α-Phosphoryl Sulfoxides. II. Synthesis of α,β-Unsaturated Sulfoxides and Configurational Assignments to Geometrical Isomers[1]

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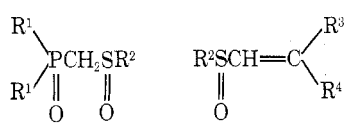
A new synthesis of α,β-unsaturated sulfoxides which involves the reaction of carbonyl compounds with 1-diethylphosphoryl-1-methylsulfinylmethyllithium (4) is described. The reaction was found to be nonstereoselective, mixtures of *E* and *Z* isomers being formed from aldehydes and unsymmetrical ketones. The geometry of mono- and disubstituted vinyl sulfoxides so formed was assigned with the aid of NMR spectroscopic methods (INDOR, NOE) and chemical correlations.

We have recently described[2] the synthesis of α-phosphoryl sulfoxides (1) arising from selective oxidation of corresponding α-phosphoryl sulfides using sodium metaperiodate. Other synthetic routes to **1**, which include the reaction of phosphonate carbanions with sulfinic esters and dialkyl phosphite anions with α-halogeno sulfoxides, are now being investigated in this laboratory.[3] This new class of compounds is of considerable interest for both synthetic and stereochemical studies. Owing to the presence of an asymmetric center at the sulfur atom, the α-phosphoryl sulfoxides **1** are chiral. Two additional centers of chirality may be created at the phosphorus and α-carbon atoms either by varying the substituents R^1 at phosphorus or by substitution of one of the two diastereotopic protons of the methylene group. In the latter case, owing to the presence of highly electron-withdrawing phosphoryl and sulfinyl groups, proton elimination may readily occur on treatment with a strong base, yielding the appropriate carbanion. This anion may be used in the same way as related anions generated from α-phosphoryl sulfides[4] and α-phosphoryl sulfones[4b,c,5] in the Horner–Wittig olefination to afford α,β-unsaturated sulfoxides (**2**).



1 **2**

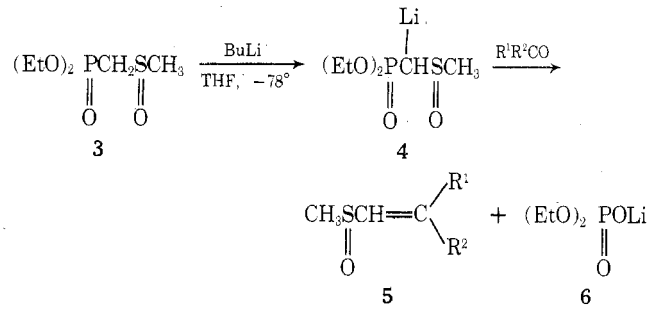
Although a number of synthetic methods for α,β-unsaturated sulfoxides are known, they are not general and do not lead to arbitrarily substituted systems. So far, α,β-unsaturated sulfoxides have usually been obtained by oxidation of appropriate α,β-unsaturated sulfides,[6] the oxidizing agents being hydrogen peroxide,[6a] peracids,[6b,c] hypochlorites,[6d] fuming nitric acid,[6e] iodobenzene dichloride,[6f] and sodium metaperiodate.[6c,6g] They are formed in elimination reactions from suitably β-substituted sulfoxides.[7] The sulfoxides **2** also arise from a reaction of vinyl Grignard reagents with sulfinic esters[8] and by addition to alkynes of sulfenic acids formed as a result of thiolsulfinate and sulfoxide decomposition.[9]

The synthesis of vinyl sulfoxides in a Peterson-type reaction of α-trimethylsilyl sulfoxides with carbonyl compounds, described recently by Carey and Hernandez,[10] has a more general character, but the relatively low thermal stability of the starting α-silyl substituted sulfoxides constitutes a serious limitation to this method.

In the present paper we describe a general and highly efficient synthesis of α,β-unsaturated sulfoxides (**2**) using diethylphosphorylmethyl methyl sulfoxide (**3**)[2] as a key compound for the Horner–Wittig reaction with carbonyl compounds. We also report studies on geometric isomerism is some suitably substituted sulfoxides (**2**).

Results and Discussion

Metalation of sulfoxide **3** was carried out in tetrahydrofuran solution at −78° using a small molar excess of *n*-butyllithium. It was found that raising of the temperature to above −50° after formation of lithium derivative **4** leads to its partial decomposition. For this reason attempts to prepare **3** by reaction with sodium hydride in boiling dimethoxyethane or tetrahydrofuran failed, even in the presence of the carbonyl component. Thus, in order to obtain high yields of α,β-unsaturated sulfoxides (**5**) it is necessary to add carbonyl compounds to **4** at ca. −70°. The adduct formed probably undergoes decomposition to **5** and the lithium salt of diethylphosphoric acid (**6**) at ca. −20°, which is evidenced by distinct turbidity of the reaction mixture brought about by precipitation of **6** from solution.



3 **4** **5** **6**

Representative aldehydes and ketones react with **4** giving in all cases sulfoxides **5** in good yields. These results are summarized in Table I.

The good yield (over 50%) of sulfoxides **5b, 5i,** and **5k** from cyclopentanone and acetophenones is noteworthy, since in the Horner–Wittig reaction these ketones undergo aldol condensation either exclusively or to a large extent.[4d] Crude sulfoxides **5** were in most cases purified by column chromatography on silica gel or by crystallization. The structure of the products obtained was established by elemental analysis and the usual spectroscopic techniques (NMR, ir) and in some cases by comparison of physical properties with those previously reported.

