

## The Chemistry of Carbanions. XVIII. Preparation of Trimethylsilyl Enol Ethers<sup>1a</sup>

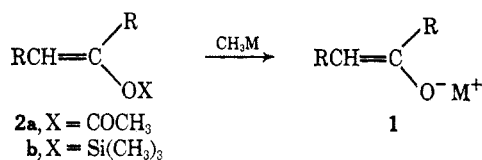
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Two procedures for the preparation of trimethylsilyl enol ethers from aldehydes and ketones are described. Reaction of the ketone with chlorotrimethylsilane and triethylamine in dimethylformamide solution usually affords an equilibrium mixture of the trimethylsilyl enol ethers. Successive reaction of the ketone with lithium diisopropylamide and with chlorotrimethylsilane in 1,2-dimethoxyethane solution normally produces a mixture in which the less highly substituted enol ether (from kinetically controlled enolate formation) is the principal product. A number of representative structurally and stereochemically isomeric trimethylsilyl enol ethers have been characterized (see Table II) and their physical properties have been studied.

In earlier studies<sup>2</sup> specific structural isomers and stereoisomers of enolate anions **1** were generated by reac-



tion of enol acetates **2a** with 2 equiv of methyl lithium. One of the by-products of this reaction is the strongly basic lithium *t*-butoxide which may complicate subsequent alkylation of the enolate anions by promoting further alkylation of the initially formed product. In an effort to find a procedure which would produce specific enolate anions not accompanied by a strongly basic by-product, we were led to consider the reactions of enol derivatives of phosphorus,<sup>3</sup> tin,<sup>4</sup> and silicon<sup>5</sup> (e.g., **2b**) with organometallic reagents. After preliminary experimentation, we concluded that the ease of syntheses and stability<sup>6</sup> of the trimethylsilyl enol ethers **2b** recommended these intermediates over the phosphorus and tin derivatives. The same conclusion was reached independently by Stork and Hudrlik, who recently published<sup>5f</sup> a preliminary account of their studies of silyl enol ethers with objectives similar to our own. In this paper are described the preparative methods that we employed and the characterization of various trimethylsilyl enol ether derivatives, including the conversion of a number of these silyl ethers into enolate anions and subsequently to enol acetates. A subsequent publication

will describe our study of these materials as precursors for enolate anion intermediates in alkylation reactions<sup>7</sup>

The preparative methods previously employed<sup>5</sup> for silyl enol ethers have involved preliminary treatment of ketones with bases of sufficient strength to convert the ketones completely into their enolate anions; the bases which have been employed include sodium bis(trimethylsilyl)amide,<sup>5a</sup> the sodium radical anion of anthracene,<sup>5d</sup> sodium hydride,<sup>5f</sup> and triphenylmethylpotassium.<sup>5f</sup> Depending upon the way in which the ketone and base are mixed, either a kinetically controlled mixture of enolate anions or an equilibrium mixture of enolate anions may be obtained.<sup>2,5f</sup> Subsequent reaction of the enolate anion(s) with excess trimethylsilyl chloride has produced the silyl enol ethers in good yield.<sup>5</sup> Since we wished to use these silyl ethers, like the previously studied enol acetates,<sup>2</sup> for the preparation of specific structural isomers of unsymmetrical ketone enolates, as well as enolates of symmetrical ketones and aldehydes, considerable effort was expended in seeking synthetic methods which would produce the pure silyl ethers easily and in synthetically useful amounts. Of the various methods examined, the most satisfactory procedure for aldehydes and ketones which are symmetrical or which can enolize in only one direction involved direct reaction of the carbonyl compound with either triethylamine or 1,4-diazabicyclo[2.2.2]octane (DABCO) and excess trimethylsilyl chloride in dimethylformamide (DMF) solution. Typical examples are illustrated in Scheme I and the various reactions studied are summarized in Tables I and II. The enol ether products were readily isolated by fractional distillation, and could be stored without decomposition or hydrolysis provided that they were protected from water and, especially, aqueous acids. Our studies are consistent with the simple view that enol ether formation proceeds by reaction of the ketone with the amine to form an enolate anion which then reacts with the trimethylsilyl chloride to form the O-silylated product.

When the same preparative procedure was applied to unsymmetrical ketones capable of forming structurally isomeric enol ethers (Tables I and II), mixtures of structural isomers were obtained in all cases except with phenylacetone (**14**, Scheme II) and the octalone **28** where only the conjugated isomers **15**, **16**, and **29** were observed. The proportions of structural isomers present (e.g., **22b** and **23b**, Scheme II) in the reaction mixtures was observed to change as the reaction progressed suggesting that the mixture of reagents triethylamine hydrochloride and trimethylsilyl chloride in dimethyl-

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(2) For a review, see H. O. House, *Rec. Chem. Progr.*, **28**, 99 (1967).

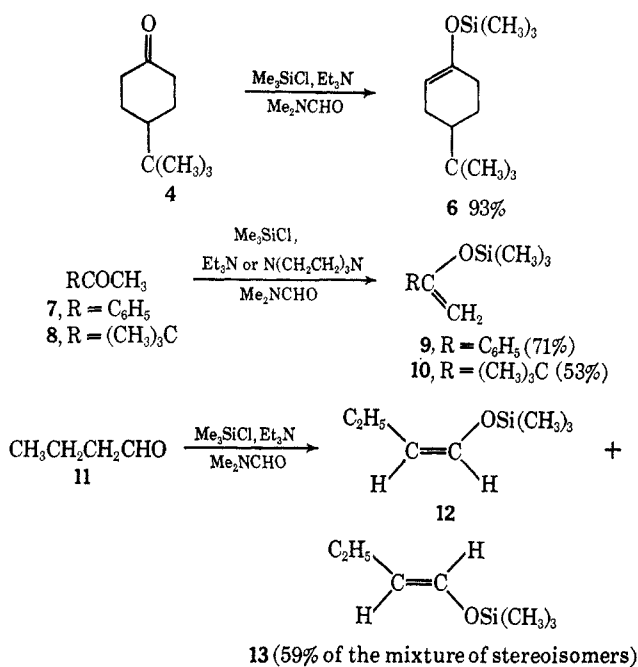
(3) For discussions of the preparation of enol phosphates, see (a) F. W. Lichtenthaler, *Chem. Rev.*, **61**, 607 (1961); (b) P. S. Magee, *Tetrahedron Lett.*, 3995 (1965); (c) T. Mukaiyama, T. Kumamoto, and T. Nagaoka, *ibid.*, 5563 (1966).

(4) For a recent discussion of trialkyltin enol ethers, see M. Pereyre, B. Bellegarde, J. Mendelsohn, and J. Valade, *J. Organometal. Chem.*, **11**, 97 (1968).

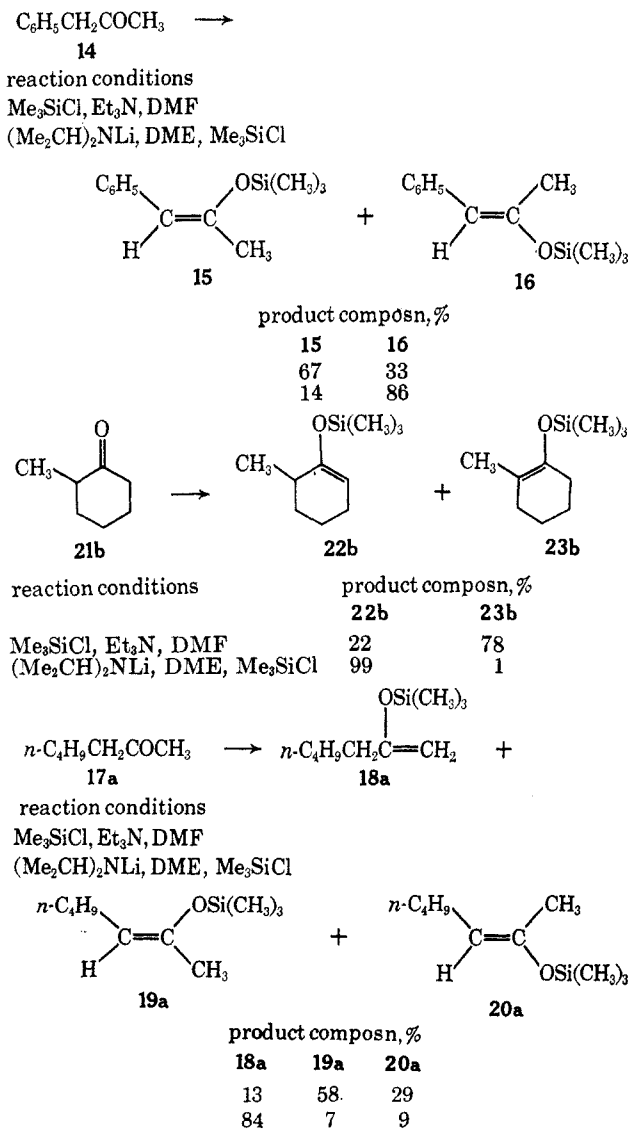
(5) For descriptions of the preparation of silyl enol ethers, see (a) C. R. Krüger and E. G. Rochow, *J. Organometal. Chem.*, **1**, 476 (1964); (b) J. I. Baukov, G. S. Burlachenko, and I. F. Lutsenko, *ibid.*, **3**, 478 (1965); (c) R. J. Fessenden and J. S. Fessenden, *J. Org. Chem.*, **32**, 3535 (1967); (d) R. Bourhis and E. Frainnet, *Bull. Soc. Chim. Fr.*, 3552 (1967); (e) U. Schmidt and M. Schwochan, *Tetrahedron Lett.*, 4491 (1967); (f) G. Stork and P. F. Hudrlik, *J. Amer. Chem. Soc.*, **90**, 4462, 4464 (1968).

(6) For examples of the rearrangement of 2-silyl ketones to enol ethers, see (a) A. G. Brook, D. M. MacRae, and W. W. Limburg, *J. Amer. Chem. Soc.*, **89**, 5493 (1967); (b) I. F. Lutsenko, Yu. I. Baukov, O. V. Dudukina, and E. N. Kramarova, *J. Organometal. Chem.*, **11**, 35 (1968).

SCHEME I



SCHEME II



formamide solution would slowly isomerize the trimethylsilyl enol ethers to form an equilibrium mixture.




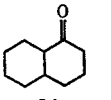
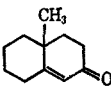
Further investigation established that these reaction conditions would equilibrate silyl enol ethers. In fact, this method of equilibration was the most satisfactory procedure that we found. In our hands, the use of acids such as anhydrous *p*-toluenesulfonic acid (recommended by Stork and Hudrlik<sup>5f</sup>), anhydrous hydrogen chloride, or trifluoroacetic acid was seriously complicated by the concurrent formation of substantial amounts of higher molecular weight materials and ketones (from a hydrolytic or related cleavage of the silyl enol ethers). The equilibrations were complicated by concurrent formation of some ketone even when the silyl enol ethers were treated with trimethylsilyl chloride and triethylamine hydrochloride in dimethylformamide. However, we were able to establish equilibrium more rapidly than the enol ethers were cleaved and obtained the approximate equilibrium data for trimethylsilyl enol ethers presented in Scheme III. (A mixture containing 9% **22b** and 91% **23b** was observed by Stork and Hudrlik after treatment of the silyl ethers with toluenesulfonic acid.) In Scheme III, these equilibrium compositions are compared with earlier data obtained by the acid-catalyzed equilibration<sup>7</sup> of the analogous enol acetates and enol ethers to illustrate the apparent trend for the silyl ethers to have equilibrium compositions similar to or in between the equilibrium compositions of the corresponding enol ethers and enol acetates (*cf.* ref 5f). In instances where an equilibrium mixture of trimethylsilyl enol ethers is desired for preparative work, we recommend use of a prolonged heating period during the reaction of the ketone with trimethylsilyl chloride and triethylamine in dimethylformamide.

It was apparent that the less highly substituted silyl enol ethers (*e.g.*, **18a** and **22b**, Scheme II) could be obtained more efficiently by the initial reaction of the ketones with a strong base under conditions of kinetically controlled deprotonation.<sup>2,5f</sup> Further reaction with trimethylsilyl chloride would produce the desired enol ethers (*cf.* ref 5f). Although triphenylmethyl lithium or triphenylmethylpotassium might be used for this purpose, the presence of substantial amounts of triphenylmethane in a reaction mixture complicates product isolation. The relatively slow reaction of a ketone with sodium hydride<sup>5f</sup> to produce an enolate solution normally affords an equilibrium mixture of enolates and is often complicated by the concurrent formation of aldol products.<sup>2</sup> Our attempts to obtain silyl ethers by reaction of ketones with sodium hydride in the presence of excess trimethylsilyl chloride to trap the enolate anions as formed were uniformly unsuccessful. This observation is in keeping with the common supposition that traces of alcohols (and the corresponding alkoxides) are the usual proton transfer agents in reactions of ketones with the insoluble polymeric sodium hydride. Since the trimethylsilyl chloride would be an excellent scavenger for traces of alkoxides,<sup>8</sup> the absence of any reaction between the ketones and sodium hydride under these conditions is understandable.

