acetonitrile, according to the general procedure, at a potential maintained at +1.0 V. On workup, a mixture of brugierol and isobrugierol was isolated in a ratio of 58:42 (5 mg, 17%) together with **3**, X = H, Y = $OSiMe_2(t\text{-Bu})$, as a mixture of cis and trans isomers in a ratio of 38:62 (26 mg, 39%) as determined by ^1H NMR analysis.

Controlled Potential Oxidation of 1, R = t-Bu, X = $OSiMe_2(t\text{-Bu})$, R′ = Y = H. A sample of **1**, R = *t*-Bu, X = $OSiMe_2(t\text{-Bu})$, R′ = Y = H (88 mg, 0.29 mmol), was oxidized in dry acetonitrile, according to the general proedure, at a potential maintained at +1.0 V. On workup, a mixture of brugierol and isobrugierol was isolated in a ratio of 58:42 (5 mg, 13%) together with **3**, X = $OSiMe_2(t\text{-Bu})$, Y = H, which was isolated as a colorless viscous liquid composed of a mixture of cis and trans isomers in a ratio of 41:59 (35 mg, 48%): IR (CCl_4) 1051, 1077, 1097 cm^{-1}; mass spectrum, *m/z* cacld for $C_9H_{21}O_2S_2Si$ (M^+ + H) 253.0753, found 253.0741; calcd for $C_5H_{11}O_2SSi$ ($M^+ - C_4H_9$) 194.9970, found 194.9967. These isomers can be separated by preparative HPLC on a silica column (Altex Ultrasil-Si, 10 × 250 mm), eluting with ethyl acetate/hexane (1:3) at a flow rate of 3 mL/min, and a UV detector set at 280 nm was used as a monitor.

Cis isomer: ^1H NMR ($CDCl_3$, 250 MHz) δ 0.09 (s, 3 H), 0.10 (s, 3 H), 0.88 (s, 9 H), 3.23 (dd, 1 H, *J* = 6.2, 13.2 Hz), 3.38 (dd, 1 H, *J* = 5.0, 11.4 Hz), 3.72 (dd, 1 H, *J* = 6.3, 13.2 Hz), 3.82 (dd, 1 H, *J* = 7.4, 11.4 Hz), 4.78 (m, 1 H); ^{13}C NMR (CD_3COCD_3), δ −4.8, 18.5, 26.0, 45.7, 70.4, 78.9.

Trans isomer: ^1H NMR ($CDCl_3$, 250 MHz) δ 0.11 (s, 6 H), 0.87 (s, 9 H), 3.26 (dd, 1 H, *J* = 8.8, 12.6 Hz), 3.28 (dd, 1 H, *J* = 7.3, 10.4 Hz), 3.46 (dd, 1 H, *J* = 4.4, 12.6 Hz), 3.70 (dd, 1 H, *J* = 5.5, 10.4 Hz), 5.38 (m, 1 H); ^{13}C NMR (CD_3COCD_3) δ −4.8, 18.5, 26.0 43.4, 77.8.

Hydrolysis of a Mixture of 3, X = $OSiMe_2(t\text{-Bu})$, Y = H, and 3, X = H, Y = $OSiMe_2(t\text{-Bu})$. A mixture of **3**, X = $OSiMe_2(t\text{-Bu})$, Y = H, and **3**, X = H, Y = $OSiMe_2(t\text{-Bu})$ (31 mg, 0.12 mmol, 59:41 mixture), was dissolved in 1% hydrochloric acid in 95% ethanol (4 mL), and the solution was stirred overnight and analyzed periodically by TLC on silica gel eluting with a 1:1 solution of ethyl acetate/dichloromethane. After completion of the reaction (about 36 h), a small amount of solid sodium bicarbonate was added to neutralize the acid. The mixture was filtered, and the filtrate was concentrated under reduced pressure by using a rotary evaporator. The crude product was subjected to preparative TLC on silica gel eluting with a 1:1 solution of ethyl acetate/dichloromethane to obtain brugierol and isobrugierol (16 mg, 94% yield) in a ratio of 36:64 as determined by ^1H NMR analysis.

Controlled Potential Oxidation of 1, R = t-Bu, R′ = H, X,Y = OCH_2CH_2O. A sample of **1**, R = *t*-Bu, X,Y = OCH_2CH_2O (73 mg, 3.1 mmol), prepared by the procedure of Eliel and Juaristi,[17] was oxidized, according to the general procedure, at a potential maintained at +0.8 V. On workup **3**, X,Y = OCH_2CH_2O, was isolated (41 mg, 72%): IR (neat) 1035–1120 cm^{-1}; ^1H NMR ($CDCl_3$, 250 MHz) δ 3.49 (d, 1 H, *J* = 11.6 Hz), 3.50 (d, 1 H, *J* = 13.6 Hz), 3.60 (d, 1 H, *J* = 13.6 Hz), 3.90 (d, 1 H, *J* = 11.6 Hz), 4.05 (m, 2 H), 4.14 (m, 2 H); ^{13}C NMR ($CDCl_3$) δ 42.4, 65.3, 67.5 (×2); mass spectrum, *m/z* calcd for $C_5H_8O_3S_2$ 179.9915, found 179.9913.

