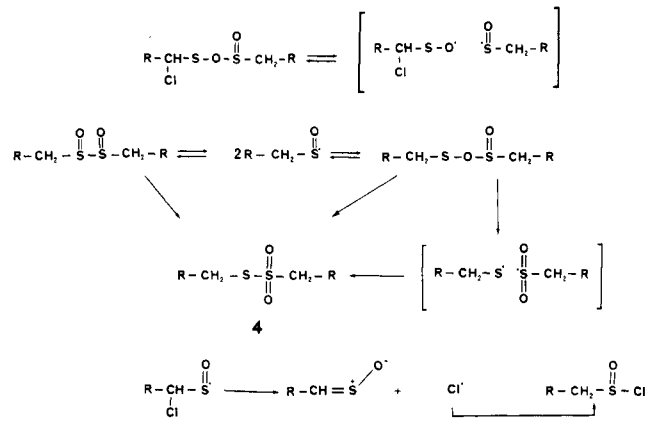
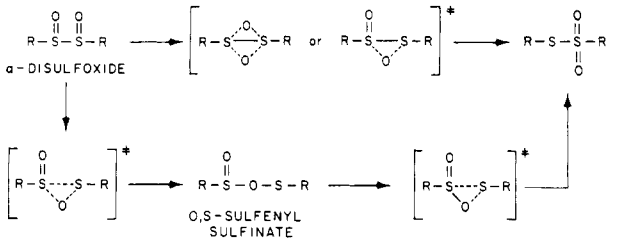
(31) Kice, J. L.; Rogers, T. E. *J. Am. Chem. Soc.* **1974**, *96*, 8015.

Scheme II

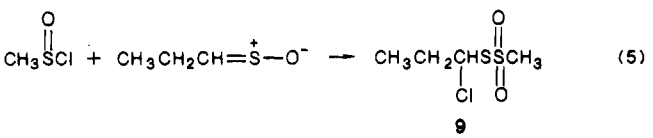


Scheme III



That is, methanethial *S*-oxide, which is generated from methanesulfinyl chloride, reacts with methanesulfinyl chloride and benzenesulfinyl chloride to give the respective proposed *O,S*-chloroalkylsulfenyl sulfinates which rearrange to the corresponding *S*-chloromethyl sulfonothioates **5** (R = H) and **6** (eq 4). The relatively high yield and formation of **8** are discussed below.

In order to further demonstrate that sulfines are intermediates in the reaction of alkanesulfinyl chlorides and DMF (Scheme I), methanesulfinyl chloride was reacted with propanethial *S*-oxide (eq 5).[3,11,12,31-33] The only

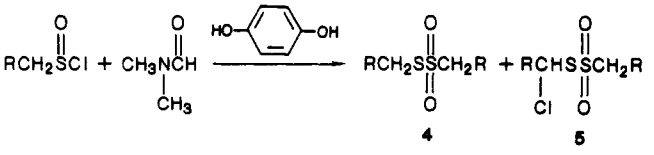


(5)

product isolated was *S*-1-chloropropyl methanesulfonothioate (**9**). Although this does not prove sulfines are intermediates, it is consistent with the mechanism proposed in Scheme I.[3,11-14,17] Attempts to trap methanethial *S*-oxide with 1,3-cyclohexadiene or other 1,3-dienes during treatment of methanesulfinyl chloride with DMF led to complex product mixtures.[34]

Formation of the minor products, *S*-alkyl alkanesulfonothioates **4** (eq 3), during treatment of alkanesulfinyl chlorides **1** with DMF could involve sulfinyl radicals, vicinal disulfoxides (α-disulfoxides), and/or *O,S*-sulfenyl sulfinates (Scheme II).[18,22] If it is assumed that *S*-alkyl alkanesulfonothioates **4** are formed via a free radical chain mechanism (Scheme II) and that *S*-1-chloroalkyl alkanesulfonothioates **5** are not formed via a free radical chain pathway (Scheme I), then one would predict that 1,4-dihydroxybenzene (hydroquinone), an effective chain radical

Table II. Effects of 1,4-Dihydroxybenzene on Product Formation from Alkanesulfinyl Chlorides[a]



