added. After adding excess *tert*-butyl alcohol, the ethyl bromoacetate was slowly added to initiate the reaction at 0 °C. The reactions are complete after 0.5 h at 0 °C and 2 h at room temperature. The products and yields obtained of the resulting β,γ-unsaturated esters are presented in Table I. Similarly, β,γ-unsaturated ketones and β,γ-unsaturated nitriles were prepared in good yields (Tables II and III).

Thus, this α-alkenylation reaction does provide a direct route to highly stereoselective syntheses of β,γ-unsaturated esters, ketones, and nitriles. Stereochemically pure[14] (≥95%) products are obtained from *B-trans*-1-alkenyl-9-BBN derivatives. An exploratory experiment under the same conditions attempting to utilize the organoborane from an internal alkyne and 9-BBN with ethyl bromoacetate under the influence of 2,6-di-*tert*-butylphenoxide gave a mixture of cis and trans isomers (50:50). The nonstereospecificity exhibited by internal alkenyl-9-BBN compounds renders the reaction much less useful in these cases.

The following procedure for the preparation of ethyl (3*E*)-3-decenoate (**3**) is representative. To an ice-cooled solution of 2,6-di-*tert*-butylphenol in THF (10 mmol, 6.94 mL of 1.44 M solution) was added slowly 5.6 mL of a 1.78 M solution of potassium *tert*-butoxide in THF. After stirring for 0.5 h at 0 °C, neat *B*-1-octenyl-9-BBN (2.7 mL, 10 mmol) was added, followed by 10 mL of *tert*-butyl alcohol. Immediately following was added 1.10 mL (10 mmol) of neat ethyl bromoacetate dropwise. The reaction was stirred for 0.5 h at 0 °C and 2 h at 25 °C to ensure complete reaction. The residual organoborane was oxidized with $NaOAc/H_2O_2$ and stirred 3 h at 25 °C. The reaction mixture was extracted with pentane and the extract dried over anhydrous $MgSO_4$. The crude product was purified by chromatography over silicic acid. It was further purified by high vacuum distillation to yield pure ethyl (3*E*)-3-decenoate (**3d**; 1.30 g, 65%): bp 78–80 °C (0.60 mm); n^{20}_D 1.4372. GC analysis indicated 95% isomeric purity. **3d**: IR (neat) ν 1735 (ester carbonyl), 1654, 967 (C=C) cm^{-1}; ^1H NMR ($CDCl_3$, Me_4Si) δ 0.6–1.0 (t, 3 H), 1.33 (m, 11 H), 2.06 (m, 2 H), 3.0 (d, J = 4 Hz, 2 H), 4.13 (m, 2 H), 5.53 ppm (m, 2 H); ^{13}C NMR[15] ($CDCl_3$, Me_4Si) δ 171.52, 134.34, 121.72, 60.07, 37.91, 32.35, 31.62, 29.66, 28.65, 22.47, 13.99, 13.81 ppm; mass spectrum, M^+ 198.

The same procedures were employed for preparing β,γ-unsaturated ketones **4a–c** and β,γ-unsaturated nitriles **5a–c**.

Acknowledgment. We express our deep appreciation to the National Science Foundation (Grant CHE 8414171) for the support which made this research possible.

(14) Stereochemistry of the double bond was established by analyzing the samples on a 5890A capillary GC. Both cis and trans isomers separate cleanly on Supelcowax 10, 15 M, 0.25 in. I.D. column. Reference for the preparation of cis isomers: Brown, H. C.; Bhat, N. G., unpublished results.

(15) In a mixture of isomers, the vinylic carbons of cis isomers can be distinguished from the corresponding carbons of trans isomers. Reference: Dorman, D. E.; Jautelat, M.; Roberts, J. D. *J. Org. Chem.* **1971**, *36*, 2757.

(16) Postdoctoral research associate on Grant CHE 8414171 provided by the National Science Foundation.

(17) Graduate research assistant on Grant 76-20846 provided by the National Science Foundation.