Acknowledgment. We gratefully acknowledge support of this work by the U.S. Public Health Service, National Institutes of Health (Grant HL15104), the National Science Foundation (Grant INT-8312711), and Consejo Nacional de Ciencia y Tecnología. We also thank Professor A. Kato for supplying us with spectra of authentic brugierol and isobrugierol and authentic samples of their corresponding *N*-ethylcarbamates.

Registry No. **1** (R = R′ = X = Y = H), 505-23-7; **1** (R = Me, R′ = X = Y = H), 6007-26-7; **1** (R = *t*-Bu, R′ = X = Y = H), 6007-21-2; **1** (R = *t*-Bu, X = OH, R′ = Y = H), 14044-03-2; **1** (R = *t*-Bu, R′ = X = H, Y = OH), 14044-04-3; **1** (R = *t*-Bu, X = OMe, R′ = Y = H), 68449-87-6; **1** (R = *t*-Bu, R′ = X = H, Y = OTMS), 104574-99-4; **1** (R = *t*-Bu, R′ = Y = H, X = $OSiMe_2(t\text{-Bu})$), 104575-00-0; **1** (R = *t*-Bu, R′ = X = H, Y = $OSiMe_2(t\text{-Bu})$), 104575-01-1; **1** (R = *t*-Bu, R′ = H, X, Y = OCH_2CH_2O), 104575-02-2; **1** (R = Ph, R′ = X = Y = H), 5425-44-5; **1** (R = Ph, R′ = Me, X = Y = H), 6331-22-2; **1** (R = *p*-$MeOC_6H_4$, R′ = X = Y = H), 24588-72-5; **1** (R = *p*-$MeOC_6H_4$, X = OH, R′ = Y = H), 104574-96-1; **3** (X = Y = H), 79032-16-9; *cis*-**3** (X = OMe, Y = H), 104574-97-2; *trans*-**3** (X = H, Y = OMe), 104574-98-3; **3** (X, Y = OCH_2CH_2O), 104575-03-3; *cis*-**3** (X = $OSiMe_2(t\text{-Bu})$, Y = H), 104598-33-6; *trans*-**3** (X = H, Y = $OSiMe_2(t\text{-Bu})$), 104598-34-7; **5**, 18321-16-9; **6** (R = R′ = H), 16487-10-8; *cis*-**6** (R = Me, R′ = H), 60349-78-2; *trans*-**6** (R = H, R′ = Me), 60349-75-9; brugierol, 36437-85-1; isobrugierol, 36437-86-2; *p*-methoxybenzaldehyde, 123-11-5; brugierol *N*-ethylcarbamate, 75663-85-3; isobrugierol *N*-ethylcarbamate, 75655-76-4.

A New Synthesis of β-Keto Phosphonates and β-Keto Silanes

Paul Sampson, Gerald B. Hammond, and David F. Wiemer*†

Department of Chemistry, University of Iowa, Iowa City, Iowa 52242

Received December 30, 1985

A new preparation of β-keto phosphonates from α-bromo ketones, by reaction of dialkyl chlorophosphate electrophiles with the dilithiated derivative of the bromo ketone, is described. This umpolung approach is complementary to the classical Arbuzov synthesis in two important ways. It extends the range of possible ketone substrates, allowing use of secondary α-halo ketones or α-bromo ketones where the Arbuzov reaction often fails. It also extends the variety of phosphonates available, by allowing, for example, the direct preparation of bis(trifluoroethyl) phosphonates. These fluoroalkyl phosphonates are not readily available via the Arbuzov reaction, because tris(trifluoroethyl) phosphite is only weakly nucleophilic. From our efforts to employ (trialkylsiloxy)vinyl bromides and *n*-butyllithium to generate an intermediate vinyllithium reagent, in place of forming the lithium enolate and using *tert*-butyllithium, a facile migration of trialkylsilyl groups from oxygen to the α-carbon has been discovered. This has been exploited in the development of a new route from α-bromo ketones to α-trialkylsilyl ketones.

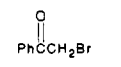
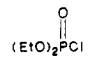
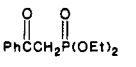
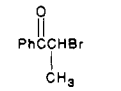
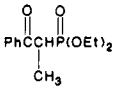
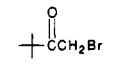
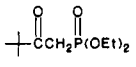
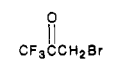
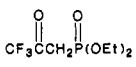
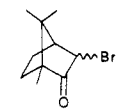
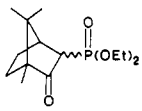
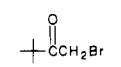
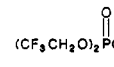
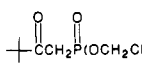
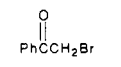
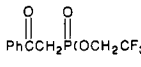
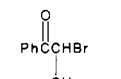
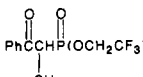
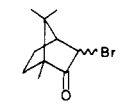
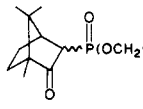
β-Keto phosphonates are often used for the preparation of α,β-unsaturated ketones via the Horner–Wadsworth–Emmons reaction,[1] and new variations on this reaction appear destined to further increase its usefulness.[2] Unfortunately, synthetic routes to β-keto phosphonates are rather limited. One common route, the acylation of alkyl phosphonate anions,[3] is restricted by the limited availa-

† Fellow of the Alfred P. Sloan Foundation, 1985–1987.