(7) (a) H. O. House and V. Kramar, *J. Org. Chem.*, **28**, 3362 (1963); (b) H. O. House and B. M. Trost, *ibid.*, **30**, 1341, 2502 (1965).

(8) The use of trimethylsilyl chloride as a scavenger for alkoxides has been used to advantage in the acyloin condensation. See (a) J. J. Bloomfield, *Tetrahedron Lett.*, 587, 591 (1968); (b) G. E. Gream and S. Worthley, *ibid.*, 3319 (1968).

TABLE I  
 CONVERSION OF KETONES INTO SILYL ENOL ETHERS

Ketone	Preparative method <sup>a</sup> (reaction time, hr)	Yield of enol ether(s), % [bp, $n_D^{20}$ for product]	Enol ether product (composn, %) listed in order of elution on gas chromatography
 3	A (4.0)	70 [74-75° (20 mm), $n_D^{24}$ 1.4451]	5 (>98) <sup>b</sup>
4	A (18.0)	93 [94-96° (3.9 mm), $n_D^{23}$ 1.4549]	6 (>98) <sup>b</sup>
7	A (19.0)	71 [89-91° (12 mm), $n_D^{26}$ 1.4988]	9 (>98) <sup>c</sup>
8	A (6.0) <sup>d</sup>	53 [140-142° (760 mm), $n_D^{21}$ 1.4061]	10 (>98) <sup>e</sup>
11	A (4.0)	59 [56-62° (75 mm), $n_D^{25}$ 1.4042- 1.4071]	12 (62), 13 (38) <sup>e</sup>
14	A (13.5)	42 [106° (10 mm), $n_D^{20}$ 1.5142-1.5149]	16 (33), 15 (67) <sup>f</sup>
	B	34 [106-110° (10 mm)]	16 (86), 15 (14) <sup>f</sup>
	C <sup>g</sup>	61 [81° (2.0 mm), $n_D^{24}$ 1.5140-1.5149]	16 (4), 15 (96) <sup>f</sup>
17a	A (60)	52 [94-95° (52 mm), $n_D^{25}$ 1.4207-1.4224]	18a (13), 19a (58), 20a (29) <sup>h</sup>
	B	65 [104-106° (35-36 mm), $n_D^{25}$ 1.4178] <sup>i</sup>	18a (84), 19a (7), 20a (9) <sup>h,i</sup>
CH <sub>3</sub> CH <sub>2</sub> COCH <sub>3</sub> 17b	A (16)	77 [115-123° (760 mm), $n_D^{26}$ 1.4057]	18b (12), 19b (64), 20b (24) <sup>e</sup>
	B <sup>j</sup>	23 [100-130° (760 mm)]	18b (71), 19b (13), 20b (16) <sup>e</sup>
 21a	A (4.0)	69 [73-78° (34 mm), $n_D^{25}$ 1.4336- 1.4392]	22a (43), 23a (57) <sup>e</sup>
 34	A (8.0)	59 [158-159° (760 mm), $n_D^{25}$ 1.4377]	35 (>98) <sup>e</sup>
(CH <sub>3</sub> ) <sub>2</sub> CHCOCH <sub>2</sub> CH <sub>3</sub> 30	A (54)	50 [72-76° (58 mm), $n_D^{25}$ 1.4137-1.4220]	33 (20), 32 (62), 31 (18) <sup>e,h</sup>
	B	87 [94-97° (88 mm), $n_D^{25}$ 1.4169]	33 (53), 32 (42), 31 (5) <sup>e,h</sup>
21b	A (48.0)	80 [90-93° (20 mm)]	22b (22), 23b (78) <sup>h</sup>
	B	74 [59-61° (7 mm), $n_D^{25}$ 1.4440]	22b (99), 23b (1) <sup>h</sup>
	A (30)	86 [74-86° (0.4 mm), $n_D^{25}$ 1.4760]	25 (17), 26 (5), 27 (78) <sup>f</sup>
	B	81 [75-87° (0.03 mm), $n_D^{25}$ 1.4737]	25 (71), 26 (27), 27 (2) <sup>f</sup>
 24	A (23)	65 [95.5-98° (1.3 mm), $n_D^{24}$ 1.5008-1.5025]	29 (>98) <sup>e</sup>
 28	B	47[...] <sup>g</sup>	29 (>98) <sup>e</sup>

<sup>a</sup> In procedure A, the ketone was treated with a mixture of Et<sub>3</sub>N and Me<sub>3</sub>SiCl. In procedure B, the enolate, formed by initial reaction of the ketone with (*i*-Pr)<sub>2</sub>NLi in 1,2-dimethoxyethane, was treated with excess Me<sub>3</sub>SiCl. <sup>b</sup> A gas chromatography column packed with Apiezon M suspended on Chromosorb G was employed for this analysis. <sup>c</sup> A gas chromatography column packed with nitrile gum, no. XE-60, suspended on Chromosorb P was employed for the analysis. <sup>d</sup> In this preparation, 1,4-diazabicyclo[2.2.2]octane (DABCO) was used as the base instead of Et<sub>3</sub>N. When Et<sub>3</sub>N was used, the yield of silyl ether was 44%: bp 141-143°;  $n_D^{21}$  1.4090. <sup>e</sup> A gas chromatography column packed with silicone fluid, no. 710, suspended on either Chromosorb P or Chromosorb W was employed for this analysis. <sup>f</sup> A gas chromatography column packed with 1,2,3-tris( $\beta$ -cyanoethoxy)propane suspended on Chromosorb P was employed for this analysis. <sup>g</sup> In this case, the enolate was prepared by reaction of the ketone with NaH and then treated with Me<sub>3</sub>SiCl. In a small-scale reaction containing naphthalene as an internal standard, gas chromatographic analysis indicated that the silyl ether mixture was formed in 90% yield and contained 4% 16 and 96% 15. <sup>h</sup> A gas chromatography column packed with Carbowax 20M suspended on Chromosorb P was employed for this analysis. <sup>i</sup> In this case the distilled product mixture contained 5% unidentified impurity in addition to the silyl ethers indicated. <sup>j</sup> In this case the enolate was formed in diethylene glycol dimethyl ether rather than 1,2-dimethoxyethane to simplify separation of the volatile enol ethers.

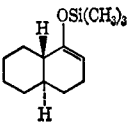
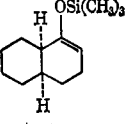
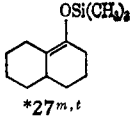
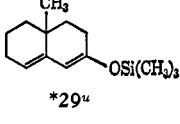
TABLE II  
 CHARACTERIZATION AND PROPERTIES OF THE SILYL ENOL ETHERS

Structure	Bp, °C (mm) <sup>a</sup> [ <i>n</i> <sub>D</sub> <sup>t</sup> (t, °C)]	$\nu_{C=C}$ (CCl <sub>4</sub> ), cm <sup>-1</sup>	Nmr spectrum, $\delta$ values in CCl <sub>4</sub> soln (splitting) <sup>b</sup>		Mass spectrum, <i>m/e</i> values (% of base peak)	
			Vinyl CH	Other <sup>c</sup>	Abundant peaks and molecular ion (relative intensity)	Metastable peaks
5 <sup>d</sup>	74-75 (20) [1.4451 (24)]	1670	4.73 (m)		170 (56), 155 (40), 127 (33), 75 (100), 73 (52)	113.6, 141.7, 169.5
*6 <sup>e,v</sup>	98 (4.2) [1.4547 (22)]	1670	5.65 (m)	1.87 (s, <i>t</i> -butyl)	226 (10), 211 (33), 169 (18), 147 (58), 142 (30), 127 (26), 75 (100), 73 (40)	197.0, 113.7
9 <sup>f</sup>	89-91 (12) [1.4988 (26)]	1620	4.27 (d, <i>J</i> = 1.7), 4.73 (d, <i>J</i> = 1.7)	7.05 (m, <i>m</i> and <i>p</i> -H), 7.34 (m, <i>o</i> -H)	192 (22), 147 (100), 191 (32), 75 (47), 177 (28), 73 (20)	163.4
*10 <sup>g</sup>	140-141 (760) [1.4061 (27)]	1625 (s), 1665 (w)	3.78 (d, <i>J</i> = 1.4), 3.93 (d, <i>J</i> = 1.4)	1.02 (s, <i>t</i> -Bu)	172 (20), 157 (100), 75 (83), 73 (75), 44 (45)	143.3, 35.9, 34.0
*12 <sup>h</sup>	56 (75) [1.4042 (25)]	1655	4.35 (d of <i>t</i> , <i>J</i> = 6.1 and 7.3), 5.97 (d of <i>t</i> , <i>J</i> = 6.1 and 1.3)	2.03 (m, CH <sub>2</sub> ), 0.90 (t, Me, <i>J</i> = 7.5)	144 (37), 129 (90), 75 (79), 73 (100)	115.6, 43.7, 41.3
*13 <sup>i</sup>	62 (75) [1.4071 (25)]	1665	4.90 (d of <i>t</i> , <i>J</i> = 12.1 and 7.1), 6.12 (d of <i>t</i> , <i>J</i> = 12.1 and 1.3)	2.83 (m, methy- lene), 0.95 (t, Me, <i>J</i> = 7.1)	144 (36), 129 (84), 75 (85), 73 (100)	115.6, 43.7, 41.3
*15 <sup>j</sup>		1654	5.41 (s, broad)	1.98 (d, Me, <i>J</i> = 0.8)	206 (100), 191 (35), 75 (22), 73 (78)	177.2, 156.8, 29.5, 27.8, 26.0
*16 <sup>k</sup>		1651	5.71 (s, broad)	1.84 (d, Me, <i>J</i> = 0.8)	206(100), 191 (55), 75 (37), 73 (95)	177.1, 156.8, 29.5, 27.8, 26.0
*18a <sup>m</sup>		1654 (m), 1632 (s), 1617 (s)	3.93 (s)		186 (19), 171 (21), 144 (19), 143 (97), 130 (95), 115 (100), 75 (75), 73 (53), 45 (21), 43 (29)	27.7, 29.4, 37.3, 90.9, 101.8
*19a <sup>m</sup>	92 (50-52) [1.4225 (21.5)]	1675 (s)	4.36 (t, <i>J</i> = 6.8) <sup>l</sup>	1.73 (s, broad, vinyl Me) <sup>l</sup>	186 (12), 144 (15), 143 (95), 130 (15), 75 (31), 73 (100)	37.3, 32.9, 110.0
*20a <sup>m</sup>	94 (52) [1.4224 (25)]	1668 (s)	4.53 (t, <i>J</i> = 7.3) <sup>l</sup>	1.68 (s, broad, vinyl Me) <sup>l</sup>	186 (11), 144 (13), 143 (92), 75 (29), 73 (100)	37.3, 32.9, 110.0

TABLE II (Continued)