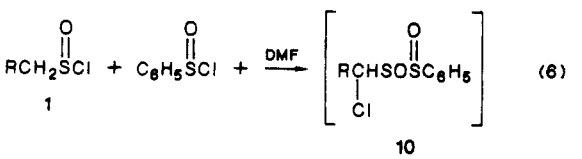
R	reactn time, *h*	[1,4-dihydroxybenzene], mmol	yield,[b] % 4	5
H	24	0	11	63
H	24	0.5	0	88
H[c]	24	0.1	0	95
H[c,d]	24	0.1	18	82
C_2H_5	24	0	13	87
C_2H_5	24	0.5	6	93
C_3H_7	24	0	15	85
C_3H_7	72	0.5	16	78
C_2H_5[e]	24	0.5	21	82
C_2H_5[f]	12	0.5	13	83
C_2H_5[g]	60	0.5	7	89
C_2H_5[h]	24	0.5	6	93

[a] Experiments performed in light with 10 mmol of alkanesulfinyl chloride and 30 mmol of DMF. [b] Isolated and/or ^1H NMR yields. [c] 5 mmol of methanesulfinyl chloride and 30 mmol of DMF. [d] Experiment performed in dark. [e] 1,3-Dinitrobenzene inhibitor. [f] Ethanenitrile solvent. [g] Diethyl ether solvent. [h] 1,2-Dimethoxyethane solvent.

inhibitor, will influence the outcome of the interaction of DMF with methane-, ethane-, propane, or butanesulfinyl chloride. This is indeed the case (Table II).

Scheme III shows possible nonradical pathways to thiosulfonates **4** and **5** (cf. Schemes I and II).[18-22,30,35-41]

The products in Table III (cf. eq 4) are also consistent with the mechanisms depicted in Schemes I, II, and III. The sulfine formed from alkanesulfinyl chloride and DMF reacts with benzenesulfinyl chloride to afford the proposed *O,S*-sulfenyl sulfinate intermediate **10**, which can dissociate and/or rearrange (eq 6, Schemes I, II, III) to the observed



(6)

products. The absence of disulfides and vicinal disulfones suggests that transient intermediate **10** does not dissociate into thiyl and sulfonyl radicals (Scheme III).[18,22,38-41]

The ^1H NMR and ^{13}C NMR spectra of *S*-alkyl alkanesulfonothioates **4** and *S*-1-chloroalkyl alkanesulfonothioates have been presented.[3,13,14,42-46]

Experimental Section

Melting points were obtained on a Thomas-Hoover melting

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(33) Block and Bazzi[3] have also reported that a propanethial *S*-oxide reacts with methanesulfinyl chloride to yield *S*-1-chloropropyl methanesulfonothioate (**9**, 64%).
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Table III. Crossover Products from Alkanesulfinyl Chlorides and Benzenesulfinyl Chloride in the Presence of DMF and 1,4-Dihydroxybenzene[a,b]

RCH_2SCl, R	$[RCH_2SCl]$, mmol	$[C_6H_5SCl]$, mmol	$[1,4\text{-}(HO)_2C_6H_4]$, mmol	yield, %			
				$RCH(Cl)SSCH_2R$ (4)	$RCH(Cl)SSC_6H_5$ (6)	$C_6H_5SSCH_2R$ (7)	$C_6H_5SSC_6H_5$ (8)
H	0.50	0.50	0	17	30	4.5	41
H	0.75	0.25	0.05	21.5	2.6	13.6	32
H	0.50	0.50	0.50	17	4	33	21
H	0.50	0.50	0.05	34.5	7	7	25
C_3H_7[c]	0.50	0.50	0.05	26	2.5	11.5	36

[a] [DMF] = 3.0 mmol; reaction time 48 h at 22–24 °C. [b] Isolated and/or NMR yields. [c] Reaction time 96 h.

point apparatus and are uncorrected. Microanalyses were performed by Robertson Laboratory, Florham Park, NJ.

Mass spectra were obtained on a Finnigan CG/El-CI mass spectrometer with a Nova 3 data system. NMR spectra were obtained on Varian FT-80A, Bruker WH-90, Bruker WM-250, and GE 300-MHz spectrometers. The Bruker WH-90 and WM-250 FT NMR spectrometers were controlled by Bruker Model B-NC-12 and Bruker Aspect 2000 computers, respectively. The NMR assignments were made on the basis of the chemical shifts of previously reported compounds.[3,11-14,30-32,42-46]

Dinitrogen was dried by passing it through a column of Drierite and 5-Å molecular sieves. Triethylamine, pyridine, and diethyl ether were distilled over calcium hydride and stored under nitrogen.

