Communications

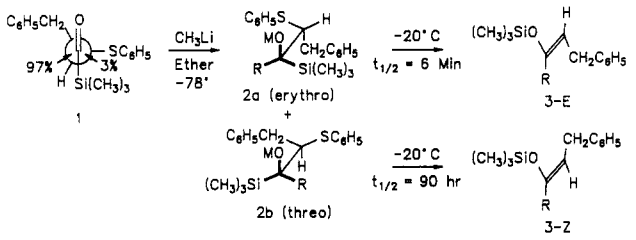
Silyl Ketone Chemistry. Synthesis of Regio- and Stereoisomerically Pure Enol Silyl Ethers Using α-Phenylthio Silyl Ketones[1]

Summary: The addition of a number of organometallic reagents to α-phenylthio silyl ketones proceeds with good to excellent diastereoselectivity. The products undergo Brook rearrangement and fragmentation to enol silyl ethers with, in most cases, excellent stereochemical control.

Sir: Stereoisomerically pure enol derivatives have important applications in the stereoselective synthesis of acyclic molecules bearing multiple asymmetric centers.[2] Techniques for the preparation of such enol derivatives have usually relied on specially designed carbonyl substrates or sterically encumbered bases to achieve high stereoselection in the enolization process.[2,3] We report here a C–C connective procedure for preparing the enol silyl ethers of ketones, enones, and ynones, as well as aldehydes, acyl silanes, stannanes, cyanides, and phosphonates which in several cases proceeds with virtually complete (>99:1) stereoselectivity.

The process, one example of which is summarized in Scheme I, is based on the following: (1) the high stereoselectivity[4] of the addition of nucleophiles to 2-(phenylthio)-3-phenyl-1-(trimethylsilyl)-1-propanone (1);[5] (2) the stereospecificity[4] of the conversion of the intermediate α-silyl alkoxides **2** to enol ethers **3** by a Brook rearrangement–elimination process;[1a,6] (3) the much faster elimination rate of the major (erythro[8]) diastereomer of **2**

Scheme I[a]

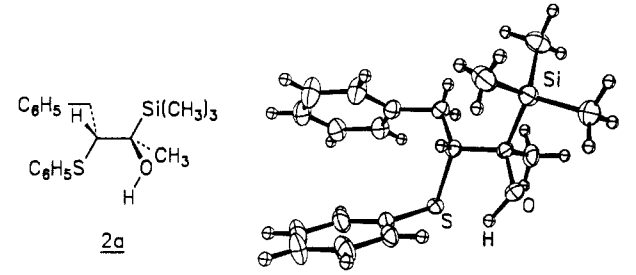


[a] R = CH_3.

compared to the minor one.

We have most closely studied the case of methyllithium addition (R = CH_3) to **1**. A 97/3 ratio[9] of diastereomeric alcohols **2** (M = H) was formed when the reaction mixture was quenched at −78 °C. The major isomer was crystalline, and an X-ray structure revealed it to have the erythro stereochemistry.[9]

If the reaction mixture was warmed to −20 °C, the major diastereomer (**2a**, M = Li, see Scheme I) proceeded to only the (*E*)-enol silyl ether (**3-E**), at a rate approximately 1500 times as fast as the minor diastereomer (**2b**) proceeded to the *Z* isomer (**3-Z**). If the elimination of the 97/3 mixture



was carried out at 0 °C for 30 min, ≥99.5% isomerically pure **3-E** was obtained in 88% distilled yield and ~2% of unreacted **2b** was isolated from the reaction mixture.

We believe these results are best explained by a Felkin–Anh transition state (with C_6H_5S as the group anti to the attacking nucleophile),[10] followed by a more or less concerted C to O silyl migration and expulsion of the anti phenylthio leaving group.[12] Because of the strong ster-

(1) (a) Reich, H. J.; Kelly, M. J. *J. Am. Chem. Soc.* **1982**, *104*, 1119. Reich, H. J.; Rusek, J. J.; Olson, R. E. *J. Am. Chem. Soc.* **1979**, *101*, 2225. Reich, H. J.; Kelly, M. J.; Olson, R. E.; Holtan, R. C. *Tetrahedron* **1983**, *39*, 949. (b) Reich, H. J.; Olson, R. E.; Clark, M. C. *J. Am. Chem. Soc.* **1980**, *102*, 1423.