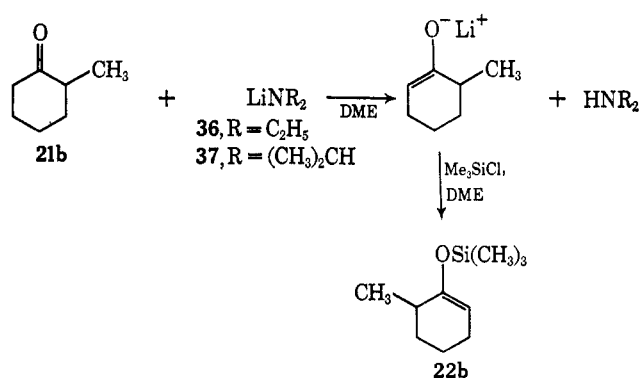
Structure	Bp, °C (mm) <sup>a</sup> [ <i>n</i> <sub>D</sub> <sup>20</sup> (t, °C)]	$\bar{\nu}_{C=C}$ (CCl <sub>4</sub> ), cm <sup>-1</sup>	Nmr spectrum, $\delta$ values in CCl <sub>4</sub> soln		Mass spectrum, <i>m/e</i> values (% of base peak)	
			Vinyl CH (splitting) <sup>b</sup>	Other <sup>c</sup>	Abundant peaks and molecular ion (relative intensity)	Metastable peaks
$\begin{array}{c} \text{CH}_3\text{CH}_2\text{COSi}(\text{CH}_3)_3 \\    \\ \text{CH}_2 \\ \text{*18b} \\ \text{*19b} \end{array}$	108-110 (760) [1.4008 (26)]	1635 (s), 1660 (w)	3.92 (s)	1.00 (t, Me, <i>J</i> = 7.5), 2.00 (q, CH <sub>2</sub> , <i>J</i> = 7.5)	144 (50), 129 (77), 75 (100), 73 (46)	43.6, 115.6
20b		1685	4.41 (q of q, <i>J</i> = 0.88 and 6.6)	1.43 (d of q, Me, <i>J</i> = 1.4 and 6.6), 1.61 (over- lapping q's, Me)	144 (34), 119 (40), 75 (100), 73 (57)	43.5, 115.7
$\begin{array}{c} \text{OSi}(\text{CH}_3)_3 \\   \\ (\text{CH}_3)_2\text{C}=\text{C} \\   \\ \text{CH}_2\text{CH}_3 \\ \text{*31} \end{array}$		1675 (s)	4.53 (q of q, <i>J</i> = 0.94 and 6.7)	1.51 (d of q, Me, <i>J</i> = 1.0, and 7.0), 1.67 (over- lapping q's, Me)	144 (32), 119 (40), 75 (100), 73 (58)	43.5, 115.7
$\begin{array}{c} \text{OSi}(\text{CH}_3)_3 \\   \\ (\text{CH}_3)_2\text{C}=\text{C} \\   \\ \text{CH}_2\text{CH}_3 \\ \text{*32} \end{array}$		1678 (s)	4.46 (q of d, <i>J</i> = 6.8 and 0.8)	1.58 (s, vinyl Me), 1.52 (s, vinyl Me), 0.98 (t, Me, <i>J</i> = 7.3)	172 (47), 157 (42), 75 (84), 73 (100), 45 (15),	33.9, 35.8, 119.0, 120.7, 143.3
$\begin{array}{c} \text{H} \\   \\ (\text{CH}_3)_2\text{CH}-\text{C}=\text{C} \\   \quad   \\ (\text{CH}_3)_3\text{SiO} \quad \text{CH}_3 \\ \text{*33} \end{array}$		1675 (s)	4.37 (q, <i>J</i> = 6.8)	1.47 (d of d, vinyl Me, <i>J</i> = 7.1 and 1.0), 1.01 (d, Me, <i>J</i> = 6.8)	172 (41), 157 (27), 75 (100), 73 (93), 45 (14)	33.9, 35.8, 119.0, 120.7, 143.3
$\begin{array}{c} \text{CH}_3 \\   \\ (\text{CH}_3)_2\text{CH}-\text{C}=\text{C} \\   \quad   \\ (\text{CH}_3)_3\text{SiO} \quad \text{H} \\ \text{*33} \end{array}$		1663 (s)	4.43 (m)	1.52 (d, vinyl Me, <i>J</i> = 6.8), 0.93 (d, Me, <i>J</i> = 6.8)	172 (42), 157 (37), 75 (100), 73 (95), 45 (15)	33.9, 35.8, 119.0, 120.7, 143.3
$\begin{array}{c} \text{OSi}(\text{CH}_3)_3 \\   \\ \text{CH}_2 \\   \\ \text{CH} \\   \\ \text{CH}_2 \\ \text{*22a}^m \end{array}$	73 (34) [1.4336 (25)]	1644 (s)	4.43 (m)	0.96 (d, Me, <i>J</i> = 6.5)	170 (37), 169 (28), 155 (36), 75 (100), 73 (97), 45 (19)	34.6, 36.3, 141.7
$\begin{array}{c} \text{OSi}(\text{CH}_3)_3 \\   \\ \text{CH}_2 \\   \\ \text{CH} \\   \\ \text{CH}_2 \\ \text{*23a}^m \end{array}$	78 (34) [1.4392 (25)]	1690 (s)		1.48 (m, Me)	170 (61), 155 (61), 75 (76), 73 (100), 45 (19)	34.5, 36.3, 141.6
$\begin{array}{c} \text{OSi}(\text{CH}_3)_3 \\   \\ \text{CH}_2 \\   \\ \text{CH} \\   \\ \text{CH}_2 \\ \text{*35}^n \end{array}$	158-159 (760) [1.4377 (25)]	1645	4.52 (m)		156 (68), 155 (27), 75 (98), 73 (100), 59 (42), 55 (35), 45 (91), 43 (65), 41 (32), 39 (51)	155.5, 141.5, 73.5, 39.8, 27.7
*22b <sup>m,o</sup>	59-61 (7) [1.4440 (22)]	1665	4.58 (t, <i>J</i> = 3.3)	0.98 (d, Me, <i>J</i> = 6.5)	184 (98), 169 (74), 156 (24), 142 (43), 127 (29), 75 (85), 73 (100)	155, 103.5, 31.5, 27.7
*23b <sup>m,p</sup>	101-102 (45) [1.4480 (25)]	1685		1.52 (broad, s, Me)	184 (86), 169 (100), 156 (19), 155 (20), 141 (47), 75 (79), 73 (97)	155.2, 131, 127.5, 31.7

TABLE II (Continued)

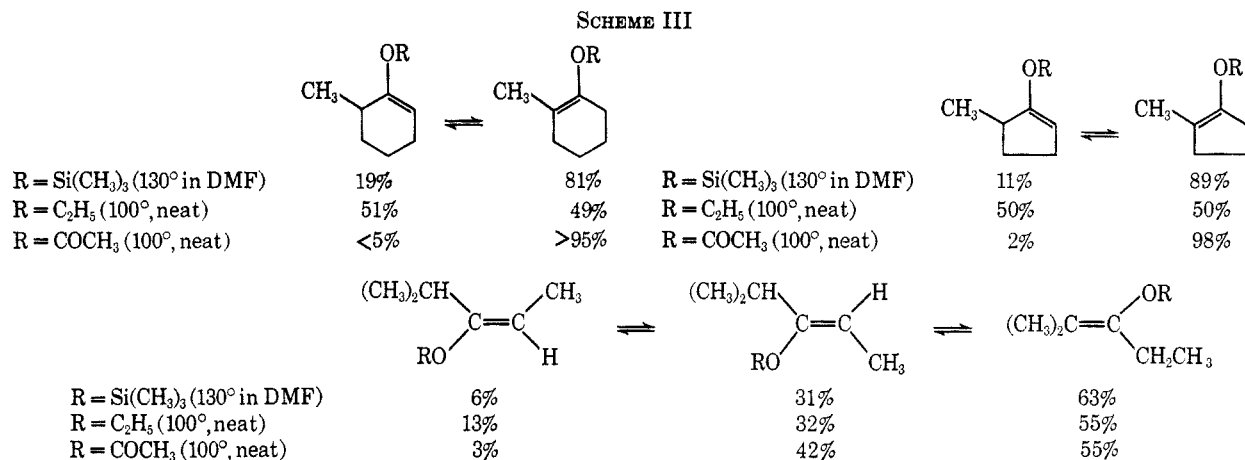
Structure	Bp, °C (mm) <sup>a</sup> [n <sub>D</sub> <sup>20</sup> (t, °C)]	ν <sub>C=C</sub> (CCl <sub>4</sub> ), cm <sup>-1</sup>	Nmr spectrum, δ values in CCl <sub>4</sub> soln (splitting) <sup>b</sup>		Mass spectrum, m/e values (% of base peak)		
			Vinyl CH	Other <sup>c</sup>	Abundant peaks and molecular ion (relative intensity)	Metastable peaks	
		1660	4.60 (m)		224 (9), 147 (22), 75 (100), 73 (18)	29.4	
*25 <sup>m,q</sup>		1660	s		224 (6), 186 (8), 147 (27), 77 (20), 75 (100), 73 (14)		
		1675			224 (40), 195 (25), 182 (25), 181 (24), 156 (22), 134 (32), 91 (23), 75 (61), 73 (100), 45 (43)	148, 105.8, 63.3, 27.8	
*26 <sup>m,r</sup>					236 (76), 221 (44), 208 (25), 91 (57), 75 (29), 73 (100), 45 (40), 41 (28)	207.3, 179.1, 27.7	
		98 (1.3) [1.5009 (24)]	1680 (w), 1650 (s), 1625 (s)	5.10 (m)	0.98 (s, Me)		
*27 <sup>m,t</sup>							
							
*29 <sup>u</sup>							

<sup>a</sup> No data are listed in cases where the pure silyl ether was isolated by collection from a gas chromatography column. <sup>b</sup> The abbreviations used are s, singlet; d, doublet; t, triplet; q, quadruplet; m, multiplet. All coupling constants, *J*, are given in hertz (cycles per second). <sup>c</sup> Broad multiplets are not listed in this table. Also a sharp singlet attributable to the 9 H of the (CH<sub>3</sub>)<sub>3</sub>SiO found in each spectrum within the range δ 0.13–0.25 is not listed. <sup>d</sup> Ultraviolet end absorption (95% EtOH), ε 1835 at 210 mμ [lit. bp 58–58.5° (11 mm), n<sub>D</sub><sup>20</sup> 1.4452 (ref 5a), and bp 77.5° (28 mm), n<sub>D</sub><sup>20</sup> 1.4467 (ref 5d)]. <sup>e</sup> Ultraviolet end absorption (isooctane), ε 1340 at 220 mμ. <sup>f</sup> Lit. bp 93–94° (13.5 mm), n<sub>D</sub><sup>20</sup> 1.5008 (ref 5a), and bp 110° (28 mm), n<sub>D</sub><sup>20</sup> 1.5011 (ref 5d). <sup>g</sup> Lit. bp 138° (760 mm), n<sub>D</sub><sup>20</sup> 1.4105 (ref 5d). <sup>h</sup> Ultraviolet end absorption (isooctane), ε 475 at 220 mμ. <sup>i</sup> Ultraviolet end absorption (isooctane), ε 532 at 220 mμ. <sup>j</sup> Ultraviolet maximum (95% EtOH), 258 mμ (ε 19,200). <sup>k</sup> Ultraviolet maximum (95% EtOH), 253.5 mμ (ε 15,400) with a shoulder at 285.5 mμ (ε 1490). <sup>l</sup> In each of these peaks a further long-range coupling of approximately 0.8 Hz was partially resolved. <sup>m</sup> A mixture of silyl ethers containing this product has been described (ref 5f). The reported spectral values for the isomer 22b were ir 1661 cm<sup>-1</sup>; nmr δ 4.65 (m), 0.97 (d), and 0.15 (s). <sup>n</sup> Ultraviolet end absorption (95% EtOH), ε 1210 at 220 mμ. <sup>o</sup> Ultraviolet end absorption (95% EtOH), ε 2280 at 210 mμ. <sup>p</sup> Lit.<sup>5f</sup> bp 78–79° (17 mm); ir 1686 cm<sup>-1</sup>; nmr δ 1.55 (s) and 0.16 (s). Ultraviolet end absorption (95% EtOH), ε 2980 at 210 mμ. <sup>q</sup> Ultraviolet end absorption (95% EtOH), ε 2850 at 210 mμ. <sup>r</sup> Ultraviolet end absorption (95% EtOH), ε 2650 at 210 mμ. <sup>s</sup> An insufficient amount of this isomer was isolated in pure form to obtain a satisfactory nmr spectrum. <sup>t</sup> Ultraviolet end absorption (95% EtOH), ε 6320 at 210 mμ. <sup>u</sup> Ultraviolet maximum (95% EtOH), 240.5 mμ (ε 20,800) with a shoulder at 283 mμ (ε 232). <sup>v</sup> Each of the silyl enol ethers marked with an asterisk (\*) has been analyzed for carbon and hydrogen. In all cases the analytical values agreed with the calculated values to within ±0.30%; the actual analytical data were made available to the editors and referees.

We therefore turned to the lithium dialkylamides in 1,2-dimethoxyethane (DME) solution as bases capable of converting ketones into enolate anions under conditions of kinetic control.<sup>7b</sup> Although the usual reagent, lithium diethylamide (36), was not satisfactory because of subsequent reaction of the diethylamine with the silyl chloride, the more hindered diisopropylamide 37 was satisfactory. In this way the preparations of a number (Tables I and II) of the less highly substituted silyl ethers were accomplished as exemplified in Scheme II. In certain cases (see Experimental Section) involving methyl ketones (*e.g.*, 17), aldol by-products were observed to result even from the slow addition of the ketones 17 to a solution of the lithium amide 37. Evidently, in these cases, the rate of aldol condensation is competitive either with the rate of proton abstraction or with the rate of mixing of the reactants.