(1) Wadsworth, W. S., Jr.; Emmons, W. D. *J. Am. Chem. Soc.* **1961** *83*, 1733. Horner, L.; Hoffman, H.; Wippell, H. G.; Klahre, G. *Chem. Ber.* **1959**, *92*, 2499. Horner, L.; Hoffman, H.; Klink, W.; Ertel, H.; Toscano, V. G. *Chem. Ber.* **1962**, *95*, 581. Wadsworth, W. S., Jr. *Org. React. (N.Y.)* **1977**, *25*, 73.

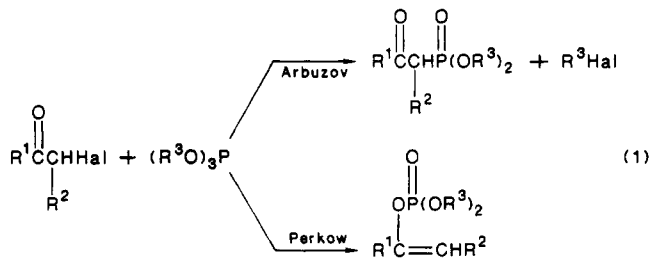
0022-3263/86/1951-4342$01.50/0 © 1986 American Chemical Society

Table I. Preparation of β-Keto Phosphonates

α-bromo ketone	dialkyl chlorophosphate	β-keto phosphonate	% yield[a]
		 **6**	74 (24)
		 **7**	72 (62)
		 **8**	48 (31)
		 **9**	54
		 **10**	31 (20)
		 **11**	79 (56)
		 **12**	47 (32)
		 **13**	59 (40)
		 **14**	0

[a] Yield by gas chromatography. (Isolated yield).

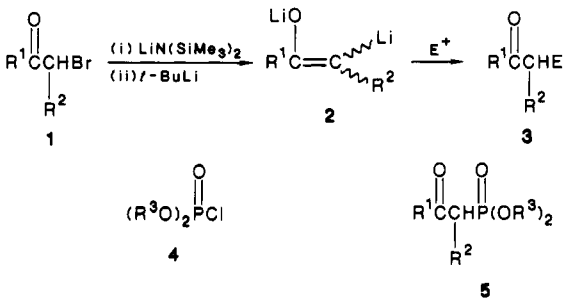
bility of alkyl phosphonates. Another classical synthesis is via the Arbuzov reaction,[4] which involves displacement of halide from an α-halo ketone by a trialkyl phosphite (eq 1). This reaction works best with primary α-iodo ketones



(1)

and nucleophilic trialkyl phosphites. Primary α-bromo or α-chloro ketones often undergo a competitive Perkow process to afford enol phosphates,[5] and substitution reactions are often difficult for secondary halides, limiting the usefulness of Arbuzov reactions with any secondary α-halo ketones.[6] Finally, the employment of weakly nucleophilic trialkyl phosphites is also problematic. For example, tris(2,2,2-trifluoroethyl) phosphite reacts with methyl iodide only when heated at 170 °C in a sealed tube.[7]

The range of problems associated with the Arbuzov approach to β-keto phosphonates became an annoyance for us when we required a series of β-keto phosphonates to study an extension of the Horner–Wadsworth–Emmons reaction to the synthesis of 3(2*H*)-furanones[8] and to explore an interesting rearrangement of γ-(acyloxy)-β-keto phosphonates.[9] Accordingly, we sought a new method for the preparation of β-keto phosphonates which could utilize electrophilic phosphorus reagents. Kowalski[10] has developed a convenient method for the conversion of α-bromo ketones **1** into dilithiated species, such as compound **2**, which may be viewed as both enolates and vinyllithium reagents. His investigations have shown that reaction of such species with a number of electrophiles (trimethylsilyl chloride, deuterium oxide,[10] and representative aldehydes and ketones[11]) occurs exclusively at carbon to produce α-substituted products **3**. By employing a phosphorus



electrophile (e.g., a dialkyl chlorophosphate, **4**), this approach might be expected to afford β-keto phosphonates **5**. Such an umpolung approach would reverse the problems of electron demand at phosphorus which are apparent in the Arbuzov reaction, making electron-deficient phosphorus moieties particularly reactive. The ready accessibility of α-bromo ketones makes this method appealing, while the change in mechanism should facilitate the conversion of secondary α-bromo ketones into the analogous β-keto phosphonates. Because of these apparent advantages, we decided to test this hypothesis with a series of model compounds.

Several vinyllithium reagents were generated by the method of Kowalski,[10] employing lithium hexamethyldisilazide to form the α-bromo enolate and then an excess of *tert*-butyllithium to invoke halogen–metal exchange. The resulting solution was cooled to ca. −110 °C, 1 equiv of the dialkyl chlorophosphate was added, and the product was isolated, after an aqueous ammonium chloride workup, by flash or radial chromatography. The use of very low reaction temperatures is important, for even at −78 °C the

(2) (a) Still, W. C.; Gennari, C. *Tetrahedron Lett.* **1983**, *24*, 4405. (b) Blanchette, M. A.; Choy, W.; Davis, J. T.; Essenfeld, A. P.; Masamune, S.; Roush, W. R.; Sakai, T. *Tetrahedron Lett.* **1984**, *25*, 2183.