(2) (a) Heathcock, C. H.; Buse, C. T.; Kleschick, W. A.; Pirrung, M. C.; Sohn, J. E.; Lampe, J. *J. Org. Chem.* **1980**, *45*, 1066. (b) Masamune, S.; Choy, W.; Kerdesky, F. A. J.; Imperiali, B. *J. Am. Chem. Soc.* **1981**, *103*, 1566. Evans, D. A.; Bartroli, J.; Shih, T. L. *J. Am. Chem. Soc.* **1981**, *103*, 2127. Ireland, R. E.; Mueller, R. H.; Willard, A. K. *J. Am. Chem. Soc.* **1976**, *98*, 2868.

(3) Typically only one of a pair of *E*/*Z* isomers or regioisomers is available by such techniques. (a) Corey, E. J.; Gross, A. W. *Tetrahedron Lett.* **1984**, *25*, 495. (b) Masamune, S.; Ellingboe, J. W.; Choy, W. *J. Am. Chem. Soc.* **1982**, *104*, 5526. (c) Fleming, I.; Newton, T. W. *J. Chem. Soc., Perkin Trans 1* **1984**, 119. (d) Taguchi, H.; Yamamoto, H.; Nozaki, H. *Bull. Chem. Soc. Jpn.* **1977**, *50*, 1588. Vedejs, E.; Larson, S. D. *J. Am. Chem. Soc.* **1984**, *106*, 3030. (e) Matsuda, I.; Sato, S.; Hattori, M.; Izumi, Y. *Tetrahedron Lett.* **1985**, *26*, 3215.

(4) We use the terms stereospecificity and -selectivity in their traditional physical organic sense (see: House, H. O. *Modern Synthetic Reactions*, 2nd ed.; W. A. Benjamin: Menlo Park, CA 1972; pp 307–308, ref 40a,b therein).

(5) Prepared by sulfenylation of 3-phenyl-1-(trimethylsilyl)-1-propanone. Minami, N.; Abe, T.; Kuwajima, I. *J. Organomet. Chem.* **1978**, *145*, C1.

(6) Brook, A. G. *Acc. Chem. Res.* **1974**, *7*, 77. Similar eliminations of β-X α-silyl alkoxides have been observed for X = N_2^+,[7a] $(C_6H_5)_3P^+$,[7b] OH,[7c] OR[7e]. When X is a good leaving group (e.g., N_2^+,[7a] Cl[7d]), silicon migration to the carbon bearing the X group competes with the C to O migration.

(7) (a) Brook, A. G.; Limburg, W. W.; MacRae, D. M.; Fieldhouse, S. A. *J. Am. Chem. Soc.* **1967**, *89*, 704. (b) Brook, A. G.; Fieldhouse, S. A. *J. Organomet. Chem.* **1967**, *10*, 235. (c) Hudrlik, P. F.; Hudrlik, A. M.; Kulkarni, A. K. *J. Am. Chem. Soc.* **1985**, *107*, 4260. (d) Sato, T.; Abe, T.; Kuwajima, I. *Tetrahedron Lett.* **1978**, 259. (e) Kuwajima, I.; Atsumi, K.; Tanaka, T.; Inoue, T. *Chem. Lett.* **1979**, 1239. Kuwajima, I.; Kato, M. *Tetrahedron Lett.* **1980**, *21*, 623.

(8) For a definition, see: Noyori, R.; Nishida, I.; Sakata, J. *J. Am. Chem. Soc.* **1981**, *103*, 2106, footnote 8.

(9) Erythro alcohol **2a** (R = CH_3): mp 50–51 °C; NMR (200 MHz, $CDCl_3$) δ 0.28 (s, 9 H), 1.30 (s, 3 H), 2.65 (dd, *J* = 13.5, 12 Hz, 1 H), 2.88 (s, 1 H), 3.2 (dd, *J* = 14, 2.5 Hz, 1 H), 3.38 (dd, *J* = 12.5, 2.5 Hz, 1 H), 6.8–7.4 (m, 10 H).