It is interesting to note that reaction with the amide base 37 not only favors formation of the kinetically favored (and usually less substituted) structural enolate

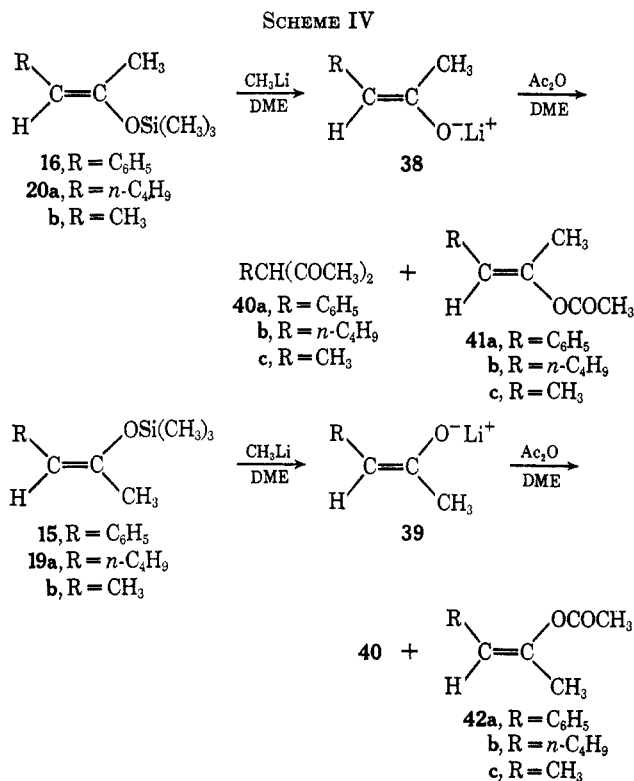


isomer, but also favors slightly the formation of *cis* enolate anion **38** rather than the *trans* isomer **39**. Several of the *cis* (e.g., **12**, **16**, **20a**, and **20b**) and *trans* (e.g., **13**, **15**, **19a**, and **19b**) silyl ethers were converted into the corresponding enolates **38** and **39**, and then into the enol acetates **41** and **42**, as illustrated in Scheme IV. This

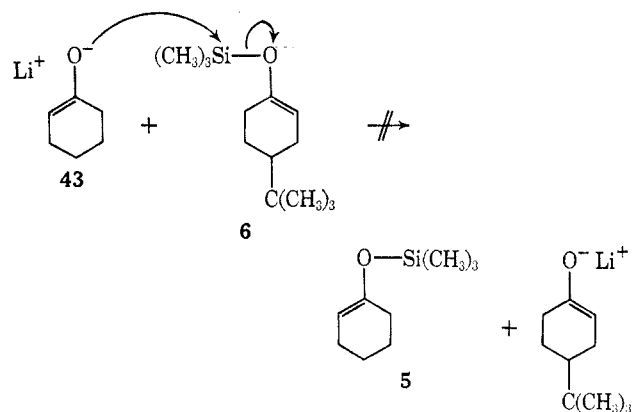
methylsilyl enol ethers, the only exception being a sterically crowded system **32** and **33**, in which the positions of the vinyl proton peaks are very similar.

We also note in passing that reaction of the *cis* enolate anions **38** with acetic anhydride gives significantly more C-acylated product than is observed on acetylation of the *trans* enolate anions **39**. Further discussion of this and related observations will be presented elsewhere.

To examine the possibility that silyl ethers might undergo equilibration with enolate anions by attack of the enolate oxygen at silicon a mixture of the silyl enol ether



transformation served to interrelate the stereoisomeric silyl ethers with the known<sup>7</sup> enol acetate stereoisomers. We had noted earlier<sup>7a,9</sup> that the position of the nmr peak for the  $\beta$ -vinyl proton of enol ethers and enol acetates in benzene solution is helpful in assigning stereochemistry. In the isomer with the  $\beta$ -vinyl proton and oxygen function *cis* (e.g., **41**) the position of the vinyl proton resonance is at lower field by 0.2–0.3 ppm than is the case when the oxygen function and  $\beta$ -vinyl proton are *trans* (e.g., **42**). As illustrated in Table III, this same generalization appears to be applicable to the tri-



**6** and the enolate anion **43** was prepared, allowed to stand for 1 hr, and then quenched in water. None of the silyl ether **5** was detected. Consequently, formation of the silyl enol ether in the presence of enolate anions and the reverse process can be performed in 1,2-dimethoxyethane solution without concern for equilibration of the trimethylsilyl function.

**Mass Spectra of the Trimethylsilyl Enol Ethers.**—A recent investigation<sup>10</sup> of the mass spectral fragmentation of alkyl trimethylsilyl ethers indicated the importance of the general fragmentation pattern illustrated in Scheme V. Examination of the mass spectra (Table II) obtained from the trimethylsilyl enol ethers prepared in this study indicated both similarities and differences from the fragmentation pattern noted (Scheme V) for alkyl ethers. Stork and Hudriik also observed<sup>5f</sup> abundant fragment peaks in the mass spectrum of the silyl enol ether **23b** at  $M - 15$ , 75, and 73.

Since the mass spectrum of the silyl enol ether **20a** was typical of the mass spectra of the acyclic enol ethers

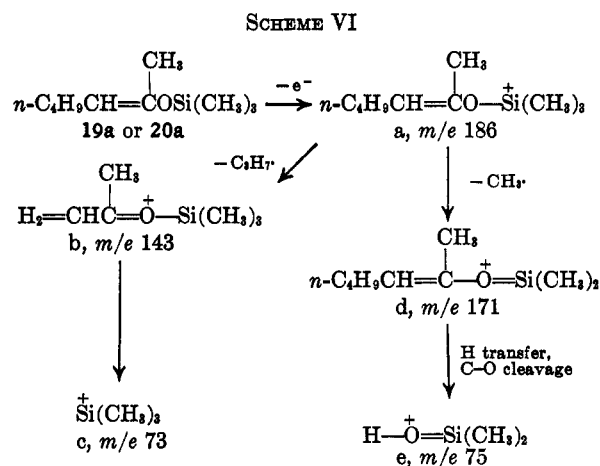
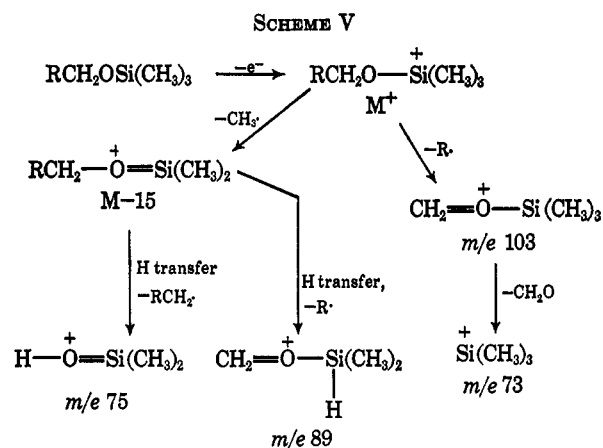
(9) A. comparable correlation for enol ethers in carbon tetrachloride solution was noted by F. Bohlmann, C. Arndt, and J. Starnick, *Tetrahedron Lett.*, No. 24, 1605 (1963).

(10) J. Diekman, J. B. Thomson, and C. Djerassi, *J. Org. Chem.*, **32**, 3904 (1967).

TABLE III  
CHEMICAL SHIFT DIFFERENCES IN THE  $\beta$ -VINYL PROTON NMR SIGNAL FOR STEREOISOMERIC TRIMETHYLSILYL ENOL ETHERS

Isomer at lower field	Isomer at higher field	$\Delta\delta$	
		Benzene soln <sup>a</sup>	CCl <sub>4</sub> soln <sup>a</sup>
$\begin{array}{c} \text{R} \quad \text{CH}_3 \\ \diagdown \quad / \\ \text{C}=\text{C} \\ / \quad \diagdown \\ \text{H} \quad \text{OSiMe}_3 \end{array}$ 20a, R = <i>n</i> -Bu 16, R = Ph 20b, R = Me	$\begin{array}{c} \text{R} \quad \text{OSiMe}_3 \\ \diagdown \quad / \\ \text{C}=\text{C} \\ / \quad \diagdown \\ \text{H} \quad \text{CH}_3 \end{array}$ 19a, R = <i>n</i> -Bu 15, R = Ph 19b, R = Me	0.29	0.18
$\begin{array}{c} \text{Et} \quad \text{H} \\ \diagdown \quad / \\ \text{C}=\text{C} \\ / \quad \diagdown \\ \text{H} \quad \text{OSiMe}_3 \end{array}$ 13	$\begin{array}{c} \text{Et} \quad \text{OSiMe}_3 \\ \diagdown \quad / \\ \text{C}=\text{C} \\ / \quad \diagdown \\ \text{H} \quad \text{H} \end{array}$ 12	0.58	0.38
$\begin{array}{c} i\text{-Pr} \quad \text{H} \\ \diagdown \quad / \\ \text{C}=\text{C} \\ / \quad \diagdown \\ \text{Me}_3\text{SiO} \quad \text{CH}_3 \end{array}$ 32	$\begin{array}{c} i\text{-Pr} \quad \text{CH}_3 \\ \diagdown \quad / \\ \text{C}=\text{C} \\ / \quad \diagdown \\ \text{Me}_3\text{SiO} \quad \text{H} \end{array}$ 33	0.02	0.06

<sup>a</sup> These chemical shift differences were obtained from measurements made with solutions containing known amounts of each of the stereoisomeric enol ethers.



studied, we selected this compound for the high resolution mass measurements summarized in Table IV.<sup>11</sup>

TABLE IV  
HIGH RESOLUTION MASS MEASUREMENTS ON THE  
TRIMETHYLSILYL ENOL ETHER 20a

Ion	Composn	Mass units	
		Calcd	Found
a	C <sub>10</sub> H <sub>22</sub> OSi	186.1439	186.1446
d	C <sub>9</sub> H <sub>19</sub> OSi	171.1205	171.1208
b	C <sub>7</sub> H <sub>15</sub> OSi	143.0897	143.0892
e	C <sub>2</sub> H <sub>7</sub> OSi	75.0266	75.0259
c	C <sub>3</sub> H <sub>9</sub> Si	73.0474	73.0459

The general fragmentation pattern which we believe operative for the acyclic trimethylsilyl enol ethers studied is illustrated in Scheme VI for the ethers 19a and 20a which have very similar mass spectra.

The allylic cleavage a  $\rightarrow$  b (Scheme VI) in the *trans* isomer 19a, a process vinylogous to a process observed for alkyl silyl ethers (Scheme V), is consistent with a

metastable peak at  $m/e$  110.0 (calcd  $143^2/186 = 110.0$ ). Although we found no evidence from metastable peaks to indicate the direct formation of the trimethylsilyl ion c ( $m/e$  73) from the parent ion a, a metastable peak at  $m/e$  37.3 (calcd  $73^2/143 = 37.3$ ) provides evidence for the cleavage b  $\rightarrow$  c (Scheme VI) which finds analogy in the fragmentation of the alkyl silyl ethers (Scheme V). Analogous metastable peaks consistent with the sequence a  $\rightarrow$  b  $\rightarrow$  c are found in the spectra (Table II) of most of the silyl ethers where an allylic cleavage is possible.