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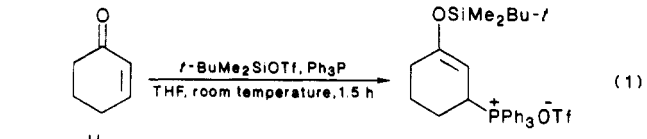
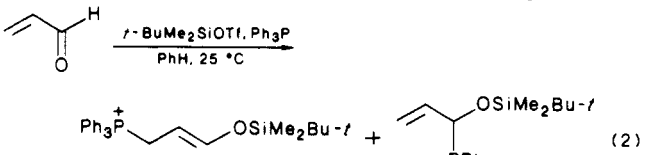
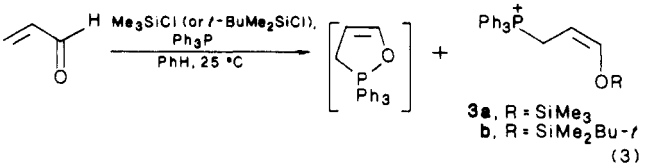
Phosphoniosilylation: An Efficient and Practical Method for the β-Functionalization of Enones

Summary: A useful procedure for the β-functionalization of enones is described in which the Wittig reaction is combined with an initial phosphoniosilylation process.

Sir: During studies related to the construction of the adenylate cyclase activator forskolin,[1] we needed to construct variously substituted dienes[2] as key starting materials. This need led us to investigate the reactions of an array of enones with triphenylphosphine in the presence of reactive silylating agents, a reaction type studied in some detail (especially for the silicon phosphite esters) previously by Evans and co-workers.[3] In contrast to this earlier report of Evans, we have now found that one can react cyclic enones, such as cyclohexenone, with *t*-Bu-$(Me)_2SiOTf/Ph_3P$ to generate products formed by the addition of Ph_3P to the β-position of the enone with silylation of the ketone oxygen (eq 1). The success of the







present study is in part a consequence of the present day availability of these more reactive silylating agents.[4a] Since the acyclic enone acrolein gave rise to the (*E*)-silyl enol ether (300-MHz ^1H NMR analysis) together with some of the 1,2-addition product under our reaction conditions (eq 2), while Evans conditions (Ph_3P, Me_3SiCl, PhH, 25 °C) led exclusively to the (*Z*)-olefin isomer (eq 3), we suggest that with the more reactive silyl triflate reagents the reaction pathway may be quite different from that proposed by Evans.

It would appear likely that with the more reactive silyl

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(2) For an excellent review of hetero-substituted 1,3-dienes, see: Petrzilka, M.; Grayson, J. I. *Synthesis* **1981**, 753. Also, see: Makin, S. M. *Russ. Chem. Rev. (Engl. Transl.)* **1969**, *38*, 237.

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(4) (a) Riediker, M.; Graf, W. *Helv. Chim. Acta* **1979**, *62*, 205. Corey, E. J.; Cho, H.; Rucker, C.; Hua, D. H. *Tetrahedron Lett.* **1981**, *22*, 3455. (b) Me_3SiCl is known to activate enones toward conjugate addition. See, inter alia: Nakamura, E.; Kuwajima, I. *J. Am. Chem. Soc.* **1984**, *106*, 3368.

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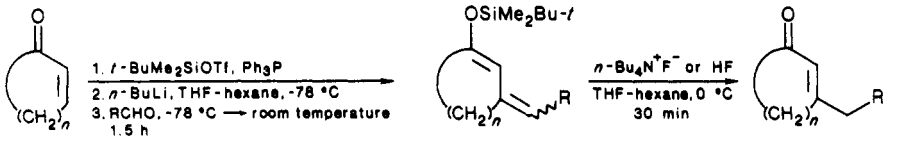
0022-3263/86/1951-3400$01.50/0

Table I. Synthesis of β-Substituted Enones by Phosphoniosilylation[a]