(10) Chérest, M.; Felkin, H.; Prudent, N. *Tetrahedron Lett.* **1968**, 2199. The same stereochemistry is observed for attack on most α-X ketones and aldehydes,[11] provided that conditions do not favor chelation control. The origin of this effect has been variously described as principally due to interaction of the partially formed C–C bond at the carbonyl group with the C–X σ* (Anh, N. T.; Eisenstein, O. *Nouv. J. Chim.* **1977**, *1*, 61) or the C–X σ orbital (Cieplak, A. S. *J. Am. Chem. Soc.* **1981**, *103*, 4540).

(11) (a) X = RS: Shimagaku, M.; Maeda, T.; Matsuzaki, Y. *Tetrahedron Lett.* **1984**, *25*, 4775. Eliel, E. L.; Koskimies, J. K.; Bohri, B. *J. Am. Chem. Soc.* **1978**, *100*, 1614. (b) X = RSO_2: Julia, M.; Launay, M.; Stacino, J.-P.; Verpeaux, J.-N. *Tetrahedron Lett.* **1982**, *23*, 2465. (c) X = RSe: Leonard-Coppens, A. M.; Krief, A. *Tetrahedron Lett.* **1976**, 3227. (d) X = Cl, Br: Cornforth, J. W.; Cornforth, R. H.; Mathew, K. K. *J. Chem. Soc.* **1959**, 112. Takahashi, T.; Kataoka, H.; Tsuji, J. *J. Am. Chem. Soc.* **1983**, *105*, 147. (e) X = R_2PO: Buss, A. D.; Mason, R.; Warren, S. *Tetrahedron Lett.* **1983**, 5293. (f) X = R_3Si: Hudrlik, P. F.; Kulkarni, A. K. *J. Am. Chem. Soc.* **1981**, *103*, 6251.

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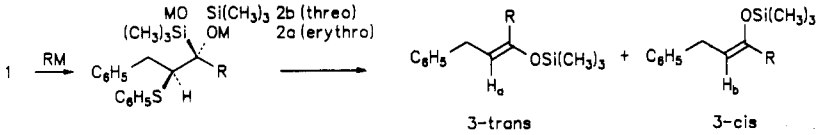
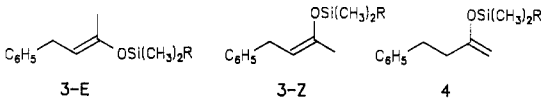
Table I. Preparation of Enol Silyl Ethers

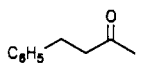
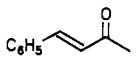
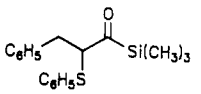
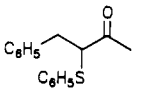


entry	RM	2a/2b (M = H) erythro/threo	3t/3c[a,b]	yield, %	δ ($CDCl_3$) H_a	δ ($CDCl_3$) H_b
1	$LiAlH_4$	98/2[c]	>99/1	68	5.18	4.73
2	CH_3Li	97/3	>99.5/0.5	88	4.90	4.71
3	C_2H_5Li	95/5[d]	>99/1	74	4.80	4.70
4	CH_2=CHLi	95/5	95/5	81	5.10	5.03
5	C_6H_5Li	82/18, 92/8[e]	82/18, 93/7[e]	89	5.25	5.45
6	*m*-$CF_3C_6H_4Li$	95/5	63/37[e]	75	5.42	5.63
7	*i*-C_3H_7C≡CLi	>95/5	67/33[c]	72	5.35	5.15
8	$(CH_3)_3SnLi$	g	99/1[h]	94	5.72	5.32
9	$(CH_3)_3SnLi$	g	>99.5/0.5	81	5.79	5.05
10[i]	$(CH_3O)_2POLi$	g	97/3	86	5.81	6.05
11[i]	$NC^-(C_4H_9)_4N^+$	g	67/33[c]	93	5.97	5.86