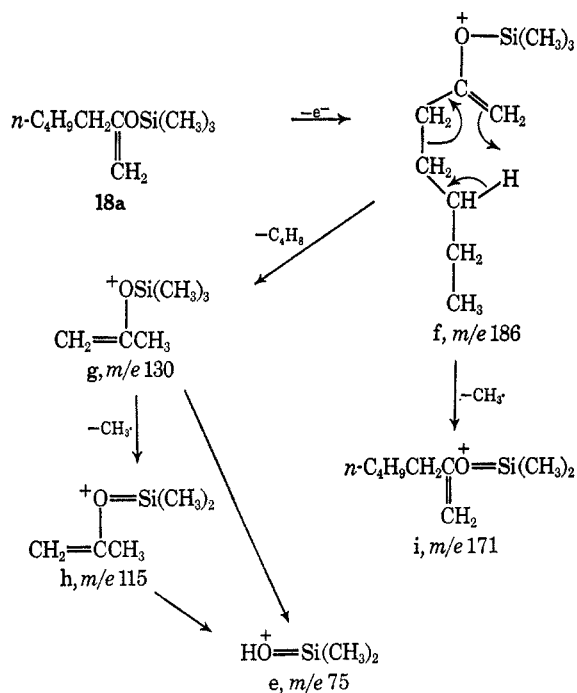
The loss of a methyl group bound to silicon to form fragment d ( $m/e$  171) and subsequent conversion into fragment e ( $m/e$  75) is indicated by a metastable peak at  $m/e$  32.9 (calcd  $75^2/171 = 32.9$ ). The sequence a  $\rightarrow$  d  $\rightarrow$  e (Scheme VI) is analogous to one of the processes seen with alkyl silyl ethers (Scheme V). A sequence analogous to the process a  $\rightarrow$  d  $\rightarrow$  e appears to be the major pathway for silyl ethers 32 and 33, a pathway consistent with the presence of metastable peaks at  $m/e$  143.3 (calcd  $157^2/172 = 143.3$ ) and 35.8 (calcd  $75^2/157 = 35.8$ ).

(11) We are indebted to Professor Klaus Biemann and his associates for these measurements.



The mass spectrum of the terminally unsaturated enol ether **18a** exhibited certain distinct differences from the previously discussed spectra. In particular the fragmentation path  $f \rightarrow g \rightarrow h \rightarrow e$  (Scheme VII) seems more important for the terminal double-bond isomer; this sequence was indicated by the presence of metastable peaks at  $m/e$  90.9 (calcd  $130^2/186 = 90.9$ ), 101.8

SCHEME VII



(calcd  $115^2/130 = 101.8$ ), 43.3 (calcd  $75^2/130 = 43.3$ ), and 49.0 (calcd  $75^2/115 = 48.9$ ). We have no labeling evidence indicating which hydrogen atom is transferred in the fragmentation  $f \rightarrow g$  and suggest the cyclic process (structure **f**, Scheme VII) as one likely mode of hydrogen transfer. The formation of fragment **i** ( $m/e$  171) is analogous to the previous cases (Scheme V and  $a \rightarrow d$ , Scheme VI). We suspect that peaks in the spectrum of the enol ether **18a** at  $m/e$  143 and 73 with a metastable peak at  $m/e$  37.3 (calcd  $73^2/143 = 37.3$ ) may result from partial isomerization of the terminal isomer **18a** to one of the internal isomers **19a** or **20a**. Likewise peaks in the spectrum of the internal isomer **20a** at  $m/e$  130 and 115 may be the result of partial isomerization to **18a**.

Perhaps the most invariant feature in the mass spectra of all the trimethylsilyl enol ethers is the presence of abundant fragment peaks at  $m/e$  75 and 73. Both of these peaks are seen even with the derivatives **9** and **10** of acetophenone and pinacolone where initial fragmentation at allylic bonds (*cf.* Scheme VI) is not feasible.

### Experimental Section<sup>12</sup>

**Preparation of Starting Materials.**—Commercial samples of the starting carbonyl compounds were available except for

(12) All melting points are corrected and all boiling points are uncorrected. Unless otherwise stated magnesium sulfate was employed as a drying agent. The infrared spectra were determined with a Perkin-Elmer Model 237 infrared recording spectrophotometer fitted with a grating. The ultraviolet spectra were determined with a Cary recording spectrophotometer, Model 14. The nmr spectra were determined at 60 Mc with a Varian Model A-60 nmr spectrometer. The chemical shift values are expressed either in cycles per

ketones **21a**, **24**, and **28**. The ketones **21a** and **24** were prepared as previously described.<sup>7</sup> The procedure of Marshall and Fanta<sup>13</sup> was used to prepare 10-methyl-9-hydroxy-2-decalone, mp 122.5–124° (lit.<sup>13</sup> mp 124–125°), and the dehydrated ketone **28**: bp 72–80° (0.15–0.25 mm) [lit.<sup>13</sup> bp 82–83° (0.7 mm)]; ir ( $\text{CCl}_4$ ) 1685 (conjugated C=O) and 1625  $\text{cm}^{-1}$  (conjugated C=C); uv (95% EtOH) 239  $\text{m}\mu$  ( $\epsilon$  17,800) and 309 (70); nmr ( $\text{CCl}_4$ )  $\delta$  5.57 (1 H multiplet, vinyl CH), 0.8–2.9 (12 H multiplet, aliphatic CH), and 1.25 (3 H singlet,  $\text{CH}_3$ ); mass spectrum, molecular ion peak at  $m/e$  164 with abundant fragment peaks at  $m/e$  136, 121, 91, 79, 77, 41, 39, and 24.

Commercial samples of dimethylformamide and diisopropylamine were purified by redistillation from calcium hydride; 1,2-dimethoxyethane and triethylamine were distilled from  $\text{LiAlH}_4$  prior to use. Commercial samples of trimethylsilyl chloride were distilled immediately before use. For use in reactions with enolate anions, solutions of the freshly distilled trimethylsilyl chloride in anhydrous 1,2-dimethoxyethane were treated with 0.2–1.0 equiv of anhydrous triethylamine and then filtered through a sintered-glass funnel or centrifuged to remove any residual hydrogen chloride in the form of the insoluble triethylamine hydrochloride. From measurement of nmr spectra of benzene solutions containing triethylamine, trimethylsilyl chloride, and mixtures of these two reagents, we found no evidence for reaction between the amine and the chlorosilane. Commercial halide-free solutions of methylolithium were used after standardization.

**Illustrative Procedures for the Preparation of the Trimethylsilyl Enol Ethers.** **Procedure A.**—To a solution of 32.60 g (0.30 mol) of chlorotrimethylsilane and 60.60 g (0.60 mol) of triethylamine in 100 ml of dimethylformamide was added 28.00 g (0.25 mol) of 2-methylcyclohexanone (**21b**). The resulting mixture, from which some pale yellow solid (presumably triethylamine hydrochloride) separated immediately and more separated during the reaction, was refluxed with stirring for 48 hr and then cooled, diluted with 200 ml of pentane, and washed with three 300-ml portions of cold aqueous  $\text{NaHCO}_3$ . The organic layer was combined with the pentane extract from the aqueous washes and washed rapidly in succession with portions of cold aqueous 1.5 M HCl and cold aqueous  $\text{NaHCO}_3$ . The resulting pentane solution was dried and concentrated to leave 55.5 g of the crude mixture of silyl ethers **22b** and **23b**. Distillation through a short Vigreux column separated 1.878 g of an early fraction, bp 83–90° (20 mm), which contained<sup>14</sup> about 20% of the starting ketone and 36.73 g (80%) of a colorless liquid fraction, bp 90–93° (20 mm), which contained (in order of elution)<sup>14</sup> the starting ketone **21b** (1%), the enol ether **22b** (22%), and the enol ether **23b** (77%). During the course of this reaction, small aliquots were removed and analyzed<sup>14</sup> periodically; after 5 hr the mixture contained **21b** (4%), **22b** (45%), and **23b** (51%) and after 17 hr the composition was **21b** (1%), **22b** (38%), and **23b** (61%).

Fractional distillation of the mixture of enol ethers with a spinning Teflon-band column separated 15.52 g of fractions, bp 94–101° (45 mm), containing various proportions of the enol ethers **22b** and **23b** and 15.31 g of fractions, bp 101–102° (45 mm),  $n_D^{20}$  1.4480 [lit.<sup>14</sup> bp 78–79° (17 mm)], containing<sup>14</sup> the pure higher boiling ether **23b**.

**Procedure B.**—An ethereal solution containing 100 mmol of methylolithium was concentrated under reduced pressure and the residual lithium reagent was dissolved in 100 ml of 1,2-dimethoxyethane containing several milligrams of triphenylmethane as an indicator. The resulting solution was cooled to 0° and treated with 10.10 g (100 mmol) of diisopropylamine. To this solution of lithium diisopropylamide was added, dropwise and with stirring over a 10-min period, 2-methylcyclohexanone (**21b**, 11.18 g or 99.8 mmol) until the red color of the triphenylmethide indicator was almost completely discharged. Meanwhile a quenching solution, prepared from 50 ml of 1,2-dimethoxyethane, 5.0 ml (4.4 g or 44 mmol) of triethylamine, and 20 ml (18.4 g or 169 mmol) of chlorotrimethylsilane was centrifuged to remove any of the insoluble triethylamine hydrochloride. By use of a stain-

second or  $\delta$  values (parts per million) relative to a tetramethylsilane internal standard. The mass spectra were obtained with a Hitachi-Perkin-Elmer mass spectrometer. The microanalyses were performed by Dr. S. M. Nagy and his associates. All reactions involving strong bases or reactive organometallic reagents were performed under a nitrogen atmosphere.

(13) J. A. Marshall and W. I. Fanta, *J. Org. Chem.*, **29**, 2501 (1964).

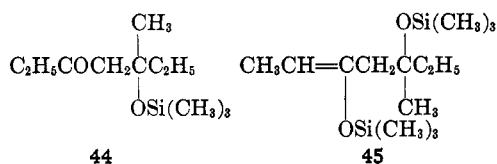
(14) A gas chromatography column packed with Apiezon M suspended on Chromosorb G was employed for this analysis.

less steel cannula, this chlorotrimethylsilane solution was added, rapidly and with stirring, to a cold (0°) solution of the lithium enolate. After the addition was complete, a white solid (LiCl) began to separate after 15 sec. The resulting mixture was stirred at room temperature for 15 min and then partitioned between pentane and cold aqueous NaHCO<sub>3</sub>. The organic layer was dried and concentrated to leave 49.5 g of residual liquid containing<sup>14</sup> the crude silyl ether **22b**. Fractional distillation through a short Vigreux column separated a 0.70-g forerun [bp 30–59° (7 mm)] and 14.82 g (74%) of the silyl ether **22b** [bp 59–61° (7 mm), *n*<sub>D</sub><sup>20</sup> 1.4440], which contained<sup>14</sup> less than 2% isomeric silyl ether **23b**.

When this procedure employing lithium diisopropylamide was applied to the alkyl methyl ketones **17**, substantial amounts of higher molecular weight products were obtained as a result of competing aldol condensation. In reactions with 2-heptanone (**17a**), this problem was partially overcome by the use of a low reaction temperature (–78 rather than 0°) for the formation of the enolates and subsequent reaction with chlorotrimethylsilane. In this way reaction of 14.60 g (128 mmol) of the ketone **17a** with 190 mmol of lithium diisopropylamide in 1,2-dimethoxyethane followed by reaction with 19.0 g (171 mmol) of chlorotrimethylsilane and 5.0 ml of triethylamine all at –78° afforded, upon distillation, 0.40 g of forerun [bp 102–104° (35 mm)], 16.26 g (65%) of a mixture of silyl ethers [bp 104–106° (35–36 mm), see Table I], and 7.8 g of a residual high-boiling liquid.

The nature of the high-boiling by-products was examined in the reaction of 6.92 g (96.3 mmol) of 2-butanone (**17b**) with 100 mmol of lithium diisopropylamide in 700 ml of bis(β-methoxyethyl) ether.<sup>15</sup> The solution of enolates was treated with a solution of 18.4 g (169 mmol) of chlorotrimethylsilane and 5.0 ml of trimethylamine in 50 ml of bis(β-methoxyethyl) ether. The reaction mixture was distilled to separate 100 ml of distillate, bp 30–155°, which was diluted with pentane and then washed successively with cold, aqueous HCl and with aqueous NaHCO<sub>3</sub>. Redistillation of the volatile organic products separated a forerun (bp 40–85°), 5.32 g (41% yield) of fractions (bp 85–130°) containing<sup>16</sup> primarily the enol ethers (see Table I), and higher boiling fractions (bp 130–170°) containing<sup>16</sup> mainly bis(β-methoxyethyl) ether.

The less volatile portion of the original reaction mixture was concentrated to remove most of the remaining reaction solvent and the residual material was taken up in pentane and filtered from the insoluble amine hydrochlorides present. After the pentane solution had been washed with aqueous NaCl, dried, and concentrated, distillation separated 6.87 g of fractions of colorless to pale yellow liquid, bp 57–107° (10 mm), which contained<sup>16</sup> various proportions of the reaction solvent and the two aldol derivatives **44** and **45**. A pure sample of the monosilyl ether **44**



was collected:<sup>16</sup> ir (CCl<sub>4</sub>) 1710 cm<sup>-1</sup> (C=O); uv (95% EtOH) 239 mμ (ε 68) and 284 (32); nmr (CCl<sub>4</sub>) δ 0.09 (9 H singlet, OSiMe<sub>3</sub>), 0.97 (6 H overlapping triplets, *J* ~ 7 cps, CH<sub>3</sub> of two ethyl groups), 1.28 (3 H singlet, (CH<sub>3</sub>C), 1.58 (2 H quartet, *J* = 7 cps, CH<sub>2</sub> of one ethyl group), and 2.06–2.68 (4 H multiplet, two CH<sub>2</sub> groups); mass spectrum, no molecular ion, abundant fragment peaks at *m/e* 201, 187, 145, 129, 75, 73, 57, 45, 43, and 29.