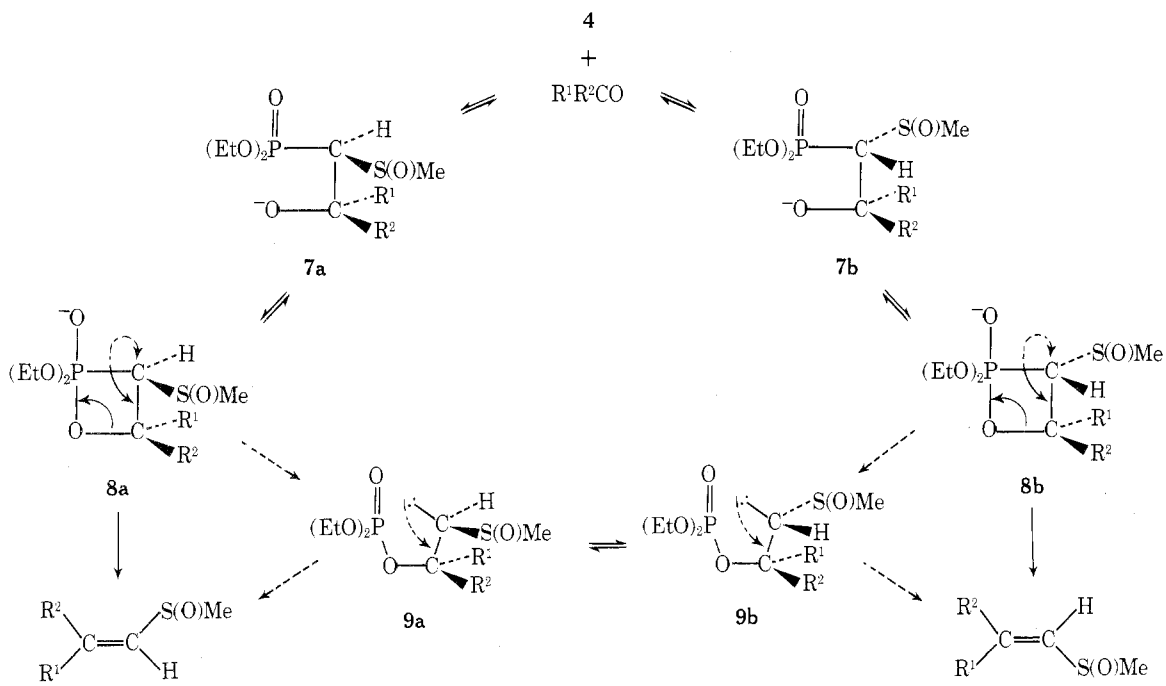
If aldehydes and unsymmetrical ketones were used, sulfoxides **5** were obtained as mixtures of *E* and *Z* geometrical isomers. Since geometrical isomers of sulfoxides **5** have been found to be configurationally stable under the reaction conditions used, this result shows that the Horner–Wittig type of olefination we employed is not stereoselective. The observed stereochemistry can be rationalized on the basis of the previously proposed mechanism of the Horner–Wittig reaction.[11] It appears that anion **4** reacts with

Table I
Preparation of α,β-Unsaturated Sulfoxides (5)

Registry no.	Aldehyde or ketone	Product	R^1	R^2	Yield,[a] %	E:Z ratio
119-61-9	Benzophenone	**5a**	C_6H_5	C_6H_5	84	
120-92-3	Cyclopentanone	**5b**	$-(CH_2)_4-$		50	
108-94-1	Cyclohexanone	**5c**	$-(CH_2)_5-$		81	
502-42-1	Cycloheptanone	**5d**	$-(CH_2)_6-$		81	
100-52-7	Benzaldehyde	**5e**	H	C_6H_5	70	58:42
874-42-0	2,4-Dichlorobenzaldehyde	**5f**	H	$Cl_2C_6H_3$	80	45:55
104-87-0	4-Methylbenzaldehyde	**5g**	H	$CH_3C_6H_4$	72	54:46
100-10-7	4-Dimethylaminobenzaldehyde	**5h**	H	$(CH_3)_2NC_6H_4$	75	82:18
98-86-2	Acetophenone	**5i**	CH_3	C_6H_5	70	45:55
2234-16-4	2,4-Dichloroacetophenone	**5k**	CH_3	$Cl_2C_6H_3$	51	27:73

[a] Isolated yield of purified product.

Scheme I



the carbonyl compound in a reversible step to afford diastereomeric alkoxides **7a** and **7b**, which in turn form corresponding five-coordinated phosphorus intermediates **8a** and **8b** (Scheme I). Formation of similar oxaphosphetanes in the Wittig reaction has recently been demonstrated by Vedejs and Snoble[12] with the aid of FT ^{31}P NMR spectroscopy. Compounds **8a** and **8b** then undergo fragmentation to vinyl sulfoxides and the phosphate anion by a concerted, four-center mechanism involving the phosphorus–carbon and carbon–oxygen bond breaking. However, recent CNDO–MO calculations carried out by Trindle, Hwang, and Carey[13] on the decomposition of species of the type $XCH_2CH_2O^-$ (X = H_3P^+, H_3Si) typical for the Wittig and Peterson reaction led us to consider the formation of final reaction products via diastereomeric carbanions **9a** and **9b** formed as a result of carbon–phosphorus bond cleavage. This latter process may be favored over scission of the carbon–oxygen bond in **8**, owing to the presence of the sulfinyl group, which is known to effectively stabilize adjacent carbanion centers.[14] In this context it is noteworthy that the Horner–Wittig reaction proceeds much faster with α-phosphoryl sulfones and sulfoxides than with α-phosphoryl sulfides.

The ratio of isomeric vinyl sulfoxides would then be expected to depend on the degree of reversibility of the formation of the two alkoxides **7a** and **7b** and on the rate of epimerization and stability of the oxy- and carbanions **7** and **9**. This point needs further study.

The isomeric compositions of vinyl sulfoxides **5** were determined from ^1H NMR spectra of crude products (see Table I). For all *E* and *Z* isomers distinct differences in chemical shifts of methylsulfinyl group protons as well as corresponding vinyl protons were observed. The isomer ratio was estimated by integration of the methylsulfinyl signals and in the case of sulfoxides **5i** and **5k** by also integrating signals for the vinyl protons.

Assignment of configuration *E* and *Z* to respective isomers of sulfoxides **5e–h** was based on the well-established geometrical dependence of vicincal proton coupling constants in olefins.[15] The ^1H NMR spectra of the above-mentioned sulfoxides reveal AB systems for trans and cis vinyl protons with $^3J_{H-H}$ of ca. 15.5 and 11.0 Hz, respectively. Another fact is that the singlet of the methylsulfinyl group for the *E* isomers appears at higher field than that for *Z* isomers. If examination of a greater number of examples shows this to be a general rule the methylsulfinyl chemical shift might allow a rapid assignment of configuration to geometrical isomers of α,β-unsaturated sulfoxides. The chemical shift and coupling constant values for *E* and *Z* isomers of the sulfoxides **5e–h** are collected in Table II.