(3) Aboujaoude, E. E.; Collignon, N.; Savignac, P. *J. Organomet. Chem.* **1984**, *264*, 9. Mikolajczyk, M.; Balczewski, P. *Synthesis* **1984**, 691. Honda, M.; Katsuki, T.; Yamaguchi, M. *Tetrahedron Lett.* **1984**, *25*, 3857. Coutrot, P.; Savignac, P.; Mathey, F. *Synthesis* **1978**, 36.

(4) Arbuzov, B. A. *Pure Appl. Chem.* **1964**, *9*, 307. Bhattacharya, A. K.; Thyagarajan, G. *Chem. Rev.* **1981**, *81*, 415.

(5) Perkow, W.; Ullerich, K.; Meyer, F. *Naturwissenschaften* **1952**, *39*, 353. Bianchini, J. P.; Gaydou, E. M. *C. R. Seances Acad. Sci., Ser. C* **1975**, *280*, 1521. Baroulare, M.; Sturtz, C. *Bull Soc. Chim. Fr.* **1974**, *7–8*, 1585. Gaydou, E. M.; Bianchini, J. P. *J. Chem. Soc., Chem. Commun.* **1975**, *14*, 541.

(6) Only a few secondary alkyl halides react satisfactorily, e.g. isopropyl iodide (Arbuzov, A. E.; Kamai, G. Kh.; Belorossova O. N. *J. Gen. Chem. USSR (Engl. Transl.)* **1945**, *15*, 766) and ethyl bromopropionate (Arbuzov, A. E.; Arbuzov, B. A. *J. Russ. Phys.-Chem. Soc.* **1929**, *61*, 1599). Generally, secondary and tertiary alkyl halides either fail to react or decompose to give olefins.

(7) Maslennikov, I. G.; Lavrent'ev, A. N.; Kuz'mina, N. Ya.; Kirichenko, L. N. *J. Gen. Chem. USSR (Engl. Transl.)* **1981**, *51*, 1329.

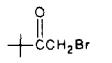
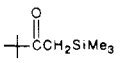
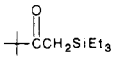
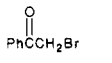
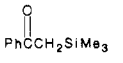
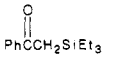
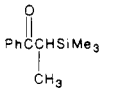
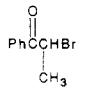
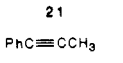
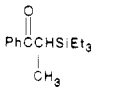
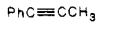
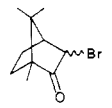
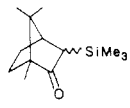
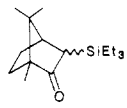
(8) Sampson, P.; Roussis, V.; Drtina, G. J.; Koerwitz, F. L.; Wiemer, D. F. *J. Org. Chem.* **1986**, *51*, 2525.

(9) Drtina, G. J.; Sampson, P.; Wiemer, D. F. *Tetrahedron Lett.* **1984**, *25*, 4467.

(10) Kowalski, C. J.; O'Dowd, M. L.; Burke, M. C.; Fields, K. W. *J. Am. Chem. Soc.* **1980**, *102*, 5411.

(11) Kowalski, C. J.; Fields, K. W. *J. Am. Chem. Soc.* **1982**, *104*, 1777.

Table II. Synthesis of α-Trialkylsilyl Ketones

α-bromo ketone	α-trialkylsilyl ketone	yield, %
	 **17**	68[a]
	 **18**	67[a]
	 **19**	51[a]
	 **20**	62[b]
	 **21**	6[c]
	 **22**	83[c]
	 **23**	8[c]
	 **22**	80[c]
	 **24**	80[a,d,e]
	 **25**	78[a,d,f]

[a] Isolated yield after distillation. [b] Isolated yield after flash chromatography. [c] Yields by gas chromatography. [d] Rearrangement occurs upon warming to room temperature. [e] Isolated as a 50:50 ratio of epimers. [f] Isolated as a 60:40 ratio of epimers.

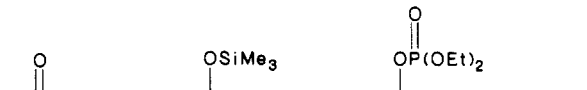
yields are significantly lower. The results of some of our experiments are shown in Table I. With diethyl chlorophosphate as the electrophile, only a modest yield of the β-keto phosphonate product was obtained from α-bromoacetophenone (entry 1). However, somewhat higher yields were obtained with α-bromopropiophenone (entry 2), yielding a β-keto phosphonate not readily available via the classical Arbuzov approach, and with α-bromopinacolone (entry 3). Under the same reaction conditions, α-bromocamphor gave only the corresponding enol phosphate, but by utilizing more forceful conditions for the halogen–metal exchange, the β-ketophosphonate **10** was obtained in low yield.

Still has recently reported using bis(trifluoroethyl) phosphonoesters[2a] for the stereoselective synthesis of *Z*-α,β-unsaturated esters, stimulating interest in bis(trifluoroethyl) phosphonates in general. A direct Arbuzov approach to such compounds is impractical due to the very low nucleophilicity of tris(trifluoroethyl) phosphite.[4] An approach analogous to that of Still would involve several steps, and, because it also requires an Arbuzov reaction, would be difficult with secondary α-halo ketones. However, employment of this umpolung methodology would appear highly suited to the facile construction of fluoroalkyl β-keto phosphonates.