*Anal.* Calcd for C<sub>11</sub>H<sub>24</sub>O<sub>2</sub>Si: C, 61.05; H, 11.18. Found: C, 61.19; H, 11.14.

A sample of the more slowly eluted disilyl ether **45** was also collected:<sup>16</sup> ir (CCl<sub>4</sub>) 1670 cm<sup>-1</sup> (enol C=C); uv (95% EtOH) end absorption, ε 2940 at 210 mμ; nmr (CCl<sub>4</sub>) δ 0.08 (9 H singlet, OSiMe<sub>3</sub>), 0.17 (9 H singlet, OSiMe<sub>3</sub>), 0.85 (2 H triplet, *J* = 7 cps, CH<sub>3</sub> of ethyl group), 1.20 (3 H singlet, CH<sub>3</sub>C), 1.48 (3 H doublet, *J* = 6.5 cps, vinyl CH<sub>3</sub>) superimposed on a multiplet in the region 1.10–1.68 (2 H, CH<sub>2</sub> of ethyl group), 2.10 (2 H broad singlet, allylic CH<sub>2</sub>), and 4.52 (1 H, quartet, *J* = 6.5 cps,

vinyl CH); mass spectrum, no molecular ion peak, abundant fragment peaks at *m/e* 145, 75, 73, and 45.

*Anal.* Calcd for C<sub>14</sub>H<sub>32</sub>O<sub>2</sub>Si<sub>2</sub>: C, 58.27; H, 11.18. Found: C, 58.45; H, 11.20.

**Equilibration of the Trimethylsilyl Enol Ethers. A. 2-Methylcyclohexanone Derivatives.**—A mixture of 47.9 mg (0.348 mmol) of triethylamine hydrochloride, 63.3 mg (0.583 mmol) of chlorotrimethylsilane, 548 mg (2.98 mmol) of the enol ether **22b**, a known amount of tetralin (as an internal standard), and 5.0 ml of dimethylformamide was heated to 130° under reflux with stirring for 6 hr and then partitioned between pentane and aqueous NaHCO<sub>3</sub>. After the organic phase had been dried and concentrated, analysis<sup>14</sup> indicated the following composition (listed in order of elution): **21b** (17% yield), **22b** (13% yield), **23b** (58% yield), and tetralin. Thus, the composition of the enol ether mixture is 18% **22b** and 82% **23b**.

A comparable experiment employing 34.9 mg (0.254 mmol) of triethylamine hydrochloride, 55.6 mg (0.512 mmol) of chlorotrimethylsilane, 624 mg (3.39 mmol) of the isomeric enol ether **23b**, tetralin, and 5.0 ml of dimethylformamide heated to 130° for 4 hr yielded a mixture containing **21b** (16% yield), **22b** (15% yield), **23b** (60% yield), and tetralin. These yields correspond to an enol ether mixture containing 20% **22b** and 80% **23b**.

**B. 2-Methylcyclopentanone Derivatives.**—The procedure was applied to 36.1 mg (0.264 mmol) of triethylamine hydrochloride, 55.9 mg (0.515 mmol) of chlorotrimethylsilane, 581 mg (3.42 mmol) of the enol ether **23a**, and *n*-butylbenzene (as an internal standard) in 5.0 ml of dimethylformamide. After a 6-hr heating period, the crude product contained (in order of elution)<sup>14</sup> **21a** (16% yield), **22a** (10% yield), **23a** (73% yield), and *n*-butylbenzene corresponding to an enol ether composition of 12% **22a** and 88% **23a**. Similarly, an equilibration experiment starting with 545 mg of the enol ether **22a** gave a mixture containing **21a** (20% yield), **22a** (10% yield), and **23a** (71% yield) corresponding to an enol ether composition of 12% **22a** and 88% **23a**. Additional measurements of these equilibrium compositions gave values in the range 9–11% **22a** and 89–91% **23a**.

**C. 2-Methyl-3-pentanone Derivatives.**—Three samples (2.2 mmol) of mixtures of enol ethers **31–33**, each containing<sup>17</sup> mainly (>85%) one of the three enol ethers, were added to mixtures of 0.8 mmol of triethylamine hydrochloride, 3.8 mmol of chlorotrimethylsilane, and toluene (an internal standard) in 4.0 ml of dimethylformamide. The mixtures were heated to 130° and aliquots were removed after periods of 14 and 24 hr and subjected to the usual work-up and analysis procedures. Since these isomerizations were significantly slower than the processes described in previous sections, the proportion of ketone **30** in the crude product was greater (37–60%). Each of the mixtures contained (in order of elution)<sup>17</sup> the enol ethers **33**, **32**, and **31**, the internal standard (toluene), and the ketone **30**. After 14 hr the proportions of the enol ether isomers in each reaction mixture remained approximately constant and were within the ranges given: **33**, 6–7%; **32**, 31–35%; and **31**, 59–63%. The average values were 6% **33**, 31% **32**, and 63% **31**.

**Absence of Exchange between Enolate Anions and Trimethylsilyl Enol Ethers.**—To a solution of 387 mg (2.28 mmol) of the enol ether **5**, a few milligrams of triphenylmethane (as an indicator), and a known amount of durene (as an internal standard) in 2.0 ml of 1,2-dimethoxyethane was added 2.4 ml of a 1,2-dimethoxyethane solution containing 2.30 mmol of methylolithium. The presence of excess methylolithium was indicated by the persistence of the red color of the triphenylmethyl anion. After 5 min a 0.20-ml aliquot of the reaction mixture was removed and partitioned between pentane and aqueous acetic acid. After the organic phase had been dried and concentrated, analysis<sup>14</sup> indicated the presence of cyclohexanone (**3**) (74 and 84% yields in duplicate runs) and the absence of the more slowly eluted ether **5**. The original enolate anion solution was treated with 432 mg (1.92 mmol) of the enol ether **6** and the resulting mixture was stirred for 1.0 hr and subjected to the same isolation and analysis procedure. The crude product contained (in order of elution)<sup>14</sup> **3** (87% yield), durene, **4** (10% yield), and **6** (85% yield). Repetition of this experiment gave comparable results. None of the enol ether **5**, the product expected if exchange of the trimethylsilyl group had occurred, was detected in any case.

(15) A higher boiling solvent was used in this case because the enol ether products had boiling points very similar to 1,2-dimethoxyethane.

(16) A gas chromatography column packed with silicone fluid, no. 710, suspended on Chromosorb P was employed for this analysis.

(17) A gas chromatography column packed with 1,2,3-tris-(β-cyanoethoxy)propane (TCEP) suspended on Chromosorb P was employed for this analysis.

**Interconversions of the Trimethylsilyl Enol Ethers and the Enol Acetates. A. 2-Heptanone Derivatives.**—Authentic samples of the enol acetates **41b** and **42b** were prepared as previously described<sup>7</sup> and an authentic sample of the  $\beta$ -diketone **40b** was prepared by the boron trifluoride catalyzed acetylation of 2-heptanone.<sup>18</sup> The pure<sup>18</sup> diketone **40b** was collected from a spinning-Teflon-band column as a colorless liquid: bp 100–101° (20 mm);  $n_D^{20}$  1.4460–1.4482 [lit.<sup>18</sup> bp 104–106° (20 mm)]; ir (CCl<sub>4</sub>) 1730 (shoulder) and 1705 cm<sup>-1</sup> (C=O); uv (95% EtOH) 292 m $\mu$  ( $\epsilon$  3360); nmr (CCl<sub>4</sub>)  $\delta$  16.63 (ca. 0.3 H singlet, enolic OH), 3.57 (ca. 0.7 H triplet,  $J = 7$  cps, COCHCO), 2.07 (6 H, partially resolved singlets, CH<sub>2</sub>C of keto and enol forms), 0.7–2.3 (9 H multiplet, aliphatic CH); mass spectrum, molecular ion peak at  $m/e$  156 with abundant fragment peaks at  $m/e$  100, 71, 58, and 43.

Solutions of 0.70 mmol of methyllithium and several milligrams of bipyridyl (as an indicator)<sup>19</sup> in 0.50 ml of 1,2-dimethoxyethane were treated with slightly less than 1 equiv (see Table V) of one of the silyl ethers **19a** or **20a**. After the solutions had been stirred at 25° for 1 hr, they were diluted with 3.5 ml of 1,2-dimethoxyethane<sup>20</sup> containing known amounts of *n*-dodecane (as an internal standard). Alternatively, enolate anion solutions were prepared by adding about 0.6 mmol (see Table V)

TABLE V

PREPARATION AND ACETYLATION OF ENOLATE ANIONS DERIVED FROM 2-HEPTANONE

Starting material (mmol)	Products, % yield			
	Ketone <b>17a</b>	<i>trans</i> Acetate <b>42b</b>	<i>cis</i> Acetate <b>41b</b>	Diketone <b>40b</b>
<i>cis</i> -Silyl ether <b>20a</b> (0.63)	24	2	36	28
<i>trans</i> -Silyl ether <b>19a</b> (0.42)	15	74	1	4
<i>cis</i> -Enol acetate <b>41b</b> (0.58)	14	0	24	43
<i>trans</i> -Enol acetate <b>42b</b> (0.62)	9	72	0	7

of one of the enol acetates **41b** or **42b** to a solution containing 1.4 mmol of methyllithium and several milligrams of bipyridyl<sup>19</sup> in 4.0 ml of 1,2-dimethoxyethane. In all cases, the resulting solutions of enolate anions retained the purple color of the methyllithium-bipyridyl charge-transfer complex indicating the presence of a slight excess of methyllithium.

Each of the enolate anion solutions was added, rapidly and with stirring, to 4.0 ml of acetic anhydride. After the resulting solutions had been stirred for 15 min, they were stirred with a cold (0°) mixture of pentane, water, and excess NaHCO<sub>3</sub> until the hydrolysis of acetic anhydride was complete. The pentane layers were dried, concentrated, and analyzed by gas chromatography.<sup>16</sup> With the column used<sup>16</sup> the retention times were, for **17a**, 9.5 min; **42b**, 17.0 min; **41b**, 21.6 min; *n*-dodecane, 26.0 min; and **40b**, 36.0 min. The results of these reactions are summarized in Table V. In each case collected<sup>16</sup> samples of the principal products were identified with authentic samples by comparison of infrared spectra and gas chromatographic retention times.

In a similar experiment, a solution of the lithium enolate from 1.387 g (8.88 mmol) of the *trans*-enol acetate **42b** in 50 ml of 1,2-dimethoxyethane was treated with a solution prepared from 5.06 g (46.7 mmol) of chlorotrimethylsilane, 0.5 ml of triethylamine, and 25 ml of 1,2-dimethoxyethane. The resulting mixture was stirred for 1 hr and then partitioned between pentane and aqueous NaHCO<sub>3</sub>. After the pentane solution had been washed successively with cold, dilute aqueous HCl and aqueous NaHCO<sub>3</sub>, it was dried, concentrated, and distilled to separate

0.90 g (48%) of the *trans*-silyl ether **19a**, bp 92° (50–52 mm),  $n_D^{21}$  1.4225, which contained 2–3% lower boiling impurities.