Table II
Chemical Shifts and Coupling Constants of Monosubstituted Vinyl Sulfoxides 5

	Product, ArX	E: δ CH3, ppm	E: 3JH-H', Hz	Z: δ CH3, ppm	Z: 3JH-H', Hz
5e,	C_6H_5	2.69	15.6	2.72	11.0
5f,	$Cl_2C_6H_3$	2.61	15.5	2.64	10.5
5g,	$CH_3C_6H_4$	2.62	15.6	2.66	11.0
5h,	$(CH_3)_2NC_6H_4$	2.61	16.0	2.64	11.2

By fractional crystallization we were able to isolate isomerically pure samples of (*E*)-**5e,** (*E*)-**5h,** (*Z*)-**5f,** and (*Z*)-**5g** from the initially obtained isomeric mixture of sulfoxides. Physical constants and spectroscopic data for the isomers (*E*)-**5e** and (*E*)-**5h** were identical with those reported in the literature.

As expected, the NMR spectrum of the isomeric mixture of sulfoxide **5i** revealed two singlets for the methylsulfinyl group and two quartets and two doublets for the olefinic proton and methyl group, respectively. Moreover, *E* and *Z* isomers of **5i** differ in allylic coupling constants $^4J_{H-CH_3}$, which are 1.5 and 1.0 Hz, respectively. However, in contradistinction to the vicinal coupling constant $^3J_{H-H}$ discussed above, the value of the allylic coupling constant does not constitute a sure criterion for the configurational assignments of the geometrical isomers.[16]

In view of the fact that Vermeer, de Graaf, and Meijer[17] recently obtained pure *E* and *Z* isomers of 1-thiomethyl-2-methyl-2-phenylethylene (**10c**) by stereoselective addition of the Grignard reagents to suitable alkynyl sulfides in the presence of cuprous halides, it was expected that their oxidation to isomeric sulfoxides (*E*)-**5i** and (*Z*)-**5i** would allow the configuration of the latter to be rigorously established. To this end a series of α,β-unsaturated sulfides **10** was obtained from diethylphosphoryl dimethyl sulfide and several carbonyl compounds following Green's procedure,[4a] which,

$$(EtO)_2P(O)CH_2SCH_3 + NaH + R^1R^2CO \xrightarrow{DME} CH_3SCH{=}C(R^1)R^2 + (EtO)_2P(O)ONa$$

10 **6**

in accordance with recent results of Shahak and Almog,[4b,c] should give pure *E* isomers of **10,** at least in the case of aldehydes. However, a detailed analysis of the ^1H NMR and GLC spectra of the crude reaction products showed that sulfides **10** are a mixture of isomers *E* and *Z,* though the former clearly predominate. Yields and isomeric ratios of sulfides **10** thus obtained are listed in Table III.

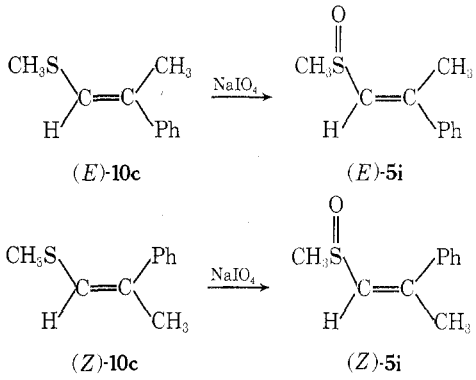
By means of preparative gas chromatography the sulfide **10c** was separated into pure *E* and *Z* isomers whose physical and spectroscopic constants were in perfect agreement with those reported by Vermeer et al. In addition, by using the INDOR technique we determined the sign of the allylic coupling constant, $^4J_{H-CH_3}$. Thus, in the isomer (*E*)-**10c** one can observe a trans allylic coupling constant equal to −1.0 Hz while for the isomer (*Z*)-**10c** it is a cis allylic coupling constant of −1.4 Hz. This result coincides with the theretical calculations of Barfield,[18] according to whom the trans $^4J_{H-CH_3}$ should be greater (i.e., less negative) than the cis $^4J_{H-CH_3}$. The correctness of the configurational assignment to sulfides (*E*)-**10c** and (*Z*)-**10c** is additionally confirmed by the agreement of experimental values of the chemical shift for the vinyl proton with those calculated on the basis of Pascual-Simon's table[19] (for isomer *E* δ_{obsd} 6.21 ppm, δ_{calcd} 6.33 ppm; for isomer *Z* δ_{obsd} 5.95 ppm, δ_{calcd} 5.96 ppm).

Table III
Preparation of α,β-Unsaturated Sulfides 10

Aldehyde or ketone	Product	R^1	R^2	Yield,[a] %	*E*:*Z* ratio
Benzaldehyde	**10a**	H	C_6H_5	66	88:12
4-Methylbenzaldehyde	**10b**	H	$CH_3C_6H_4$	63	87:13
Acetophenone	**10c**	CH_3	C_6H_5	45	82:18
2,4-Dichloroacetophenone	**10d**	CH_3	$Cl_2C_6H_3$	41	63:37

[a] Isolated yield of purified product.

Selective oxidation of sulfide (*E*)-**10c** yielded a pure isomer of sulfoxide **5i** as a crystalline compound having mp 70–71°. The same isomer with identical physical and spectroscopic properties was isolated from the crude product of the reaction of **4** with acetophenone. Oxidation of sulfide (*Z*)-**10c** gave the second pure isomer of **5i** in the form of a colorless oil. Since the configuration about the double bond



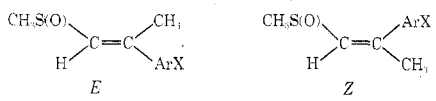
does not undergo change during oxidation, the sulfoxide obtained from (*E*)-**10c** should possess the *E* configuration while the one obtained from (*Z*)-**10c** should have the *Z* configuration.