DMF was predried over barium oxide, distilled from calcium hydride under reduced pressure, and stored under argon. *N,N*-Dimethylethanamide (DMA) was stirred over barium oxide for 1 week, refluxed for 1 h, and fractionally distilled under reduced pressure. *N*-Methylmethanamide was stored over 5-Å molecular sieves for 4 days and fractionally distilled under reduced pressure. 1-Methyl-2-pyrrolidinone (NMP), methanamide, *N*-methylethanamide, and 2-pyrrolidinone were fractionally distilled under reduced pressure.

1,4-Dihydrobenzene (hydroquinone, mp 170–171 °C) was used without further purification. 1,3-Dinitrobenzene, mp 90–91 °C, was recrystallized from aqueous ethanol.

Methane-, ethane-, propane-, butane-, pentane-, octane-, and benzensulfinyl chlorides were prepared according to literature procedures.[47,48] Their boiling points and their IR, ^1H NMR, and ^{13}C NMR spectra agreed with literature values.

Analytical TLC was performed on Analtech Uniplate 10 × 20 cm (250 μm) silica gel GF prescored glass plates which were developed in a solvent mixture of ethyl ethanoate–hexanes (1:9 v/v). For visualization of the compounds, the plates were immersed in phosphomolybdic acid solution and charred.

Flash Column Chromatography. The product mixture containing *S*-alkyl and *S*-1-chloroalkyl alkanesulfonothioates **4** and **5** was placed on a 46 × 5 cm diameter column which contained 15 cm of Mallinckrodt SilicAR CC-4 special silica gel[14] covered with 0.3 cm of sand. The *S*-alkyl (**4**) and *S*-1-chloroalkyl (**5**) alkanesulfonothioates were eluted with 1 L of ethyl ethanoate–hexanes (1:9 v/v) solution at a rate such that the eluent flowed at ca. 2 cm/min. Fractions (50 mL) were collected and combined on the basis of TLC analysis. Removal of solvent gave a mixture of **4** and **5**.

The mixture of *S*-alkyl (**4**) and *S*-1-chloroalkyl (**5**) alkanesulfonothioates (vide supra) was separated via flash column chromatography on MCB silica gel 60 (particle size 0.040–0.063 mm; 230–400 mesh) by using 1 L of ether/hexanes/dichloromethane (1:4:1 v/v) as eluant. Fractions (20 mL) were collected and combined on the basis of TLC analysis. Removal of solvent gave the pure product.

The product mixtures containing *S*-alkyl (**4**), *S*-1-chloroalkyl (**5**), and *S*-phenyl alkanesulfonothioates (**7**) and *S*-(1-chloroalkyl) (**6**) and *S*-phenyl (**8**) benzenesulfonothioates were placed on a 46 × 5 cm diameter column which contained 15 cm of MCB silica gel 60 (230–400 mesh) covered with 0.3 cm of sand. The mixtures were eluted with either 1 L of trichloromethane–tetrachloromethane (1:1 v/v) or ethyl ethanoate–hexanes–trichloromethane (1:4:1 v/v). The elution was performed at a rate such that the eluent flowed at ca. 2 cm/min in fractions of 20 mL each. The fractions were combined on the basis of TLC analysis. Removal of solvent gave mixtures of products which were analyzed via ^1H NMR and ^{13}C NMR.

In some experiments, the product mixtures containing *S*-alkyl (**4**), *S*-1-chloroalkyl, (**5**), and *S*-phenyl alkenesulfonothioates (**7**) and *S*-1-chloroalkyl (**6**) and *S*-phenyl (**8**) benzenesulfonothioates were separated on a Waters HPLC by using a Whatman P-5 Pac Rac column. The product mixtures was placed on the column in 25-μL portions, eluted with 1:1:4 dichloromethane–ethyl ethanoate–hexanes at a flow rate of 3 mL/min, and collected in vials as each peak was detected by the refractive index detector. The solvent was evaporated in vacuo from each of the fractions. The products were characterized by their physical properties, ^{13}C NMR spectra, and ^1H NMR spectra.