5 6

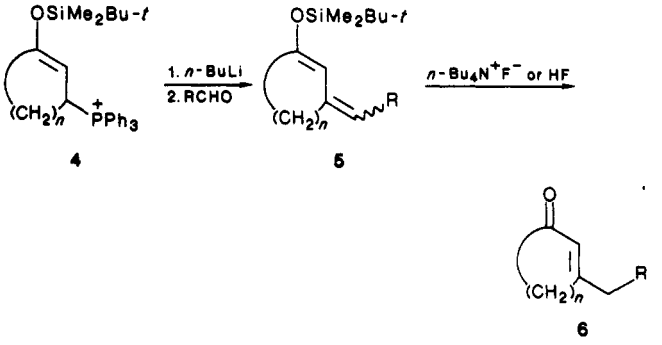
entry	cycloalkenone	R	overall yield of 5, %	overall yield of 6, %	desilylation reagent
1	cyclopentenone	*i*-Pr	81	68[b]	HF
2	cyclopentenone	Ph	75	63[b]	HF
3	cyclopentenone	*n*-pent	*a*	69[b]	HF
4	cyclohexenone	*i*-Pr	86	80	TBAF or HF
5	cyclohexenone	Ph	83	77	TBAF or HF
6	cyclohexenone	*n*-pent	*a*	82	TBAF or HF
7	cyclohexenone	MeCH=CH	74	51[c]	HF–pyridine
8	(*R*)-(−)-carvone	*n*-Pr	*a*	56[d]	HF
9	cycloheptenone	*n*-Pr	*a*	82[e]	HF

[a] The isolation of the dienol silyl ether was not attempted. [b] The lower yields of 6 found in the cyclopentenone cases derive in part from competing desilylation during phosphorane formation as evidenced by the detection of triphenylphosphine during deprotonation. The use of more hindered silyl groups for protection and/or hindered bases for deprotonation are being examined. [c] Isolated as a 3:1 mixture of the 3-[(*E*)-2-butenyl]- and 3-[(*E*)-1-butenyl]-2-cyclohexen-1-ones. [d] LDA was used as the base in this experiment. [e] Isolated as a 2.5:1 mixture of the α,β- and β,γ'-unsaturated enones.

triflates, silicon complexation occurs first to the carbonyl group[4b] and then the phosphine adds in a conjugate sense to this activated enone with maintenance of the initially preferred trans relationship between the CO group and the C_α–C_β carbons.[5] The *E* selectivity observed in our phosphoniosilylation reaction appears inconsistent with the initial production of an oxaphospholene intermediate as postulated by Evans (eq 3) to explain his stereochemical observations.[3a,6] To the extent that the silyl triflate activated enone behaves as an allylic cation, *E* stereochemistry should also obtain as is expected from the known stabilities of allyl cations generated in the solvolysis of 2,3-dimethylcyclopropyl chlorides.[7] Our mechanism also accommodates the formation of the 1,2-addition product.

The phosphonium salt products so produced can provide ready access to β-substituted enones in good overall yield. While such β-substituted enones are generally derivable from the parent enones by copper conjugate addition procedures followed by enolate trapping and subsequent oxidation, the yields which attend such processes are sometimes inadequate and the requisite organocuprates difficult to procure.[8] Starting from the product of enone phosphoniosilylation, one need only effect a single pot deprotonation, Wittig reaction, and silyl enol ether hydrolysis sequence to arrive at the β-substituted enones.