Formation of the desired fluoroalkyl β-keto phosphonates was observed by following the same approach described above. After treatment of the α-bromo ketone with lithium hexamethyldisilazide and *tert*-butyllithium, 1 equiv of bis(trifluoroethyl) chlorophosphate[12] was added at ca. −110 °C, and the β-keto phosphonate product was isolated as previously described. The results are illustrated in Table I. In this series, the isolated yields are reasonable, considering that this approach provides a short and convenient method for the synthesis of bis(trifluoroethyl) phosphonates from α-bromo ketones.

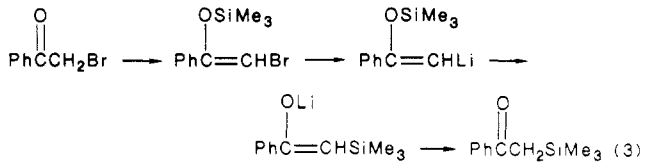
This methodology constitutes a direct and simple synthesis of keto phosphonates, but the use of *tert*-butyllithium will limit its use in the synthesis of more highly functionalized compounds. In an effort to avoid the need for *tert*-butyllithium, we considered a reaction sequence where a silyl enol ether was used in place of the initial lithium enolate. We assumed that the resulting siloxyvinyl bromide could then be converted to a vinyllithium reagent by treatment with *n*-butyllithium, if attack upon the bromine were more facile than attack upon the silicon center.

The observed reaction sequence is outlined in eq 2. When α-bromoacetophenone is treated with lithium hexamethyldisilazide at −78 °C, addition of 1 equiv of chlorotrimethylsilane and warming to room temperature results in formation of the expected (trimethylsiloxy)vinyl bromide **15** in situ. After cooling this solution to −78° C,



(2)

addition of 2 equiv of *n*-butyllithium results in halogen–metal exchange. However, our efforts to trap a vinyl anion by reaction with a phosphorus electrophile were thwarted by a rapid O to C silyl migration, resulting in the formation of the C-silylated enol phosphate **16**. While this compound was not of value for the synthesis of β-keto phosphonates, its formation did suggest a new route to α-trialkylsilyl ketones. After formation of the vinyllithium species and silyl migration, quenching the reaction with aqueous ammonium chloride gives α-trialkylsilyl ketones directly. The α-trialkylsilyl ketones can be isolated by distillation, or, with the more stable triethylsilyl (TES) compounds, by flash chromatography (see Table II).[13]



(3)

Despite the established utility of α-silyl ketones in organic synthesis, few general methods are available for their preparation.[15-18] The reaction of the dilithiated species

(12) Sellars, K. *J. Appl. Chem.* **1956**, *6*, 45.

(13) Caution should be observed when examining these reactions by GC, since thermal rearrangements of the α-silyl ketones to the corresponding silyl enol ethers can occur at typical injector port temperatures.[14a]

(14) (a) Colvin, E. *Silicon in Organic Synthesis*; Butterworths: London, 1981. (b) Colvin, E. *Chem. Soc. Rev.* **1978**, *7*, 15. (c) Fleming, I. *Chem. Soc. Rev.* **1981**, *10*, 83.

(15) For some alternative approaches to α-trialkylsilyl ketones, c.f.: Obayashi, M.; Utimoto, K.; Nozaki, H. *Bull. Chem. Soc. Jpn.* **1979**, *52*, 2646 and references cited therein. Fleming, I.; Pearce, A. *J. Chem. Soc., Perkin Trans. 1* **1981**, 251. Seitz, D. E.; Zapata, A. *Synthesis* **1981**, 557. Kuwajima, I.; Inoue, T.; Sato, T. *Tetrahedron Lett.* **1978**, 4887. Hauser, C. R.; Hance, C. R. *J. Am. Chem. Soc.* **1952**, *74*, 5091.

2 with chlorotrialkylsilanes does afford C-silylated products,[10] but this approach still requires the use of *tert*-butyllithium. It now appears that the readily available (trialkylsiloxy)vinyl bromides, such as compound **15**, can be used in a relatively simple synthesis of α-trialkylsilyl ketones.[19] The synthesis of α-trimethylsilyl and α-triethylsilyl ketones derived from primary α-bromo ketones proceeds in reasonably good isolated yield (Table II, entries 1–4). Low yields of the α-silyl ketones were obtained with α-bromopropiophenone (entries 5 and 6), because of a competing elimination which gives 1-propynylbenzene. However, with a secondary α-bromoketone where formation of the corresponding acetylene is not possible, the α-silyl ketones are produced in good yield (entries 7 and 8).

In conclusion, we have developed a new and potentially useful approach to the synthesis of β-keto phosphonates. In contrast to the widely used Arbuzov reaction, this umpolung method allows the successful employment of secondary α-halo ketones and electrophilic phosphorus reagents. Although in its present form this reaction sequence requires the use of *tert*-butyllithium, we are exploring other routes which do not rely upon this reactive species. Exploration of one such route, employing siloxyvinyl bromides, has resulted in a new and facile method for the preparation of at least primary and some secondary α-trialkylsilyl ketones from α-bromo ketones. Our studies of other potential routes will be reported in due course.