[a] Stereochemical assignments were based on literature data[2a] (entries 1–4, 11) as well as on measurement of cis and trans $^3J_{H-C=C-X}$ couplings (entries 1, 2, 7, 9, 10; X = H, C, Sn, P), chemical shifts of the X carbon (entries 2, 5, 7; δ trans upfield of δ cis) and equilibration of cis and trans isomers. [b] Reactions were carried out as follows: to a solution of RM (0.1 M) in ether (chloroform for entry 11) at −78 °C was added a solution of silyl ketone 1 in ether (inverse addition was used for entries 3 and 9). The reaction mixture was warmed to 0 °C (−50 °C for entry 10) for 0.5–1 h and poured into $NaHCO_3$ solution and worked up. The product was purified by Kugelrohr distillation. For entry 1 alcohol **2** (R = H) was isolated, conversion to **3** was carried out by treatment with LDA in ether at −78 to 25 °C. [c] The ratio depends on reaction conditions. [d] Reference 12. [e] Reaction carried out at −110 °C. [f] Solvent was 1/1 ether/THF. [g] The intermediate alcohol was not isolated. [h] The product also contains 5% of (*Z*)-$C_6H_5CH_2CH$=$C(Si(CH_3)_3OSi(CH_3)_2C_6H_5$. [i] For entries 10 and 11 the *tert*-butyldimethylsilyl analogue of 1 was used.

Table II. Comparison of Regio- and Stereoselectivities of Various Techniques for Enol Silyl Ether Preparation



entry	starting material	reagents	product ratio 3-E	3-Z	4	yield, %
1[a]		$(CH_3)_3SiCl$, $N(C_2H_5)_3$, DMF	28	58	14	84
2[a]		(1) LDA, THF; (2) $(CH_3)_3SiCl$	16	9	75	76
3[b]		LDA, $(CH_3)_3SiCl$	6	2	92	84
4[c]		$(C_6H_5)_2CuLi$, ether, $(CH_3)_3SiCl$	54	46	<1	67
5[d]		R_3SiH, Pt catalyst	~50	~50		g
6		CH_3Li, ether, −78 to 0 °C	>99	<1	<1	88
7[e]		$C_6H_5(CH_3)_2SiLi$, ether/THF, −78 to 0 °C	<1	>99	<1	77
8[f]		$C_6H_5CH_2CH(Li)SC_6H_5$, ether/THF	66	33	<1	52

[a] Procedure of: House, H. O.; Czuba, L. J.; Gall, M.; Olmstead, H. D. *J. Org. Chem.* **1969**, *34*, 2324. [b] This reaction was carried out by adding a cold solution of ketone to a solution of Me_3SiCl and LDA in THF at −78°C (procedure of ref 3a). [c] Ketone was added to a mixture of Ph_2CuLi and Me_3SiCl in ether. Poor stereoselectivity in a cuprate conjugate addition has also been observed by: Fleming, I.; Perry, D. *Tetrahedron* **1981**, *37*, 4027. High stereoselectivity can be achieved if substituents cause conformational homogeneity of the enone: Chamberlin, A. R.; Reich, S. H. *J. Am. Chem. Soc.* **1985**, *107*, 1440. [d] Barlow, A. P.; Boag, N. M.; Stone, F. G. A. *J. Organomet. Chem.* **1980**, *191*, 39. [e] This procedure for enol ether formation has been reported (ref 13). [f] The required lithium reagent was prepared by cleavage of 1-(phenylseleno)-1-(phenylthio)-2-phenylethane with *n*-butyllithium (Seebach, D.; Meyer, N.; Beck, A. K. *Liebigs Ann. Chem.* **1977**, 846). [g] High yield.

eoelectronic demands of such an E2-like transition state, the silyl group must be eclipsed with H during the C to O migration for the major diastereomer and with $PhCH_2$ for the minor, less reactive, diastereomer. Hence the large difference in rate. It is perhaps significant that the X-ray structure of the alcohol **2a** (M = H) showed it to be in a

conformation like that which may precede the elimination transition state of the alkoxide **2a** (M = Li).

As summarized in Table I, other nucleophiles such as ethyllithium,[13] hydride ($LiAlH_4$), (phenyldimethylsilyl)-lithium, and (trimethylstannyl)lithium showed parallel behavior: i.e., good Felkin–Anh selectivity during the carbonyl addition and exclusive formation of a single enol ether isomer. With R groups such as phenyl and vinyl capable of modest carbanion stabilization the rate of elimination was much higher than for R = CH_3, being complete in at most a few hours at −78 °C. The rate difference between **2a** and **2b** was much smaller than for R = CH_3 (~7x for R = C_6H_5) so that both enol ethers were formed at 0 °C.