**B. Phenylacetone Derivatives.**—To obtain authentic samples of the enol acetates **41a** and **42a**, a solution of 26.8 g (0.20 mol) of phenylacetone and 200 g (1.96 mol) of acetic anhydride in 600 ml of carbon tetrachloride was treated with 1.0 ml of aqueous 70% HClO<sub>4</sub> and the resulting mixture was stirred for 1.5 hr at 25°. After the reaction mixture had been stirred with a cold (0–5°) mixture of pentane, water, and excess NaHCO<sub>3</sub> for 4 hr to hydrolyze the acetic anhydride, the pentane layer was washed with water, dried, concentrated, and fractionally distilled. After separation of 4.71 g of forerun [bp 82–109° (5 mm),  $n_D^{20}$  1.5172–1.5280] containing<sup>16</sup> primarily the starting ketone, the mixture of enol acetates (23.7 g or 67%, ca. 67% **42a**, and 33% **41a**) was collected at 112–116° (5 mm),  $n_D^{20}$  1.5312–1.5328 [lit.<sup>21</sup> bp 67–69° (0.8 mm),  $n_D^{20}$  1.5320, stereochemistry unspecified]. Samples of each of the pure enol acetates were collected from the gas chromatograph.<sup>16</sup> The more rapidly eluted *trans* acetate **42a** was separated as a colorless liquid: ir (CCl<sub>4</sub>) 1765 (enol ester C=O) and 1685 cm<sup>-1</sup> (enol C=C); uv (95% EtOH) 248.5 m $\mu$  ( $\epsilon$  18,000) and 325 sh (415); nmr (CCl<sub>4</sub>)  $\delta$  6.9–7.3 (5 H multiplet, aryl CH), 5.80 (1 H doublet,  $J = 1.1$  cps, vinyl CH), 2.08 (3 H singlet, OCOCH<sub>3</sub>), and 2.01 (3 H partially resolved doublet, vinyl CH<sub>2</sub>); mass spectrum, molecular ion peak at  $m/e$  176 with abundant fragment peaks at  $m/e$  134, 91, 45, 43, and 39.

Anal. Calcd for C<sub>11</sub>H<sub>12</sub>O<sub>2</sub>: C, 74.97; H, 6.86. Found: C, 74.93; H, 6.93.

The more slowly eluted<sup>16</sup> *cis* isomer **41a** was also collected as a colorless liquid: ir (CCl<sub>4</sub>) 1765 (enol ester C=O) and 1685 cm<sup>-1</sup> (enol C=C); uv (95% EtOH) 242.5 m $\mu$  ( $\epsilon$  15,200) and 324 sh (253); nmr (CCl<sub>4</sub>)  $\delta$  7.2 (5 H partially resolved multiplet, aryl CH), 6.15 (1 H broad singlet, vinyl CH), 2.07 (3 H singlet, OCOCH<sub>3</sub>), and 2.04 (3 H partially resolved doublet, vinyl CH<sub>2</sub>); mass spectrum, molecular ion peak at  $m/e$  176 with abundant fragment peaks at  $m/e$  134, 91, 45, 43, and 39.

Anal. Calcd for C<sub>11</sub>H<sub>12</sub>O<sub>2</sub>: C, 74.97; H, 6.86. Found: C, 75.18; H, 6.94.

Samples of the silyl ethers (181–196 mg or 0.88–0.95 mmol of a mixture of 85% **16** and 15% **15**) were added to solutions of 1.0 mmol of methyllithium and several milligrams of bipyridyl (as an indicator)<sup>19</sup> and known weights of 1,3,5-triisopropylbenzene (internal standard) in 10 ml of 1,2-dimethoxyethane. After the resulting purple solutions (excess methyllithium present) had been stirred for 15–20 min, 1.0-ml aliquots were removed and quenched in an equal volume of acetic anhydride. After the usual isolation procedure, the crude neutral product was analyzed by gas chromatography,<sup>16,22</sup> the retention times<sup>16</sup> being, for **14**, 24.5 min; 1,3,5-triisopropylbenzene, 34.0 min; **42a**, 51.6 min; and **41a**, 56.4 min. The mixtures contained the ketone **14** (6–18% yield) and the enol acetates (68–78% yield) having a composition of 20% **42a** and 80% **41a**. When a 1.0-ml sample of oxygen gas was added to the atmosphere above the enolate solution, and the resulting solution was stirred for 5 min, the product contained the ketone **14** (19% yield) and the enol acetates (65% yield) having a composition 38% **42a** and 62% **41a**. Thus, the presence of oxygen can catalyze the interconversion of stereoisomeric enolate anions as has been noted elsewhere.<sup>23</sup> The corresponding reaction employing 802 mg (3.9 mmol) of the *trans*-silyl ether **15** and 4.0 mmol of methyllithium in 2.0 ml of 1,2-dimethoxyethane gave a crude product containing<sup>16,22</sup> the ketone **14** (5% yield) and the enol acetates (95% yield, 99% of **42a** and 1% of **41a**). From each of these reactions, collected<sup>16</sup> samples of the principal products were identified with authentic samples by comparison of infrared spectra and gas chromatographic retention times. From the reaction with the *trans*-silyl ether **15** none of the  $\beta$ -diketone **40a** was detected;<sup>22</sup> from the *cis* isomer **16** a small peak (less than 2% of the reaction product) was present which had a retention time<sup>22</sup> corresponding to the  $\beta$ -diketone **40a**. With the column used for this analysis,<sup>22</sup> the retention times were, for 1,3,5-triisopropylbenzene, 8.2 min; **14**, 16.0 min; **41a** and **42a** (not resolved), 24.4 min; and **40a**, 27.6 min. An authentic sample of this  $\beta$ -diketone **40a** was prepared by the acetylation of phenylacetone in the presence of boron

(21) G. G. Smith, *J. Amer. Chem. Soc.*, **75**, 1134 (1953).

(22) A gas chromatography column packed with silicone gum, XE-60, suspended on Chromosorb P was employed for this analysis.

(23) Unpublished work by Professor G. W. Whitesides and E. J. Panek, Department of Chemistry, Massachusetts Institute of Technology.

(18) C. R. Hauser, F. W. Swamer, and J. T. Adams, *Org. Reactions*, **8**, 132 (1954).

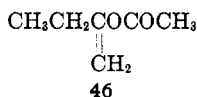
(19) S. C. Watson and J. F. Eastham, *J. Organometal. Chem.*, **9**, 165 (1967).

(20) The reaction of 1 *M* solutions of trimethylsilyl enol ethers with 1 *M* solutions of methyllithium in 1,2-dimethoxyethane requires 5–15 min for completion. It is advantageous to carry out this bimolecular reaction in relatively concentrated solution, and then to add additional solvent if a more dilute solution is desired.

trifluoride.<sup>18</sup> The product separated from petroleum ether (bp 30–60°) at Dry Ice temperature as white prisms: mp 56.5–57.5° (lit.<sup>18</sup> mp 58.5–59.5°); ir (CCl<sub>4</sub>) 1615 and 1410 cm<sup>-1</sup> (very broad, enolic β-diketone); uv (95% EtOH) 222 mμ (shoulder, ε 6050) and 286 (10,300); nmr (CCl<sub>4</sub>) δ 16.95 (1 H singlet, enol OH), 7.0–7.5 (5 H multiplet, aryl CH), 1.82 (6 H singlet, CH<sub>3</sub>C); mass spectrum, molecular ion peak at *m/e* 176 with abundant fragment peaks at *m/e* 161, 134, 115, 77, 55, and 43.

A mixture of 66.8 g (0.50 mol) of phenylacetone, 20 g (0.88 mol) of sodium hydride (pewashed with pentane), and 400 ml of 1,2-dimethoxyethane was stirred for 3.2 hr and then allowed to stand for 14 hr. The supernatant liquid was transferred under nitrogen to a separate vessel; acid-base titration of an aliquot of this solution indicated the total base concentration to be 1.00 *M*. When a 1.0-ml aliquot of the solution was mixed with 1,3,5-triisopropylbenzene (an internal standard), quenched in aqueous NH<sub>4</sub>Cl, and then analyzed,<sup>16</sup> the calculated yield of phenylacetone indicated that the solution was 0.96 *M* in phenylacetone enolate. In the 6-μ region of the infrared the solution shows peaks at 1599 (shoulder), 1575 (strong), and 1550 (strong). The nmr spectrum has a 5 H multiplet at δ 6.3–7.5 (aryl CH), a 1 H singlet at δ 4.70 (enolate vinyl CH), and a 3 H singlet at 1.83 (CH<sub>3</sub>C). Aliquots of this sodium enolate solution were also quenched as previously described in acetic anhydride and in a solution of excess chlorotrimethylsilane in 1,2-dimethoxyethane. From reaction with acetic anhydride, the crude product contained<sup>16</sup> the ketone 14 (5% yield) and the enol acetates (91% yield, 99% 42a, and 1% 41a). Similarly, from reaction with the chlorosilane with naphthalene added as an internal standard, the crude product contained the ketone 14 (9% yield) and the silyl enol ethers (90% yield, 96% 15, and 4% 16). Consequently, this sodium enolate solution contains predominantly the *trans* enolate stereoisomer.

**C. 2-Butanone Derivatives.**—An authentic sample of the diketone 40c, prepared by the reaction of methyl iodide with acetylacetone in the presence of K<sub>2</sub>CO<sub>3</sub> and acetone, was isolated as a colorless liquid, bp 30–60° (100 mm), *n*<sub>D</sub><sup>20</sup> 1.4412 [lit.<sup>24a</sup> bp 170–172° (760 mm)] with nmr absorption corresponding to the published spectrum:<sup>24b</sup> ir (CCl<sub>4</sub>) 1730 (shoulder), 1705, and 1610 cm<sup>-1</sup> (broad, keto and enol form of β-diketone); uv (95% EtOH) 290 mμ (ε 3350); mass spectrum, molecular ion peak at *m/e* 114 with abundant fragment peaks at *m/e* 99, 71, and 43. Application of the previously described reaction and isolation procedures to a solution of 36.0 g (0.50 mol) of 2-butanone, 153.0 g (1.50 mol) of acetic anhydride, and 1.6 g of aqueous 70% HClO<sub>4</sub>, in 400 ml of carbon tetrachloride yielded, after fractional distillation, 16.67 g (25%) of a colorless liquid fraction, bp 93–130° (760 mm), *n*<sub>D</sub><sup>20</sup> 1.4223, which contained<sup>16,25</sup> small amounts of carbon tetrachloride and 2-butanone and a mixture of enol acetates (79% of 42c, eluted first, and 21% 41c, eluted second).<sup>26</sup> Samples of each enol acetate were collected.<sup>25</sup> The *trans* isomer 42c has the following spectral properties: ir (CCl<sub>4</sub>) 1760 (enol ester C=O) and 1705 cm<sup>-1</sup> (enol C=C); uv (95% EtOH) end absorption with ε 963 at 210 mμ; nmr (CCl<sub>4</sub>) δ 4.97 (1 H quartet with additional small splitting not resolved, *J* = 6.4 cps, vinyl CH), 2.07 (3 H singlet, OCOCH<sub>3</sub>), 1.80 (3 H quintet, both *J* values about 1.3 cps, α-CH<sub>3</sub>C), 1.48 (3 H, doublet of quartets, *J* = 6.4 and 1.3 cps, β-CH<sub>3</sub>C); mass spectrum, molecular ion peak at *m/e* 114 with abundant fragment peaks at *m/e* 72, 71, 57, and 43. Since the nmr spectrum of this sample lacks appreciable absorption at δ 4.65 (vinyl CH) which is present in the spectrum of a mixture<sup>26</sup> containing the terminal enol acetate



(24) (a) A. W. Johnson, E. Markham, R. Price, and K. B. Shaw, *J. Chem. Soc.*, 4254 (1958); (b) J. L. Burdett and M. T. Rogers, *J. Amer. Chem. Soc.*, **86**, 2105 (1964).

(25) A gas chromatography column packed with Carbowax 20M used on Chromosorb P was employed for this separation.

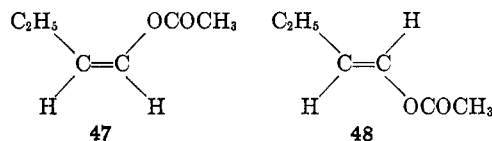
(26) W. E. Parham and J. F. Dooley [*J. Org. Chem.*, **33**, 1476 (1968)] have reported the acid-catalyzed reaction of 2-butanone with isopropenyl acetate to give the expected (see ref 7) mixture of enol acetates, 41c, 42c, and 46, bp 110–120° (760 mm), *n*<sub>D</sub><sup>20</sup> 1.4065. Since neither we nor the previous workers were able to resolve the more rapidly eluted *trans* isomer 42c and the terminal double-bond isomer 46 on the columns employed, we used the alternative preparative route to enol acetates to minimize the amount of the less stable isomer 46 present in the product mixture.

isomer 46, we conclude that our sample of enol acetate 42c contains less than 5% isomer 46.