The excellent agreement between the observed and calculated[20] vinyl proton resonance positions provides independent proof of this assignment [for the isomer (*E*)-**5i** δ_{obsd} 6.54 ppm, δ_{calcd} 6.60 ppm; for the isomer (*Z*)-**5i** δ_{obsd} 6.30 ppm, δ_{calcd} 6.23 ppm].

In view of the above results the configurational assignments to the geometrical isomers of sulfoxide **5i** and sulfide **10c** given by Russell et al.[6c,21] need correction. It is interesting to point out that, as in the case of the corresponding sulfides **10c,** the trans allylic coupling constant $^4J_{H-CH_3}$ for isomer (*E*)-**5i** is greater (−1.0 Hz) than the cis $^4J_{H-CH_3}$ (−1.5 Hz) for isomer (*Z*)-**5i.** All the proton NMR data for the above-mentioned sulfoxide **5i** are collected in Table IV.

We have also been successful in preparing and purifying both sulfoxide isomers of **5k,** which exhibit distinct differences in the ^1H NMR spectra (see Table IV). Their geometry has been established on the basis of the allylic coupling constant values discussed above and on nuclear Overhauser effect (NOE) studies.[22] Thus, the isomer with $^4J_{H-CH_3}$ = −1.5 Hz was assigned the *Z* configuration whereas the configuration *E* was given to the isomer with $^4J_{H-CH_3}$ = −1.3 Hz. In accord with this are the results of NOE experiments.

Table IV
Chemical Shifts and Coupling Constants of Disubstituted Vinyl Sulfoxides 5



	5i	5k	5i	5k
δ_{CH_3SO}, ppm	2.65	2.66	2.50	2.59
δ_{CH_3C}, ppm	2.34	2.27	2.16	2.16
δ_H, ppm	6.54	6.24	6.30	6.48
$^4J_{H-CH_3}$, Hz	−1.0	−1.3	−1.5	−1.5

Saturation of *C*-methyl protons in the isomer with a greater $^4J_{H-CH_3}$ value (−1.3 Hz) gave no observable enhancement of the vinyl proton resonance while in the isomer with the lower allylic coupling constant (−1.5 Hz) the resonance of the vinyl proton was enhanced by 11%. As the largest enhancement would be expected from the methyl group closest to the vinyl proton, these findings confirm our assignment that the methyl group is cis to the vinyl proton in the isomer with the lower allylic coupling (configuration *Z*).

Oxidation of isomeric vinyl sulfides **10d** to sulfoxides (*E*)-**5k** and (*Z*)-**5k** (63:37) enabled us to assign their *E* and *Z* geometry. It is worth stressing, however, that the major isomer obtained after oxidation was (*E*)-**5k,** whereas the Horner–Wittig reaction of **4** with 2,4-dichloroacetophenone afforded (*Z*)-**5k** as a predominant product. This clearly shows that the Horner–Wittig reaction of α-phosphoryl sulfide and α-phosphoryl sulfoxide with 2,4-dichloroacetophenone resulted in preferable formation of isomers possessing the sulfur and methyl group in reverse geometrical positions.

Experimental Section

All melting and boiling points are uncorrected. NMR spectra were recorded on a Tesla BS-487C 80-MHz spectrometer using Me_4Si as an internal standard. Ir spectra were measured on a Spektromom 2000 spectrophotometer as KBr disks for solids and pressed films for liquids. GLC analysis was carried out with a Varian Aerograph Model 1520 flame ionization gas chromatograph using a 20-ft column of 10% diethylene glycol adipate (DEGA) on Chromosorb W 60/80 at a column temperature of 190°, an injector temperature of 240°, and a detector temperature of 225°. Preparative gas chromatographic analyses were effected using a 50-ft column containing 10% Carbowax 20M at a column temperature of 180°, an injector temperature of 220°, and a detector temperature of 220°. Column chromatography was done on silica gel Merck 100–200 mesh. Commercially available aldehydes and ketones were purified by distillation or recrystallization immediately before use. All solvents used were purified according to standard procedures; tetrahydrofuran and dimethoxyethane were distilled from lithium aluminum hydride.

General Procedure for Synthesis of α,β-Unsaturated Sulfoxides (5). To a solution of diethylphosphorylmethyl methyl sulfoxide (**3,** 3.21 g, 0.015 mol) in 25 ml of THF a solution of *n*-butyllithium (16 ml, 0.016 mol) in ether was added at −78° under a nitrogen atmosphere. After 1 hr a clear and colorless solution of **4** was obtained. A solution of the carbonyl compound (0.015 mol) in 20 ml of THF was then added dropwise at −78° and the reaction mixture was stirred for 30 min at this temperature. The mixture was warmed slowly to room temperature and stirred for an additional 2 hr. At −20° the reaction mixture becomes turbid and in some cases an appearance of the yellow-orange color was observed. After removal of solvents the residue was treated with water (50 ml) and extracted with chloroform (3 × 25 ml). The chloroform solution was washed with water (25 ml), dried, and evaporated to afford the crude sulfoxide (**3**).

1-(Methylsulfinyl)-2,2-diphenylethylene (5a). The crude product (mp 102–105°) obtained from benzophenone (2.73 g, 0.015 mol) according to the procedure described above was recrystallized from *n*-hexane–ether (1:1), giving 3.05 g (84%) of **5a,** mp 106–107° (lit.[6c] mp 106–107°). Anal. Calcd for $C_{15}H_{14}OS$: C, 74.36; H, 5.83. Found: C, 74.34; H, 5.90.

1-[(Methylsulfinyl)methylene]cyclopentane (5b). Cyclopentanone (1.26 g, 0.015 mol) and **4** gave, after the usual work-up, crude **5b** as a dark-brown oil. Chromatography [elution with benzene–acetone–ethyl acetate (18:1:1)] afforded 1.08 g (50%) of pure sulfoxide **5b** as a yellow oil: $n^{20}D$ 1.5108; ^1H NMR ($CDCl_3$) δ 1.78 (m, 4, $-CH_2CH_2-$), 2.34 [m, 4, $(-CH_2)_2C=$], 2.49 (s, 3, CH_3SO), 6.12 (m, 1, $-CH=C<$); ir (film) 2850 s, 1710 m, 1430 w, 1405 m, 1310 w, 1280 w, 1200 w, 1090 w, 1010 vs (SO), 940 s, 530 w, 790 m, 710 w, 670 cm^{-1} w. Anal. Calcd for $C_7H_{12}OS$: C, 58.33; H, 8.33. Found: C, 58.22; H, 8.37.