Reaction of Methanesulfinyl Chloride with Triethylamine. In a flame-dried dinitrogen-flushed 25-mL round-bottomed flask fitted with a septum was placed 15 mL of dry diethyl ether via syringe under dinitrogen flow, followed by 1.63 g (16.5 mmol) of methanesulfinyl chloride via a glass syringe fitted with a Teflon needle. The flask was cooled to ca. 0 °C in an ice bath and dry triethylamine was slowly syringed into the stirring reaction mixture. The dinitrogen flow was stopped after addition of triethylamine and the fluffy white reaction mixture was stirred for 24 h at 22–24 °C. The product mixture was filtered into a tared 50-mL round-bottomed flask by gravity under anhydrous conditions (in a glovebag). The precipitate was washed twice with 10 mL of dry diethyl ether and transferred to a tared 25-mL round-bottomed flask, which was closed with a septum. The volume of the filtrate was reduced in vacuo and the residue analyzed via ^1H NMR ($CDCl_3$). The reaction was 67% complete (^1H NMR assay) and resonances at δ 3.50 and 5.21 ($CH_2ClSSO_2CH_3$, 27%), 3.68 (CH_3SO_2Cl, 3%), 2.70 and 3.31 ($CH_3SSO_2CH_3$, 6%), 2.09 (CH_3SCH_3, 5%), 2.72 (2%), and 2.64 (7%) were observed.

The precipitate was recrystallized by syringing 10 mL of absolute ethanol into the stoppered round-bottomed flask and heating it in a water bath under dinitrogen flow until the solid dissolved. The flask was slowly cooled to −20 °C and the triethylamine hydrochloride crystals were filtered by suction. The crystals were washed with 15 mL of absolute ethanol and placed in a dessicator. Proton NMR ($CDCl_3$) analysis of the crystals (0.40 g, 44%, mp 253–254 °C) showed resonances at δ 1.41 (t), 1.74 (s), and 3.09 (q). The solvent was removed from the filtrate in vacuo and the residue analyzed via ^1H NMR ($CDCl_3$ or D_2O). No identifiable products were observed.

Reaction of Methanesulfinyl Chloride with Pyridine. In a flame-dried, dinitrogen-flushed 25-mL round-bottomed flask fitted with a septum was placed 10 mL of dry diethyl ether and 1.64 g (16.5 mmol) of methanesulfinyl chloride via a glass syringe fitted with a Teflon needle. While stirring under dinitrogen flow, 0.79 g (10 mmol) of dry pyridine was added dropwise via syringe. The product mixture was stirred for 24 h, and the ether solution was decanted from the pyridine salt that adhered to the sides of the flask. The solvent was removed from the ether solution and analyzed via ^1H NMR ($CDCl_3$). The reaction was 72% complete. Analysis by ^1H NMR gave $CH_3SSO_2CH_3$ (δ 3.32 and 2.71, 11%)

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and $CH_2ClSSO_2CH_3$ (δ 5.20 and 3.50, 68%).

Reaction of Methanesulfinyl Chloride with Excess Pyridine. The general procedure described above was used with methanesulfinyl chloride (0.98 g, 10 mmol) and pyridine (2.37 g, 30 mmol). After workup, ^1H NMR analysis ($CDCl_3$) of the organic products gave resonances at δ 3.32 and 2.71 ($CH_3SSO_2CH_3$) and δ 5.21 and 3.51 ($CH_2ClSSO_2CH_3$).

***S*-Alkyl and *S*-1-Chloroalkyl Alkanesulfonothioates 4 and 5. General Procedures.** In a flame-dried nitrogen-flushed 10-mL round-bottomed flask fitted with a septum was placed 10 mmol of alkanesulfinyl chloride via a glass syringe fitted with a Teflon needle under predried deoxygenated dinitrogen flow. Dry amide (30 mmol) was added via syringe. The reaction mixture was magnetically stirred at 22 to 24 °C under a dinitrogen atmosphere until TLC analysis showed the absence of alkanesulfinyl chloride. The reaction mixture was transferred to a 60-mL separatory funnel which contained 10 mL of deionized water. The solution was extracted (3×) with 10 mL of diethyl ether. The combined organic solution was dried (Na_2SO_4). After solvent removal, the product mixture was purified via flash column chromatography and then analyzed for 4 and 5 via ^1H NMR and ^{13}C NMR. Product yields were based on relative integral values from ^1H NMR. In some cases the product mixture (4 and 5) was separated via flash column chromatography.

The general procedure described above was used (50-mL round-bottom flask containing 25 mL of dry solvent) in order to study solvent effects (Table I).