The *cis* isomer 41c was also a colorless liquid: ir (CCl<sub>4</sub>) 1765, 1748 (enol ester C=O, presumably split by Fermi resonance with the overtone of a peak at 890 cm<sup>-1</sup>), and 1690 cm<sup>-1</sup> (enol C=C); uv (95% EtOH) end absorption with ε 1200 at 210 mμ; nmr (CCl<sub>4</sub>) δ 5.10 (1 H quartet, *J* = 7.0 cps, vinyl CH), 1.97 (3 H singlet, OCOCH<sub>3</sub>), 1.78 (3 H quintet, both *J* values about 1.0 cps, α-CH<sub>3</sub>C), and 1.60 (3 H doublet of quartets, *J* = 7.0 and 1.0 cps, β-CH<sub>3</sub>C); mass spectrum, molecular ion peak at *m/e* 114 with abundant fragment peaks at *m/e* 72, 71, 57, and 43. As noted previously,<sup>7</sup> the chemical shift difference for the vinyl protons of the enol acetates (in CCl<sub>4</sub>, δ 4.97 for the *trans* isomer 42c and δ 5.10 for the *cis* isomer 41c) was increased by measuring the spectra in benzene-*d*<sub>6</sub> where the chemical shift values were δ 4.86 for 42c and 5.13 for 41c. These observations are consistent with the stereochemical assignments given.<sup>7,26</sup>

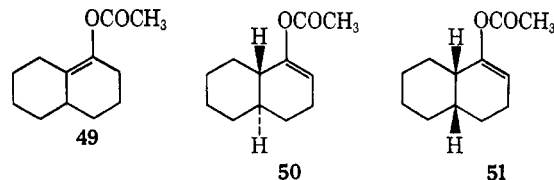
Following previously described procedures, an enolate solution was prepared by reaction for 1.0 hr of 80.1 mg (0.56 mmol) of the silyl enol ethers (92% 19b and 8% 20b) with 1.5 mmol of methyl lithium in 1.5 ml of 1,2-dimethoxyethane containing tetralin (an internal standard) and several milligrams of triphenylmethane. After reaction with acetic anhydride and the usual isolation procedure, the product was analyzed on a column<sup>26</sup> which gave the following retention times: 42c, 16.5 min; 41c, 19.5 min; 40c, 37.0 min; and tetralin, 48.7 min. The crude product contained<sup>26</sup> the *trans* acetate 42c (51% yield), the *cis* acetate 41c (2% yield), and the diketone 40c (9% yield). The corresponding reaction with 114.5 mg (0.79 mmol) of a silyl ether sample which contained 97% *cis* isomer 20b and 3% *trans* isomer 19b yielded a crude product containing<sup>26</sup> the *trans* acetate 42c (5% yield), the *cis* acetate 41c (16% yield), the diketone 40c (32% yield), and several minor unidentified higher boiling materials. Collected<sup>26</sup> samples of each of the principal products from these reactions were identified with authentic samples by comparison of infrared spectra and gas chromatographic retention times.

**D. Butyraldehyde Derivatives.**—Authentic samples of the enol acetates 47 and 48 were available from other studies.<sup>23</sup> An enolate solution was generated by reaction for 45 min of 535 mg (3.71 mmol) of the silyl ether 13 with 3.73 mmol of methyl lithium in 10 ml of 1,2-dimethoxyethane containing *n*-decane (an internal standard) and several milligrams of triphenylmethane (as an indicator). After reaction with acetic anhydride, the crude product was isolated in the usual way and analyzed with a column<sup>16</sup> which gave the following retention times: 47, 20.1 min; 48, 25.2 min; and *n*-decane, 49.2 min. The crude



product contained<sup>16</sup> the unchanged silyl ether 13 (2% recovery) and the acetate 48 (90% yield). From the corresponding reaction with 526 mg (3.65 mmol) of the silyl ether 12, the crude product contained<sup>16</sup> the unchanged silyl ether 12 (8% recovery) and the acetate 47 (92% yield). Collected<sup>16</sup> samples of the products were identified with authentic samples by comparison of infrared spectra and gas chromatographic retention times.

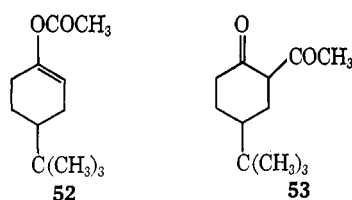
**E. 1-Decalone Derivatives.**—Authentic samples of the enol acetates 49–51 were available from earlier studies.<sup>7</sup> After reac-



tion of a solution of 79.0 mg (0.35 mmol) of a silyl enol ether mixture (77% 25, 20% 26, and 3% 27) with 1.0 mmol of methyl lithium in 1.0 ml of 1,2-dimethoxyethane for 1 hr, the reaction mixture (also containing tetralin and triphenylmethane) was quenched in acetic anhydride and subjected to the usual isolation process. With the column<sup>26</sup> used retention times were as follows: tetralin, 18.2 min; 24, 43.5 min; 49, 65.0 min; 50, 77.5 min; 51, 84.9 min; and a product believed to be 2-acetyl-1-

decalone, 150.9 min. The crude product contained **24** (6% yield), **49** (2% yield), **50** (44% yield), **51** (15% yield), and several higher boiling components. The corresponding reaction with 68.8 mg (0.31 mmol) of a silyl enol ether mixture (36% **25**, 59% **26**, and 5% **27**) yielded a crude product containing **24** (3% yield), **49** (7% yield), **50** (18% yield), **51** (32% yield), and several higher boiling peaks. Collected<sup>26</sup> samples of the enol acetate products were identified with authentic samples by comparison of infrared spectra and gas chromatographic retention times. The results of these transformations allow us to conclude that isomers **25** and **50** are stereochemically related as are **26** and **51**.

**F. 4-*t*-Butylcyclohexanone Derivatives.**—An authentic sample of the enol acetate **52** was available from previous studies.<sup>27</sup>



After reaction of 18.6 g (89.8 mmol) of the pyrrolidine enamine<sup>27</sup> of 4-*t*-butylcyclohexanone with 20.7 g (203 mmol) of acetic anhydride in 50 ml of dioxane at 25° for 24 hr, the solution was diluted with 10 ml of water, refluxed for 30 min, and concentrated. The residual liquid was partitioned between pentane and water, and the resulting organic phase was washed with aqueous NaCl, dried over Na<sub>2</sub>SO<sub>4</sub>, concentrated, and distilled in a short-path still (1.0–1.1 mm and 105–132° bath). The crude distillate (14.72 g of pale yellow oil, *n*<sub>D</sub><sup>20</sup> 1.4942) was fractionally distilled

(27) H. O. House, B. A. Tefertiller, and H. D. Olmstead, *J. Org. Chem.*, **33**, 935 (1968).

to separate 7.93 g (45%) of the diketone **53** as a colorless liquid: bp 99–100° (0.9–1.0 mm); *n*<sub>D</sub><sup>20</sup> 1.4956; ir (CCl<sub>4</sub>) 1610 cm<sup>-1</sup> (broad, enolic β-diketone); uv (95% EtOH) 290 mμ (ε 9840); nmr (CCl<sub>4</sub>) δ 1.1–2.6 (ca. 7 H multiplet, aliphatic CH), 2.08 (3 H singlet, vinylic or acetyl CH<sub>3</sub>), and 0.93 [9 H singlet, (CH<sub>3</sub>)<sub>3</sub>C]; mass spectrum, molecular ion peak at *m/e* 196 with abundant fragment peaks at *m/e* 181, 139, 125, 57, 55, 43, and 41.

*Anal.* Calcd for C<sub>12</sub>H<sub>20</sub>O<sub>2</sub>: C, 73.43; H, 10.27. Found: C, 73.14; H, 10.13.

After reaction for 1 hr of 2.7 mmol of methylolithium with 584.7 mg (2.58 mmol) of the silyl ether **6** in 10 ml of 1,2-dimethoxyethane containing several milligrams of triphenylmethane, the enolate solution was treated with *n*-tetradecane (as an internal standard) and quenched in acetic anhydride. Following the usual isolation procedure, the crude product was analyzed on a column<sup>14</sup> on which the retention times were, for **4**, 9.4 min; **52**, 22.2 min; *n*-tetradecane, 30.7 min; and **53**, 47.0 min. The crude product contained **4** (12% yield), **52** (63% yield), and **53** (12% yield). Collected<sup>14</sup> samples of the enol acetate **52**, and the diketone **53** were identified with authentic samples by comparison of infrared spectra and gas chromatographic retention times.

**Registry No.**—**5**, 6651-36-1; **6**, 19980-19-9; **9**, 13735-81-4; **10**, 17510-46-2; **12**, 19980-22-4; **13**, 19980-23-5; **15**, 19980-24-6; **16**, 19980-25-7; **18a**, 19980-26-8; **18b**, 6651-40-7; **19a**, 19980-27-9; **19b**, 19980-29-1; **20a**, 19980-30-4; **20b**, 19980-31-5; **22a**, 19980-32-6; **22b**, 19980-33-7; **23a**, 19980-34-8; **23b**, 19980-35-9; **25**, 19980-36-0; **26**, 19980-37-1; **27**, 19980-38-2; **29**, 19980-39-3; **31**, 19980-40-6; **32**, 19980-41-7; **33**, 19980-42-8; **35**, 19980-43-9; **41a**, 19980-44-0; **41c**, 15984-02-8; **42a**, 19980-46-2; **42c**, 15984-03-9; **44**, 19980-48-4; **45**, 19980-49-5; **53**, 19980-50-8.

## β-Keto Sulfoxides. IV. Conversion into β-Keto Sulfides, Vinyl Ethers, and Enol Acetates<sup>1</sup>

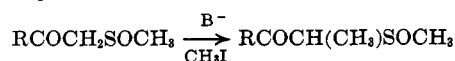
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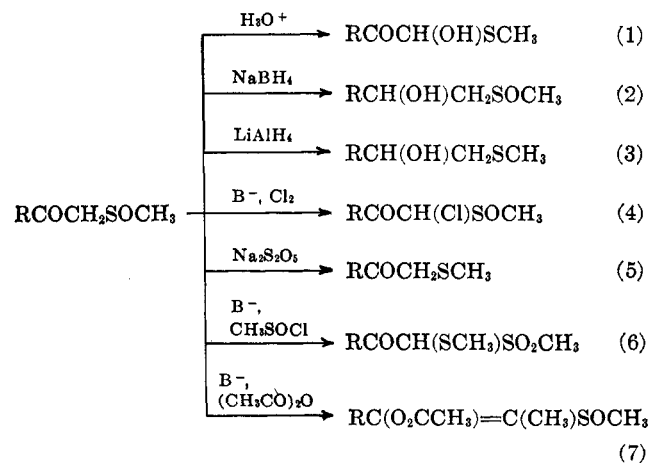
Received April 2, 1968

β-Keto sulfoxides are reduced with sodium metabisulfite to β-keto sulfides. Alkylation of the β-keto sulfide followed by reduction, O methylation, and base-catalyzed elimination in dimethyl sulfoxide solution yields the enol ether. Acylation of the keto sulfides by sodium hydride followed by acetic anhydride gives the enol acetate. Similar treatment of β-keto sulfoxides yields either the enol acetate or the α-acetoxy β-keto sulfide. Reaction of the salt of a β-keto sulfoxide with methanesulfonyl chloride yields a sulfone sulfide rather than the expected disulfide. A sulfone sulfide is also produced from the reaction of the enolate anion of acetylacetone or dibenzoylmethane with two molecules of methanesulfonyl chloride. The formation of the sulfone sulfide is pictured as a base-catalyzed modification of the Pummerer reaction.

This paper reports some of our continuing studies of the synthetic utility of β-keto sulfoxides. Such β-keto sulfoxides can be readily prepared by the condensation of esters with the methylsulfonyl carbanion (CH<sub>3</sub>SO-CH<sub>2</sub><sup>-</sup>).<sup>2,3</sup> β-Keto sulfoxides will undergo monoalkylation reactions in basic solution.<sup>4,5</sup> In addition a variety of other products still containing one sulfur atom can be formed from the β-keto sulfoxides.<sup>6</sup> We have already



described the conversions illustrated in reactions 1–4.<sup>2,4,6</sup> In the present work we describe reactions 5 and 6 and give one illustration of reaction 7.



(1) This work was supported by the Army Office of Research (Durham). For part III, see G. A. Russell and G. J. Mikol, *J. Amer. Chem. Soc.*, **88**, 5498 (1966).

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(4) G. A. Russell and G. J. Mikol, *ibid.*, **88**, 5498 (1966).

(5) P. G. Gassman and G. O. Richmond, *J. Org. Chem.*, **31**, 2355 (1966).

(6) G. A. Russell, E. Sabourin, and G. J. Mikol, *ibid.*, **31**, 2854 (1966).