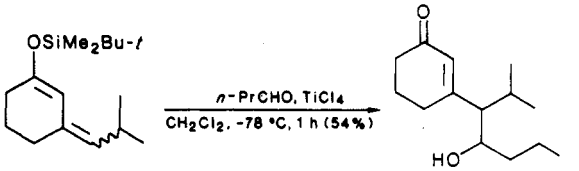
Notably, *n*-BuLi in hexanes does effect deprotonation of the enol phosphonium salt without competing desilylation. On exposure of this Wittig reagent to an aldehyde, the silyloxy diene **5** is formed. This product can be isolated if desired. Simple exposure of the silyloxy diene to HF or n-$Bu_4N^+F^-$ yields the desired β-functionalized enone system. As apparent from Table I, this chemistry works well in both the cyclopentenone and cyclohexenone series. Even the presence of an α-methyl substituent as found in carvone (entry 8) does not preclude the applicability of this chemistry. With cycloheptenone (entry 9), a mixture of the conjugated and nonconjugated enones was obtained on HF workup. Aliphatic, aromatic, and unsaturated aldehydes can be used successfully in the Wittig condensation step. With crotonaldehyde as the electrophile, 3-[(*E*)-2-butenyl]-2-cyclohexen-1-one was obtained as the major product together with the fully conjugated isomer (ratio = 3:1).



4 5 6

While we have not yet rigorously assigned stereochemistry to all of these dienol silyl ethers, a 13:1 mixture of olefin isomers was found for the reaction of isobutyraldehyde with the Wittig reagent prepared from cyclohexenone. From an analysis of chemical shift differences between the respective vinylic protons and olefinic carbon atoms, as well as NOE experiments, the major isomer was assigned *E* stereochemistry.[9]

These dienol silyl ethers can be subjected to reactions other than simple protiodesilylation. On exposure of **5** (entry 4) to *n*-butyraldehyde and titanium tetrachloride, the branched chain bearing cyclohexenone **7** was isolated as a 1:1 mixture of erythro and threo isomers. This result



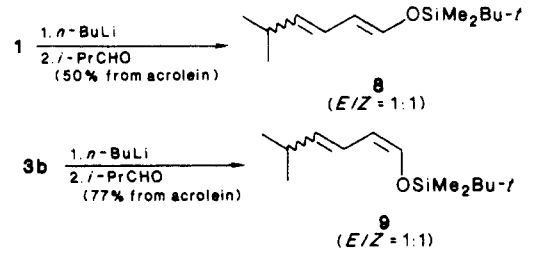
5 (entry 4) 7 (1:1 erythro/threo mixture)

is in line with previous observations regarding kinetic electrophilic attack at the γ-position of silyl dienol ethers.[10]

(6) Gorenstein, D.; Westheimer, F. H. *J. Am. Chem. Soc.* **1970**, *92*, 634. Ramirez, F.; Madan, O. P.; Heller, S. R. *J. Am. Chem. Soc.* **1965**, *87*, 731.
(7) Buss, V.; Gleiter, R.; Schleyer, P. v. R. *J. Am. Chem. Soc.* **1971**, *93*, 3927. Ree, B. R.; Martin, J. C. *Ibid.* **1970**, *92*, 1660.
(8) Posner, G. H. *An Introduction to Synthesis Using Organocopper Reagents*; Wiley: New York, 1980. Also, see: Belmont, D. T.; Paquette, L. A. *J. Org. Chem.* **1985**, *50*, 4102 and references therein.
(9) Jackman, L. M.; Sternhell, S. *Applications of Nuclear Magnetic Resonance Spectroscopy in Organic Chemistry*; Pergamon: Oxford, 1969; p 225.
(10) Ishida, A.; Mukaiyama, T. *Bull. Chem. Soc. Jpn.* **1978**, *51*, 2077; **1977**, *50*, 1161. Mukaiyama, T.; Ishida, A. *Chem. Lett.* **1975**, 1201. Hayashi, Y.; Nishizawa, M.; Sakan, T. *Ibid.* **1975**, 387.