1-[(Methylsulfinyl)methylene]cyclohexane (5c). The reaction of cyclohexanone (1.47 g, 0.015 mol) and **4** carried out according to the general procedure yielded crude **5c** as a yellow oil. Chromatography [benzene–acetone–ethyl acetate (18:1:1)] afforded 1.93 g (81%) of analytically pure **5c:** $n^{20}D$ 1.5138; ^1H NMR ($CDCl_3$) δ 1.61 [m, 6, $CH_2(CH_2-)_2$], 2.23 [m, 4, $(CH_2)_2C=$], 2.49 (s, 3, CH_3SO), 6.01 (s, 1, $-CH=C$); ir (film) 2900 s, 2850 s, 1610 m, 1440 s, 1420 m, 1400 w, 1340 w, 1300 w, 1270 w, 1155 w, 1105 w, 1030 s (SO), 970 m, 950 m, 925 m, 900 m, 820 m, 800 m, 750 m, 980 cm^{-1} w. Anal. Calcd for $C_8H_{14}OS$: C, 60.75; H, 8.86. Found: C, 60.68; H, 8.85.

1-[(Methylsulfinyl)methylene]cycloheptane (5d). Column chromatography [benzene–acetone (18:1)] of the crude product from cycloheptanone (1.68 g, 0.015 mol) gave 2.09 g (81%) of **5d** as a colorless oil: $n^{20}D$ 1.5245; ^1H NMR ($CDCl_3$) δ 1.58 (m, 8, $-CH_2CH_2CH_2CH_2-$), 2.40 [m, 4, $(-CH_2)_2C=C$], 2.49 (s, 3, CH_3SO), 6.01 (s, 1, $-CH=C<$); ir (film) 2900 s, 2800 s, 1680 w, 1600 w, 1440 m, 1420 w, 1340 w, 1240 w, 1180 m, 1120 w, 1030 vs (SO), 950 m, 860 w, 760 w, 740 w, 680 cm^{-1} w. Anal. Calcd for $C_9H_{16}OS$: C, 62.73; H, 9.30. Found: 62.29; H, 9.41.

Methyl Styryl Sulfoxide (5e). Benzaldehyde (1.51 g, 0.015 mol) and **4** gave crude product as a mixture of *E* and *Z* isomers in a ratio of 58:42 (^1H NMR assay). Column chromatography using benzene–acetone–ethyl acetate (18:1:1) as the solvent afforded 2.48 g (70%) of a pure isomeric mixture. Recrystallization from *n*-hexane–ether afforded the pure isomer (*E*)-**5e:** mp 64–65° (lit.[7e] mp 61–62°); ^1H NMR ($CDCl_3$) δ 2.69 (s, 3, CH_3SO), 6.88 and 7.23 (AB system, 2, J_{AB} = 15.6 Hz), 7.36 (m, 5, aromatic); ir (KBr) 2960 m, 2870 m, 1620 w, 1605 w, 1580 w, 1500 m, 1460 m, 1420 w, 1300 w, 1295 m, 1210 w, 1190 w, 1170 w, 1050 vs (SO), 1000 s, 960 s, 940 m, 820 w, 760 s, 740 vs, 700 s, 680 cm^{-1} w. Anal. Calcd for $C_9H_{10}OS$: C, 65.05; H, 6.07. Found: C, 65.04; H, 6.07. ^1H NMR ($CDCl_3$) for (*Z*)-**5e:** 2.72 (s, 3, CH_3SO), 6.44 and 7.02 (AB system, 2, J_{AB} = 11.0 Hz).

1-(Methylsulfinyl)-2-(2,4-dichlorophenyl)ethylene (5f). The crude product obtained from 2,4-dichlorobenzaldehyde (2.55 g, 0.015 mol) was a mixture of *E* and *Z* isomers in a ratio of 45:55 as determined by ^1H NMR ($CDCl_3$). (*E*)-**5f:** δ 2.61 (s, 3, CH_3SO), 7.02 and 7.45 (AB system, 2, J_{AB} = 15.5 Hz), 7.38 (m, 3, aromatic). (*Z*)-**5f:** δ 2.64 (s, 3, CH_3SO), 6.62 and 7.07 (AB system, 2, J_{AB} = 10.5 Hz), 7.38 (m, 3, aromatic). The pure mixture of isomers (2.81 g, 80%) was obtained as a syrupy oil after column chromatography using benzene–ethyl acetate (18:2) as the eluent. Crystallization from *n*-hexane–ether (1:1) afforded the pure isomer (*Z*)-**5f:** mp 87–88°; ir (KBr) 2960 m, 2870 m, 1700 w, 1600 w, 1570 s, 1540 w, 1460 s, 1450 s, 1400 m, 1380 s, 1295 w, 1200 w, 1120 w, 1100 s, 1040 s, 1020 vs (SO), 970 s, 960 s, 900 m, 850 s, 830 s, 800 s, 755 s, 720 w, 705 s, 699 w, 960 cm^{-1} w. Anal. Calcd for $C_9H_8OSCl_2$: C, 45.96; H, 3.40. Found: C, 46.06; H, 3.85.

1-(Methylsulfinyl)-2-(4-methylphenyl)ethylene (5g). The crude product obtained from 4-methylbenzaldehyde consisted of 54 and 46% of *E* and *Z* isomers, respectively. ^1H NMR ($CDCl_3$) for (*E*)-**5g:** δ 2.32 (s, 3, $CH_3C_6H_4$), 2.62 (s, 3, CH_3SO), 6.83 and 7.24 (AB system, 2, J_{AB} = 15.6 Hz), 7.14 and 7.32 (AB system, 4, aromatic, J_{AB} = 8.6 Hz). (*Z*)-**5g:** δ 2.35 (s, 3, $CH_3C_6H_4$), 2.66 (s, 3, CH_3SO), 6.37 and 6.97 (AB system, 2, J_{AB} = 11.0 Hz), 7.11 and 7.26 (AB system, 4, aromatic, J_{AB} = 8.6 Hz). After column chromatography [benzene–ethyl acetate–acetone (18:1:1)] a pure isomeric mixture (1.94 g, 72%) was obtained from which pure isomer (*Z*)-**5g** was isolated by crystallization from *n*-hexane–ether (1:1): mp 109–110°; ir (KBr) 2800 m, 1700 w, 1600 w, 1560 w, 1480 w, 1435 m, 1405 w, 1370 w, 1290 w, 1240 w, 1200 w, 1180 w, 1030 s (SO), 960 w, 780 m, 750 s, 700 cm^{-1} s. Anal. Calcd for $C_{10}H_{12}SO$: C, 66.67; H, 6.67. Found: C, 66.80; H, 7.00.