With R groups such as alkynyl and *m*-(trifluoromethyl)phenyl the stereoselectivity was still good during the carbonyl addition but *the elimination was nonstereospecific*. We believe that for these cases the elimination process has become E_{1cb}-like, i.e., a silyl migration to a stabilized siloxy carbanion with sufficient lifetime to lose stereochemical memory.

We have extended the process to silyl ketones with other substitution patterns. For example, reaction of methyllithium with 2-(phenylthio)-1-(dimethylphenylsilyl)-1-propanone gave an 88/12 ratio of diastereomeric alcohols and a 98/2 *E*/*Z* ratio of the appropriate enol ethers.

The approach described above is not the only way to prepare alkoxides such as **2**. The same intermediates could be generated by addition of $C_6H_5CH_2CH(SC_6H_5)Li$ to methyl trimethylsilyl ketone, or by addition of R_3SiLi to an α-phenylthio alkyl ketone.[14] Table II summarizes the results obtained by these procedures, as well as those obtained by some more traditional methods for enol ether formation. It can be seen that both stereoisomers are now available with excellent stereocontrol and essentially complete regiocontrol (entries 6 and 7) simply by interchanging the role of silyl and alkyl groups as nucleophile or pendant group.

Acknowledgment. We thank the National Science Foundation for generous support of our work and J. J. Rusek for exploratory experiments.

(12) Anti elimination of hydroxide has been observed during a similar rearrangement–elimination studied by Hudrlik[7c] and co-workers.

(13) Approximately 8% reduction (hydride addition, erythro/threo = 7/1) accompanied the ethyllithium addition product. *n*-BuLi, *sec*-BuLi, and *t*-BuLi gave increasing amounts of reduction.

(14) Vedejs, E.; Arnost, M. J.; Eustache, J. M.; Krafft, G. A. *J. Org. Chem.* **1982**, *47*, 4384.

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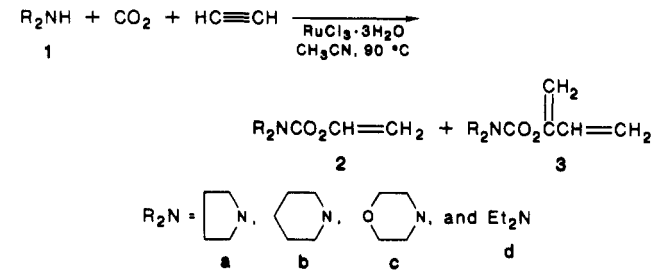
Ruthenium-Catalyzed Synthesis of Vinyl Carbamates from Carbon Dioxide, Acetylene, and Secondary Amines

Summary: $RuCl_3 \cdot 3H_2O$ catalyzed the reaction of CO_2, acetylene, and secondary amines giving vinyl carbamates $R_2NCO_2CH{=}CH_2$ with a small amount of 2-butadienyl carbamates $CH_2{=}C(R_2NCO_2)CH{=}CH_2$.

Sir: The catalytic incorporation of CO_2 into organic compounds has been an attractive goal in recent years[1] in order to produce functionalized substrates with an inexpensive and stable reagent. However, few examples are known of such reactions involving industrially available chemicals and of particular importance concerning their application to industry besides butadiene and epoxides.

As for reactions of CO_2 affording carbamates, Inoue et al. recently reported the catalytic formation of carbamic esters from CO_2, amines, and epoxides using a metalloporphyrin catalyst.[2] We have also reported a novel synthesis of vinyl carbamate derivatives from CO_2, diethylamine, and hex-1-yne or phenylacetylene in the presence of $Ru_3(CO)_{12}$.[3] $Ru_3(CO)_{12}$ showed very little activity toward acetylene. This was unfortunate as there is significant commercial interest in nonsubstituted vinyl carbamates (as precursor for varnish or agricultural chemicals[4]) previously obtained from vinyl chloroformate.[5]

We have now found that acetylene itself reacts with CO_2 and secondary amines in the presence of $RuCl_3 \cdot 3H_2O$ to give vinyl carbamates **2** in one step and in good yields. A small amount of 1-methylene-2-propenyl carbamate **3** was formed, as well.