Reaction of Alkanesulfinyl Chlorides and Benzenesulfinyl Chloride; General Procedure. In a flame-dried dinitrogen-flushed 25-mL round-bottom flask fitted with a septum were placed 0.74 g (7.5 mmol) of methanesulfinyl chloride and 0.40 g (2.5 mmol) of benzenesulfinyl chloride under an inert atmosphere. While stirring under dinitrogen flow, 2.19 g (30 mmol) of DMF was added via syringe. The reaction mixture was stirred under a dinitrogen atmosphere until the reaction was complete (48–96 h, TLC analysis). The product mixture was purified via flash column chromatography, eluting with 1 L of ethyl ethanoate–hexanes–trichloromethane (1:4:1 v/v). After solvent removal, the first fraction (R_f 0.50) gave evidence for *S*-1-chloromethyl benzenesulfonothioate (6) and *S*-phenyl benzenesulfonothioate (8). The second fraction (R_f 0.33) gave evidence for *S*-chloromethyl methanesulfonothioate (5) and *S*-phenyl methanesulfonothioate (7). In some experiments, HPLC (vide supra) was used to separate the product mixture.

The general procedure described above was also used to study the effects of radical inhibitors during the reaction of alkanesulfinyl chlorides, benzenesulfinyl chloride, and DMF (Table III).

Prepareation of *S*-1-Chloropropyl Methanesulfonothioate (9). Fresh white globe onions (1 kg) were peeled, quartered, and frozen in dry ice in a cold room (0 °C). The frozen onions were crushed to a powder, and the powder was placed in 1 L of trichlorofluoromethane in a blender. The mixture was blended for 10 min, and the $CFCl_3$ layer was separated and then dried over $MgSO_4$. The $CFCl_3$ solution was placed in a round-bottomed flask at −78 °C and the $CFCl_3$ was distilled into a flask at −100 °C (0.2 mm). Distillation of the residue (−20 °C; 0.05 mm) into a flask at −100 °C gave propanethial *S*-oxide: ^1H NMR ($CDCl_3$) δ 1.15 (t, 3 H), 2.79 (q, 2 H), 8.18 (t, 1 H).[32]

To propanethial *S*-oxide in a 25-mL round-bottomed flask at −40 °C was added dropwise 0.98 g (0.01 mmol) of methanesulfinyl chloride in 10 mL of $CFCl_3$. The product mixture was warmed to 22–24 °C, and the excess methanesulfinyl chloride was removed by chromatography on silica gel using 1:9 ethyl ethanoate/hexanes as eluant. *S*-1-Chloropropyl methanesulfonothioate (9)[3,32,33] was the only product isolated: ^1H NMR ($CDCl_3$) δ 1.15 (t, 3 H), 2.15 (q, 2 H), 5.60 (t, 1 H), 3.50 (s, 1 H).

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Synthesis of α-Pyrones from Vinylogous Thiol Esters and α-Oxo Ketene Dithioacetals†

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Vinylogous thiol esters and α-oxo ketene dithioacetals can be converted into α-pyrones by a strategy involving 1,2-nucleophilic addition of ester, ketone, or hydrazone enolate anions, followed by acid-promoted rearrangement to a δ-keto ester, thiol ester, or acid and subsequent enol lactonization. These multistep procedures can be carried out without isolation and purification of intermediates and afford α-pyrones in good overall yields. The synthetic routes are complementary in terms of substitution patterns and limitations.

Introduction

We have, over the past few years, developed several synthetic routes to α-pyrones [2*H*-pyran-2-ones] from β-(alkylthio)-α,β-unsaturated ketones (vinylogous thiol esters)[1] and α-oxo ketene dithioacetals.[2] These procedures emerged from extensive studies on the chemistry of α-oxo ketene dithioacetals[3] which have proven to be versatile three-carbon synthons that provide ample opportunities for the regio-, stereo-, and chemoselective construction of new carbon–carbon bonds. The basic strategy (Scheme I) in these approaches involves the 1,2-nucleophilic addition of an ester, ketone, or hydrazone enolate anion to the carbonyl carbon of a vinylogous thiol ester or α-oxo ketene dithioacetal, followed by an acid-promoted 1,3-carbonyl transposition and enol lactonization to afford the α-pyrone. The execution of these approaches was dependent upon the successful development of the chemoselective reactions of α-oxo ketene dithioacetals with organocuprates[4] and of the utilization of α-oxo ketene di-

† Dedicated to Professor Walter J. Gensler, 1917–1987.

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