Experimental Section

Melting points were obtained on a Thomas-Hoover melting point apparatus, and are uncorrected. Flash column chromatography was done on Merck grade 60 silica gel (230–400 mesh), and radial chromatography was done with a Chromatotron apparatus using Merck PF254 silica gel with $CaSO_4 \cdot 0.5\ H_2O$. All experiments were conducted under an argon atmosphere. The IR spectra were recorded on an IBM Model 98 FT IR instrument. The ^1H NMR and broad-band decoupled ^{13}C NMR spectra were recorded on either a JEOL FX-90Q or a Brucker WM 360 spectrometer, using deuterochloroform as the solvent. The ^1H chemical shifts are reported in parts per million downfield from internal $(CH_3)_4Si$. The ^{13}C chemical shifts are reported in parts per million downfield from $(CH_3)_4Si$ but with the deuterochloroform resonance as the internal standard (77.0). Low-resolution mass spectra were recorded with a Hewlett-Packard 5985B instrument; only selected ions are reported here. Electron-impact (EI) spectra were obtained at 70 eV; ion abundances are reported as percentages of the most abundant ion. Chemical ionization (CI) spectra were obtained with methane as the reagent gas. High-resolution mass spectra were recorded on an AEI MS-902 instrument at Cornell University, Mass Spectrometry Laboratories, or on a Kratos MS-50 instrument at the Midwest Center for Mass Spectrometry. Microanalyses were conducted by Galbraith Laboratories, Knoxville, TN.

Diethyl (2-Phenyl-2-oxoethyl)phosphonate (6). General Procedure for the Preparation of Hydrocarbon Phosphonates. A solution of α-bromoacetophenone (0.51 g, 2.6 mmol) in anhydrous THF (5 mL) was added dropwise via syringe to a stirred solution of lithium hexamethyldisilazide (1.05 equiv), prepared in situ from hexamethyldisilazane (0.6 mL) and *n*-BuLi (1.7 mL, 1.55 M), in THF (5 mL) at −65 °C. After 45 min, the resulting enolate was treated with an excess of *t*-BuLi (8.5 mmol) introduced via a stainless steel *canula*. Stirring was continued for 20 min at −65 °C before removing the cold bath for 8–10 min. The resulting solution was then cooled to −110 °C (pentane–N_2) and treated with diethyl chlorophosphate (0.4 mL, 2.8 mmol). The mixture was stirred for 1 h at −100 °C and then allowed to warm up to −80 °C. After addition of saturated NH_4Cl, the aqueous layer was extracted with diethyl ether (20 mL), and the combined organic extracts were dried over $MgSO_4$. After concentration in vacuo, purification of the residue by radial chromatography (silica gel, 68.5% hexane, 29.5% EtOAc, 2% MeOH) furnished phosphonate **6** (0.16 g, 24%). NMR (^1H and ^{13}C), mass, and IR spectra were in agreement with the reported data.[20]

Diethyl (1-Methyl-2-phenyl-2-oxoethyl)phosphonate (7). 2-Bromopropiophenone (0.39 mL, 2.55 mmol) was allowed to react with lithium hexamethyldisilazide (1.05 equiv) in THF (10 mL), and the resulting enolate was treated with *t*-BuLi (9.2 mmol) and diethyl chlorophosphate (0.4 mL, 2.8 mmol) as described above. After standard workup and a final extraction with brine (25 mL), treatment with $MgSO_4$ and concentration yielded an oil (0.86 g). Purification by radial chromatography (silica gel; 73% EtOAc, 24.5% hexane, 2.5% MeOH) gave compound **7** as a colorless oil (0.43 g, 62%): ^1H NMR δ 8.01–7.45 (m, 5, Ar H's), 4.20–4.01 (m, 5, $RCHCH_3P(O)(OCH_2CH_3)_2$), 1.54 (dd, 3, $J = 7.0$ Hz, $J_{HP} = 18.0$ Hz, $RCHCH_3P(O)(OR')_2$), 1.24 (dt, 6, $J = 7.1$ Hz, $J_{HP} = 29.9$ Hz, $P(O)(OCH_2CH_3)_2$); GC/MS, *m/z* (relative intensity) 270 (M^+, 2.1) 225 (2), 165 (13), 137 (3), 132 (7), 115 (5), 109 (6), 105 (100), 91 (3), 81 (4), 77 (17); HR-MS: calcd for $C_{13}H_{19}O_4P$ 270.1022. Found, 270.1019.

Diethyl (3,3-Dimethyl-2-oxobutyl)phosphonate (8). A solution of α-bromopinacolone (0.70 mL, 5.2 mmol) in THF (20 mL) was treated sequentially with lithium hexamethyldisilazide (1.1 equiv), *t*-BuLi (17 mmol), and diethyl chlorophosphate (5.8 mmol) using the general procedure described above. The reaction mixture was allowed to warm to −30 °C and then quenched with NH_4Cl. The usual workup produced a yellow liquid, which after purification by distillation in vacuo gave compound **8** (0.38 g, 31%): bp 68–70 °C (0.1 mm) [lit. bp 97–100 °C (0.5 mm)[20]]; IR 1706 (C=O) cm^{-1}; ^1H NMR δ 4.22–4.11 (m, 4, $P(O)(OCH_2CH_3)_2$, 3.16 (d, 2, $J_{HP} = 21.8$ Hz, $RCH_2P(O)(OEt)_2$), 1.33 (t, 6, $J = 7.1$ Hz, $P(O)(OCH_2CH_3)_2$), 1.18 (s, 9, $(CH_3)_3C$); GC/MS, *m/z* (relative intensity) 237 ($M^+ + 1$, 1), 236 (M^+, 0.5), 179 (35), 152 (100), 125 (90), 109 (35), 97 (46), 81 (46), 57 (39), 41 (40). The β-keto phosphonate **8** was accompanied by diethyl *tert*-butylphosphonate, as established by comparisons with the literature data.[21]