Acetonitrile (50 mL), $RuCl_3 \cdot 3H_2O$ (2 mmol), pyrrolidine **1a** (100 mmol), and acetylene (320 mmol) were successively placed in a 500-mL autoclave and stirred under CO_2 pressure (15 atm) at 90 °C for 20 h. The resulting solution was concentrated, and 200 mL of ether was added. After washing with 50 mL of dilute HCl solution (3%) several times, the organic layer was concentrated and distilled under reduced pressure. The primary product (6.5 g) and the secondary product (0.4 g) were identified as [(*N*,*N*-tetramethylenecarbamoyl)oxy]ethylene (**2a**) and 2-[(N,N-tetramethylenecarbamoyl)oxy]buta-1,3-diene (**3a**), respectively by IR, NMR, and GC–MS analyses.[6] The yields, based on pyrrolidine, were 46% and 2%, respectively. Secondary amines such as piperidine (**1b**), morpholine (**1c**), and diethylamine (**1d**), under similar con-

(1) Inoue, S.; Yamazaki, N. *Organic and Bio-organic Chemistry of Carbon Dioxide*; Kodansha; Tokyo, 1982.

(2) Kojima, F.; Aida, T.; Inoue, S. *J. Am. Chem. Soc.* **1986**, *108*, 391.

(3) Sasaki, Y.; Dixneuf, P. *J. Chem. Soc., Chem. Commun.* **1986**, 790.

(4) Boivin, S.; Chettovf, A.; Hemerz, P.; Boileau, S. *Polym. Bull.* **1983**, *9*, 114.

(5) Olofson, R. A.; Bauman, B. A.; Vancowicz, D. J. *J. Org. Chem.* **1978**, *43*, 752; Fr. Pat. 1 478 633. Olofson, R. A.; Schnur, R. C.; Bunes, L.; Pepe, J. P. *Tetrahedron Lett.* **1977**, 1567. Olofson, R. A.; Schnur, R. C. *Ibid.* **1977**, 1571.

(6) The boiling points and the analytical data of the products are as follows. **2a**: 49 °C (0.5 mmHg); ^1H NMR ($CDCl_3$) δ 1.8 (m, 4 H), 3.4 (m, 4 H), 4.5 (m, 2 H), 7.2 (m, 1 H); IR (neat) 1720 cm^{-1}; mass spectrum, *m*/*e* 141 (M^+). **3a**: ^1H NMR ($CDCl_3$) δ 1.9 (m, 4 H), 3.4 (m, 4 H), 4.9 (s, 2 H), 5.2 (m, 2 H), 6.2 (m, 1 H); IR (neat) 1720 cm^{-1}; mass spectrum, *m*/*e* 167 (M^+). **2b**: 53 °C (0.6 mmHg); ^1H NMR ($CDCl_3$) δ 1.5 (m, 6 H), 3.4 (m, 4 H), 4.5 (m, 2 H), 7.2 (m, 1 H); IR (neat) 1715 cm^{-1}; mass spectrum, *m*/*e* 155 (M^+). **3b**: ^1H NMR ($CDCl_3$) δ 1.5 (m, 6 H^1), 3.5 (m, 4 H), 4.9 (s, 2 H), 5.2 (m, 2 H), 6.2 (m, 1 H); IR (neat) 1715 cm^{-1}; mass spectrum, *m*/*e* 181 (M^+). **2c**: 56 °C (0.7 mmHg); ^1H NMR ($CDCl_3$) δ 3.5 (m, 8 H), 4.5 (m, 2 H), 7.2 (m, 1 H); IR (neat) 1718 cm^{-1}; mass spectrum, *m*/*e* 157 (M^+). **2d**: 41 °C (3 mmHg); ^1H NMR δ 1.1 (t, 6 H), 3.3 (q, 4 H), 4.5 (m, 2 H), 7.2 (m, 1 H); IR (neat) 1718 cm^{-1}; mass spectrum, *m*/*e* 143 (M^+). **3d**: ^1H NMR ($CDCl_3$) δ 1.2 (t, 6 H), 3.4 (q, 4 H), 4.9 (s, 2 H), 5.2 (m, 2 H), 6.2 (m, 1 H); IR (neat) 1718 cm^{-1}; mass spectrum, *m*/*e* 169 (M^+).

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