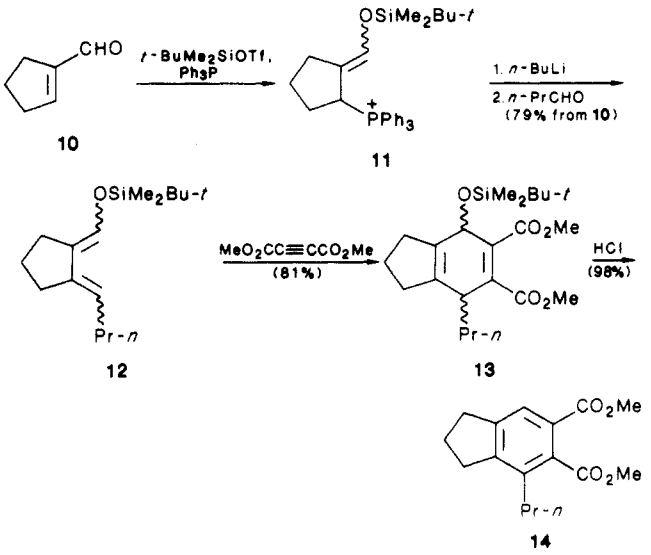
Certainly, the introduction of a host of other electrophiles into such dienol systems is feasible.

It is of further interest to point out here that the two silyloxy-bearing allylphosphonium salts **1** and **3b** can also be transformed to their corresponding phosphoranes. On reaction with isobutyraldehyde, each of these ylides gave rise to a 1:1 mixture of silyloxy dienes. In each case, the



stereochemistry about the silyl ether bearing double bond was retained, while formation of the new double bond proved indiscriminate. This Wittig process may prove valuable to the procurement of unusually substituted silyloxy dienes for the Diels–Alder process.[2,11]

The use of cyclopentene-1-carboxaldehyde in the phosphoniosilylation process was particularly intriguing, for it offered potentially a new approach to exocyclic 1,3-dienes for (4 + 2)-based molecular elaborations. Indeed, this aldehyde was found to readily yield the product of 1,4-addition. None of the alternative 1,2-addition product was observed. Subsequent Wittig condensation then led to the desired diene system **12**. While we have not yet



made a rigorous assignment of stereochemistry for this system, it was nonetheless encouraging to find that this new diene did react efficiently with dimethyl acetylenedicarboxylate. Acid treatment of the product **13** resulted in its conversion to the aromatic system **14**. Such methodology would appear to offer an attractive route to 1,4-cyclohexadienols and consequently a new means for effecting a benzannulation sequence.[12]

In summary, we suggest that this phosphoniosilylation reaction should commend itself for immediate use in the laboratory, for the techniques required for its execution are simple and the reagents needed are readily available.[13]

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Supplementary Material Available: Representative experimental procedures for the phosphoniosilylation reaction, Wittig condensation, and hydrolysis to β-substituted enone (2 pages). Ordering information is given on any current masthead page.

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(13) For a recent report on the functionalization of enones using "bifunctional" reagents, see: Leonard, W. R.; Livinghouse, T. *J. Org. Chem.* **1985**, *50*, 730.

Stereoselective Acid-Catalyzed Claisen Rearrangements[1]

Summary: An alkyl substituent in the 2-position of an *E* trisubstituted allylic alcohol confers significant diastereoselectivity on ortho ester and ketal Claisen rearrangements of the system.

Sir: The Claisen rearrangement is an important synthetic tool, due in part to the stereochemical control it affords.[3] The olefinic geometries in the initial allyl vinyl ether dictate the relative stereochemistry of the carbon atoms α and β to the new carbonyl group.[4] The enolate Claisen[5] and the amide acetal Claisen[6] rearrangements are examples that allow control over this relative stereochemical relationship. In contrast, previous examples of the acid-catalyzed ortho ester[7] and ketal[8] Claisen rearrangements have shown no significant stereoselectivity. In this paper we report that the judicious choice of the allylic alcohol leads to a diastereoselective reaction.

The basis for predicting the stereoselectivity arises from a consideration of the transition states leading to the syn and anti products (Scheme I).[9] The transition-state model

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(4) Hansen, H. J.; Schmid, H. *Tetrahedron* **1974**, *30*, 1959.

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(9) All structures, while drawn as a single enantiomer, represent racemates. The syn/anti stereostructural notation proposed by Masamune is used in this paper. Masamune, S.; Ali, S. A.; Snitman, D. L.; Garvey, D. S. *Angew. Chem., Int. Ed. Engl.* **1980**, *19*, 557.

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