Diethyl (3,3,3-Trifluoro-2-oxopropyl)phosphonate (9). A solution of 1-bromo-3,3,3-trifluoroacetone (0.55 mL, 5.3 mmol) in THF (20 mL) was treated sequentially with lithium hexamethyldisilazide (5.7 mmol) and by *t*-BuLi (17 mmol). The resulting amber solution was cooled to −100 °C before diethyl chlorophosphate (0.85 mL, 5.9 mmol) was added via syringe. The reaction mixture was kept at −100 °C for 30 min and then allowed to warm to −40 °C slowly. After quenching with NH_4Cl, the reaction mixture was worked up in the usual manner. The crude product (54% by GC) was filtered through silica gel under pressure (10% EtOAc, 90% hexane), yielding the desired phosphonate: IR 1717 (CO) cm^{-1}; ^{31}P NMR δ 28.93; GC/MS, *m/z* (relative intensity) 249 ($M^+ + 1$, 1) 248 (M^+, 1), 221 (12), 193 (27), 179 (49), 151 (29), 123 (100), 109 (31), 105 (40), 69 (16); HR MS calcd for $C_7H_{12}F_3O_4P$ 248.0425, found 248.0423.

3-(Diethoxyphosphinyl)camphor (10). α-Bromocamphor (1.19 g, 5.15 mmol) in THF (11 mL) was treated successively with lithium hexamethyldisilazide (1.1 equiv) in THF (9 mL), *t*-BuLi (3.5 equiv), and diethyl chlorophosphate (1.1 equiv) in a manner analogous to the general procedure. After normal workup, analysis by GC indicated substantial amounts of starting material (14%) plus camphor (42%). Purification by distillation in vacuo gave compound **10** (0.29 g, 20%): bp 103–105 °C (0.2 mm); ^1H NMR δ 4.07–4.32 (m, 4, $P(O)(OCH_2CH_3)_2$), 2.93 (dd, 1, $J = 5$ Hz, $J_{HP} = 13.5$ Hz), 1.34 (t, 6, $J = 7$ Hz, $P(O)(OCH_2CH_3)_2$), 1.00, 0.92 and 0.86 (each s, 3, CH_3's); GC/MS, *m/z* (relative intensity) 288 (M^+, 0.4), 178 (5), 163 (3), 152 (6), 135 (7), 123 (14), 109 (38), 83 (24),

(16) Kuwajima, I.; Takeda, R. *Tetrahedron Lett.* **1981**, *22*, 2381.
(17) Corey, E. J.; Rucker, C. *Tetrahedron Lett.* **1984**, *25*, 4345.
(18) Similar silyl migrations have been observed in aromatic systems, c.f.: Green, J. R.; Majewski, M.; Alo, B. I.; Snieckus, V. *Abstracts of Papers*, 187th National Meeting of the American Chemical Society, St. Louis, MO; American Chemical Society: Washington, DC, 1984; ORGN 184. Hengge, E.; Pletka, H. D. *Monatsh. Chem.* **1973**, *104*, 1071. Effenberger, F.; Habisch, D. *Synthesis* **1979**, 841 (especially p 852).
(19) Sampson, P.; Wiemer, D. F. *J. Chem Soc., Chem. Commun.* **1985**, 1746.
(20) Mathey, F.; Savignac, P. *Tetrahedron* **1978**, *34*, 649.
(21) Seyferth, D.; Marmor, R. S. *J. Organomet. Chem.* **1973**, *59*, 237.

81 (100), 55 (36). Anal. Calcd for $C_{14}H_{25}O_4P$: C, 58.32; H, 8.74. Found: C, 58.17; H, 8.97.

Bis(2,2,2-trifluoroethyl) (3,3-Dimethyl-2-oxobutyl)-phosphonate (11). General Procedure for the Preparation of Trifluoroethyl Phosphonates. α-Bromopinacolone (0.35 mL, 2.63 mmol) was added via syringe to a solution of lithium hexamethyldisilazide, prepared in situ by adding *n*-BuLi (2.8 mmol) to a cooled (−60 °C) solution of hexamethyldisilazane (0.6 mL, 2.85 mmol) in anhydrous THF (10 mL). The resulting solution was stirred for 40 min, and then *t*-BuLi (9.20 mmol) was introduced via a stainless steel *canula*. After being stirred an additional 30 min at −60 °C, the solution was allowed to warm to room temperature to ensure complete metalation and then cooled to −110 °C. Bis(2,2,2-trifluoroethyl) chlorophosphate[12] (0.5 mL, 3.0 mmol) was added, and the reaction mixture was allowed to warm up to −40 °C over a period of 60 min. After the mixture was quenched with saturated NH_4Cl, the layers were separated, the aqueous one was extracted with diethyl ether (25 mL), and the combined organic layers were washed with brine (25 mL). After drying ($MgSO_4$) and concentration in vacuo, the phosphonate **11** was obtained as an orange oil (0.51 g, 56%). An aliquot was further purified by radial chromatography (silica gel; 64% hexane, 35% EtOAc, 1% MeOH): IR 1706 (C=O) cm^{-1}; ^1H NMR δ 4.51–4.42 (m, 4, $P(O)(OCH_2CF_3)_2$, 3.37 (d, J_{HP} = 20.5 Hz, $C(O)CH_2P(O)(OR)_2$, 1.18 (s, 9, $(CH_3)_3CC(O)$); GC/MS, *m/z* (relative intensity) 344 (M^+, 0.9), 263 (38), 243 (3), 165 (9), 82 (74), 67 (100), 57 (9), 55 (16), 41 (24); HR MS, calcd for $C_{10}H_{15}F_6O_4P$ 344.0612, found 344.0609.