1-(Methylsulfinyl)-2-(4-dimethylaminophenyl)ethylene (5h). The crude product obtained from *p*-dimethylaminobenzaldehyde (2.24 g, 0.015 mol) was a yellow solid. Analysis of the ^1H NMR spectrum permitted the determination of the *E*:*Z* ratio as

82:18. After crystallization from *n*-hexane–ether (1:1) the pure isomer (*E*)-**5h** was obtained: 2.35 g (75%); mp 136–137° (lit.[23] mp 135–137°); ^{1}H NMR ($CDCl_3$) δ 2.61 (s, 3, CH_3SO), 2.98 [s, 6, $(CH_3)_2N$–], 6.65 and 7.14 (AB system, 2, J_{AB} = 16.0 Hz), 6.67 and 7.32 (AB system, 4, aromatic, J_{AB} = 9.0 Hz); ir (KBr) 2900 m, 2800 m, 1600 vs, 1520 s, 1445 m, 1430 m, 1360 s, 1320 w, 1300 w, 1210 m, 1190 s, 1160 s, 1110 w, 1040 vs (SO), 965 s, 940 m, 825 m, 760 w, 710 s, 670 cm^{-1} w. Anal. Calcd for $C_{11}H_{15}OSN$: C, 63.12; H, 7.22. Found: C, 63.40; H, 7.24.

1-(Methylsulfinyl)-2-methyl-2-phenylethylene (5i). Reaction of acetophenone (1.80 g, 0.015 mol) and **4** according to the general procedure gave crude product as an brown oil. The product composition was determined by ^{1}H NMR ($CDCl_3$) to be *E*:*Z* = 45:55. (*Z*)-**5i:** δ 2.16 (d, 3, CH_3C=C, *J* = −1.5 Hz), 2.50 (s, 3, CH_3SO), 6.30 (q, 1, C=CH, J = −1.5 Hz), 7.24 (m, 5, aromatic). (*E*)-**5i:** δ 2.34 (d, 3, CH_3C=C, *J* = −1.0 Hz), 2.65 (s, 3, CH_3SO), 6.54 (q, 1, C=CH, *J* = −1.0 Hz), 7.38 (m, 5, aromatic). Column chromatography [benzene–ethyl acetate (18:1)] afforded 1.89 g (70%) of pure sulfoxide **5i** from which after crystallization [*n*-hexane–ether (1:1)] pure isomer (*E*)-**5i** was obtained: mp 70–71°; ir (KBr) 2960 m, 2870 m, 1600 m, 1500 m, 1430 w, 1400 w, 1380 w, 1240 w, 1040 s (SO), 960 s, 940 m, 850 w, 830 m, 785 s, 740 w, 705 w, 680 cm^{-1} w. Anal. Calcd for $C_{10}H_{12}OS$: C, 66.67; H, 6.67. Found: C, 66.45; H, 6.96.

1-(Methylsulfinyl)-2-methyl-2-(2,4-dichlorophenyl)ethylene (5k). A mixture of *Z* and *E* isomers (73:27) was obtained from 2,4-dichloroacetophenone (2.84 g, 0.015 mol). Analysis of ^{1}H NMR spectra ($CDCl_3$) led to the following assignments. (*Z*)-**5k:** δ 2.16 (d, 3, CH_3C=C, *J* = −1.5 Hz), 2.59 (s, 3, CH_3SO), 6.48 (q, 1, HC=C, *J* = −1.5 Hz), 7.26 (m, 3, aromatic). (*E*)-**5k:** δ 2.27 (d, 3, CH_3C=C–, *J* = −1.3 Hz), 2.66 (s, 3, CH_3SO), 6.24 (q, 1, HC=C, *J* = −1.3 Hz), 7.26 (m, 3, aromatic). Column chromatography [benzene–ethyl acetate (10:1)] gave 1.92 g (51.5%) of the pure product. Rechromatography using benzene–ethyl acetate–acetone (20:1:1) as the eluent afforded the pure prodominant sulfoxide (*Z*)-**5k** as a colorless oil: n^{20}D 1.5748; ir (film) 2960 w, 2850 w, 1700 w, 1610 w, 1570 m, 1540 w, 1460 s, 1420 w, 1360 m, 1280 w, 1100 m, 1080 m, 1030 s (SO), 960 w, 860 w, 810 s, 810 s, 680 cm^{-1} w. Anal. Calcd for $C_{10}H_{10}OSCl_2$: C, 48.10; H, 4.02. Found: C, 48.32; H, 4.02.

Synthesis of α,β-Unsaturated Sulfides (10). All the sulfides (**10**) listed in Table III were obtained according to Green's procedure[4a] from α-phosphoryldimethyl sulfide and carbonyl compounds. The physical and spectral data of the products follow.

10a: a colorless oil; n^{20}D 1.6320 (lit.[4a] n^{20}D 1.6325); yield 66%; *E*:*Z* ratio 88:12. ^{1}H NMR ($CDCl_3$) (*E*)-**10a:** δ 2.28 (s, 3, CH_3S), 6.22 and 6.67 (AB system, 2, J_{AB} = 15.5 Hz), 7.20 (m, 5, aromatic). (*Z*)-**10a:** δ 6.07 and 6.30 (AB system, 2, J_{AB} = 11.0 Hz). Anal. Calcd for $C_9H_{10}S$: C, 71.94; H, 6.69. Found: C, 71.96; H, 6.81.

10b: a colorless oil; n^{20}D 1.6030; yield 63%; *E*:*Z* ratio 87:13. ^{1}H NMR ($CDCl_3$) (*E*)-**10b:** δ 2.27 and 2.29 (two s, 6, CH_3S and $CH_3C_6H_4$–), 6.20 and 6.62 (AB system, 2, J_{AB} = 15.6 Hz), 6.97 and 7.13 (AB system, 2, J_{AB} = 8.6 Hz, aromatic). (*Z*)-**10b:** δ 6.28 and 6.45 (AB system, 2, J_{AB} = 11.2 Hz).

The pure geometrical isomers of sulfide **10c** were obtained by gas chromatography of the crude reaction product (45% yield) which consisted of 82% of *E* and 18% of *Z* isomers. (*E*)-**10c:** mp 29–30° (lit.[21] mp 29–30°); ^{1}H NMR ($CDCl_3$) δ 2.08 (d, 3, CH_3C=, *J* = −1.0 Hz), 2.28 (s, 3, CH_3S), 6.21 (q, 1, HC=, *J* = −1.0 Hz), 7.20 (m, 5, aromatic). Anal. Calcd for $C_{10}H_{12}S$: C, 73.12; H, 7.36. Found: C, 72.76; H, 7.35. (*Z*)-**10c:** a colorless oil; n^{20}D 1.6130 (lit.[17] n^{20}D 1.6130); ^{1}H NMR ($CDCl_3$) δ 2.11 (d, 3, CH_3C=, *J* = −1.4 Hz), 2.20 (s, 3, CH_3S), 5.95 (q, 1, HC=, *J* = −1.4 Hz), 7.29 (m, 5, aromatic). Anal. Calcd for $C_{10}H_{12}S$: C, 73.12; H, 7.36. Found: C, 72.78; H, 7.32.

10d: a colorless oil; n^{20}D 1.5825; yield 41%; *E*:*Z* ratio 63:37. ^{1}H NMR ($CDCl_3$) (*E*)-**10d:** δ 2.01 (d, 3, CH_3C=, *J* = −1.1 Hz), 2.31 (s, 3, CH_3S), 5.91 (q, 1, HC=, *J* = −1.1 Hz), 7.18 (m, 3, aromatic). (*Z*)-**10d:** δ 2.30 (d, 3, CH_3C=, *J* = −1.4 Hz), 2.18 (s, 3, CH_3S), 5.99 (q, 1, HC=, *J* = −1.4 Hz), 7.18 (m, 3, aromatic). Anal. Calcd for $C_{10}H_{10}SCl_2$: C, 51.52; H, 4.32. Found: C, 51.48; H, 4.32.

Oxidation of (*E*)-10c to (*E*)-5i. To a mixture of 200 mg (1.22 mmol) of (*E*)-**10c,** 10 ml of acetone, and 10 ml of water was added dropwise 280 mg (1.3 mmol) of sodium metaperiodate in water at −10°. The reaction mixture was stirred at this temperature for an additional 6 hr and allowed to stand at 5° for 4 days. The precipitated sodium iodate was filtered off. After removal of the solvents at reduced pressure the residue was dissolved in acetone and dried over anhydrous $MgSO_4$. Removal of the acetone left 211 mg (96%) of (*E*)-**5i,** mp 70–71°. Anal. Calcd for $C_{10}H_{12}OS$: C, 66.67; H, 6.67. Found: C, 66.44; H, 6.31.

Oxidation of (*Z*)-10c to (*Z*)-5i. Oxidation of (*Z*)-**10c** (77 mg, 0.47 mmol) according to the procedure described above gave 79 mg (93.5%) of (*Z*)-**5i** as a pale yellow oil. Anal. Calcd for $C_{10}H_{12}OS$: C, 66.67; H, 6.67. Found: C, 66.41; H, 6.40.

Oxidation of 10d to 5k. A 932-mg (4 mmol) sample of **10d** (isomeric content 63:37) in 50 ml of chloroform was treated with an equimolar amount of *m*-chloroperbenzoic acid in chloroform solution at −10°. The reaction mixture was stirred at this temperature for an additional 10 hr and allowed to stand at −10° overnight. The precipitated acid was filtered off and chloroform solution was washed with a 5% aqueous solution of Na_2CO_3 and then with water. The chloroform layer was dried over anhydrous $MgSO_4$ and evaporated to give 945 mg (95%) of the sulfoxide **5k** which consisted of 63% *E* and 37% *Z* isomers. Anal. Calcd for $C_{10}H_{10}OSCl_2$: C, 48.20; H, 4.02. Found: C, 48.21; H, 4.23.

Column chromatography using benzene–ethyl acetate (9:1) as the eluent afforded the pure predominant isomer (*E*)-**5k** as a colorless oil, n^{20}D 1.5649. Anal. Calcd for $C_{10}H_{10}OSCl_2$: C, 48.20; H, 4.02. Found: C, 48.20; H, 4.04.

Oxidation of 10b to 5g. The oxidation of **10b** was performed in the same manner as the oxidation of **10c.** From 410 mg (2.5 mmol) of **10b** (87% of *E* and 13% of *Z* isomer) 420 mg (93.5%) of **5g** (*E*:*Z* ratio 87:13) was obtained. The product was crystallized from ether–hexane (2:1) to afford pure sulfoxide (*E*)-**5g,** mp 78–79°. Anal. Calcd for $C_{10}H_{12}SO$: C, 66.67; H, 6.67. Found: C, 66.60; H, 6.75.

Configurational Stability of Sulfoxide 5i under the Reaction Conditions. Control Experiments. A. To a solution of **4** (0.5 mmol) obtained as described above a solution of sulfoxide (*E*)-**5i** (0.5 mmol) in 5 ml of THF was added at −78° under the nitrogen atmosphere. The mixture was stirred at this temperature for 1 hr and then at room temperature for an additional 2 hr. After addition of water and the usual work-up starting sulfoxide (*E*)-**5i** was recovered.

B. Under the same conditions a mixture of *E* and *Z* isomers of sulfoxide **5i** in a ratio of 45:55 has been found to be unchanged.

C. To a solution of the lithium salt of diethylphosphoric acid (0.5 mmol) in 5 ml of THF a solution of sulfoxide (*E*)-**5i** in 5 ml of THF was added at −78°. The mixture was stirred at −78° for 1 hr. Then it was warmed slowly to room temperature and stirred for an additional 2 hr. After the usual work-up sulfoxide (*E*)-**5i** was recovered.

D. Under the same conditions a mixture of (*E*)-**5i** and (*Z*)-**5i** (45:53) has been found to undergo no changes.

Registry No.—**3,** 50746-61-7; **4,** 55059-02-4; **5a,** 21147-11-5; **5b,** 55059-03-5; **5c,** 55059-04-6; **5d,** 55059-05-7; (*E*)-**5e,** 7715-00-6; (*Z*)-**5e,** 53165-40-5; (*E*)-**5f,** 55059-06-8; (*Z*)-**5f,** 55059-07-9; (*E*)-**5g,** 55059-08-0; (*Z*)-**5g,** 55059-09-1; (*E*)-**5h,** 41411-19-2; (*Z*)-**5h,** 55059-10-4; (*E*)-**5i,** 24377-98-8; (*Z*)-**5i,** 24377-97-7; (*E*)-**5k,** 55059-11-5; (*Z*)-**5k,** 55059-12-6; (*E*)-**10a,** 15436-06-3; (*Z*)-**10a,** 35822-50-5; (*E*)-**10b,** 55059-13-7; (*Z*)-**10b,** 55059-14-8; (*E*)-**10c,** 25650-53-7; (*Z*)-**10c,** 22950-86-3; (*E*)-**10d,** 55059-15-9; (*Z*)-**10d,** 55059-16-0.

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On Conformation–Reactivity Correlations

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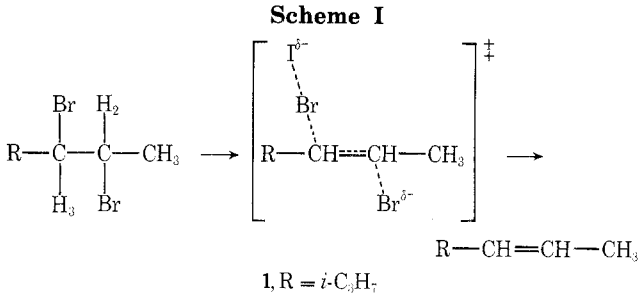
The kinetics and product studies of the reaction of 2,3-dibromo-4-methylpentanes and 2,3-dibromo-4,4-dimethylpentanes with iodide ion are reported. ^{13}C NMR studies, in conjunction with previous ^{1}H and dipole moment studies, strongly suggest that the erythro isomer of the *tert*-butyl compound occupies a different conformation than the erythro isomer of the isopropyl compound; yet the rates of reactions are not divergent. The bases for the frequently observed correlation between a favorable ground-state conformation and a rapid reaction rate are discussed.

A number of recent papers have commented upon the fact that substrates in which the reactive groups exist in the correct steric relationship for a given reaction frequently undergo rapid reaction.[1-16] Other studies have considered the obverse, namely, that a slow reaction is found where the preferred ground-state conformation is unfavorable for reaction. Occasionally, the suggestion is made that the ground-state conformation affects or determines reactivity. We wish to show a case in which a compound with an unfavorable ground-state conformation reacts more rapidly than a compound with a favorable conformation.[17]

The reaction in question is the iodide-catalyzed debromination of certain acyclic dibromides 1 and 2. Earlier work on similar debrominations showed a preference for a trans elimination of the elements of bromine (Scheme I).[18]

Scheme I

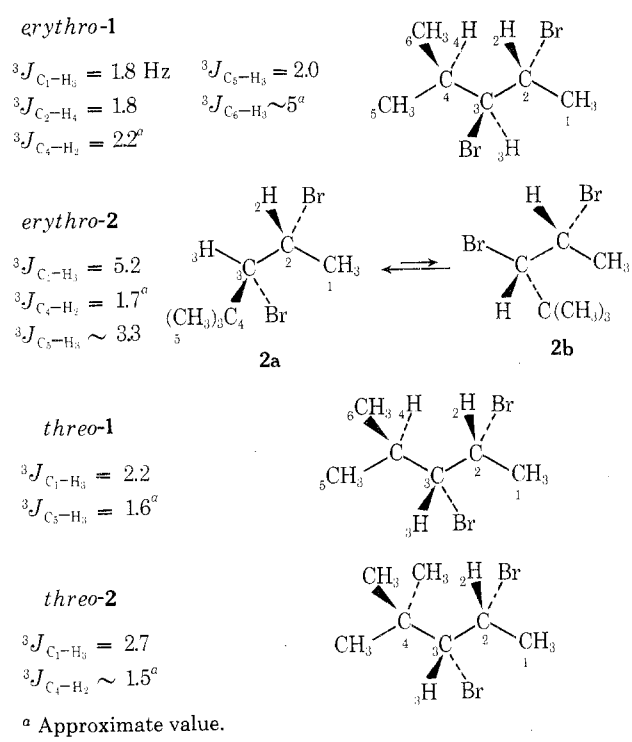


1, R = *i*-C_3H_7
2, R = *t*-C_4H_9

The ground-state conformations of *threo*-1 and -2 are quite similar.[19] For these threo isomers, very low ^{1}H NMR J_{23} values were observed, which implies a predominance of conformation(s) having gauche vicinal hydrogens. The dipole moment studies showed high resultant moments ($\mu \simeq$ 2.5 D) due to vectorially additive group moments for bromine such as expected for gauche vicinal bromines. Both lines of evidence suggest a preference for the conformers shown in Scheme II.

erythro-1 shows a high J_{23} value (10.6 Hz) and a low dipole moment (0.9 D). In contrast, *erythro*-2 shows a lower

Scheme II



[a] Approximate value.

J_{23} (2.0 Hz) and a much higher dipole moment (2.6 D). Thus, the preferred conformations of these two substrates appear quite different (Scheme II). Others have noted divergent conformations for compounds containing *tert*-butyl groups compared to compounds having isopropyl or phenyl groups.[20-24] In particular, Bodot and coworkers were able to suggest numerical weights for the different conformers in certain halohydrins analogous to 1 and 2.[23] Reasons for the divergence in conformation have been suggested in earlier work.[21,25]

A third method of conformational analysis of these sub-