Bis(2,2,2-trifluoroethyl) (2-Phenyl-2-oxoethyl)-phosphonate (12). A solution of bromoacetophenone (0.18 g, 0.89 mmol) in diethyl ether (4.8 mL) was transferred via syringe into a reaction vessel containing 1.05 equiv of lithium hexamethyldisilazide, prepared in situ at −65 °C by adding *n*-BuLi (0.93 mmol) to a solution of hexamethyldisilazane (0.20 mL, 0.95 mmol) in diethyl ether (3.5 mL). After 40 min at −65 °C, *t*-BuLi (2.72 mmol) was added to the reaction mixture, resulting in formation of an intense yellow color. Stirring was continued for 30 min at the same temperature and for 7–10 min after removal of the cold bath to allow complete metalation. The mixture was then cooled to −110 °C, and bis(2,2,2-trifluoroethyl) chlorophosphate (1.17 mmol) was added quickly via syringe. The reaction mixture was allowed to warm to −75 °C over the course of 1 h, before it was quenched by addition of saturated NH_4Cl. After separating the organic and aqueous layers, the aqueous one was extracted with diethyl ether (25 mL). The organic extracts were combined, washed once with brine (15 mL), dried over $MgSO_4$, and concentrated in vacuo. The resulting oil (47% yield by GC) was further purified by radial chromatography (silica gel; 67% hexane, 33% EtOAc): 0.10 g (32%); ^1H NMR δ 7.98–7.57 (m, 5, Ar H's), 4.49 (t, 4, J_{HF} = 8.0 Hz, OCH_2CF_3), 3.84 (d, 2, J_{HP} = 21.1 Hz, $CH_2P(O)(OR)_2$); GC/MS, *m/z* (relative intensity) 364 (M^+, 0.2), 265 (0.4), 163 (2), 143 (2), 127 (3), 105 (94), 91 (15), 77 (100), 69 (12), 51 (35); HR MS, calcd for $C_{12}H_{11}F_6O_4P$ 364.0299, found, 364.0299.

Bis(2,2,2-trifluoroethyl) (1-Methyl-2-phenyl-2-oxoethyl)-phosphonate (13). α-Bromopropiophenone (0.4 mL, 2.63 mmol) was treated first with lithium hexamethyldisilazide (2.8 mmol) in THF (10 mL) and then with *t*-BuLi (9.20 mmol) according to the general procedure. After 25 min at −60 °C and 8 min at room temperature, the deep green solution was cooled to −110 °C. Bis(2,2,2-trifluoroethyl) chlorophosphate (1.11 g, 3.95 mmol) was added via syringe, resulting in immediate formation of an orange color, and the solution was stirred for 30 min. After warming slowly to ca. −50 °C, the reaction was quenched by addition of saturated NH_4Cl and the resulting layers were separated. The aqueous layer was extracted with diethyl ether (20 mL), the combined organic phases were washed with brine (25 mL), dried ($MgSO_4$), and concentrated in vacuo. When GC/MS analysis of the crude product indicated a mixture of mono- and diphosphonated material (59% by GC), an aliquot (0.17 g) was converted to the monophosphonate by treatment (48 h at 40 °C) with trifluoroethanol (2.5 mL) and a catalytic amount of hydrochloric acid (3 M) in THF (9 mL). After concentration at reduced pressure, the residue was partitioned between diethyl ether and water, and the ethereal layer was dried and concentrated. Final purification by radial chromatography (silica gel, 80% hexane, 20% EtOAc) afforded the desired monophosphonate **13** (33 mg, 40% yield): IR 1685 (C=O) cm^{-1}; ^1H NMR δ 7.55–7.30 (m, 5, Ar H's), 4.40–4.15 (m, 5, $RCOCHCH_3P(O)(OCH_2CF_3)_2$), 1.79–1.76 (m, 3, $RCOCHCH_3P(O)(OR')_2$); GC/MS, *m/z* (relative intensity) 378 (M^+, 1.5), 263 (3), 117 (24), 116 (90), 115 (100), 105 (8), 91 (4), 83 (5), 77 (11), 51 (4); HR MS calcd for $C_{13}H_{13}F_6O_4P$ 378.0456, found 378.0454.

Attempted Preparation of 3-[Bis(2,2,2-trifluoroethoxy)-phosphinyl]camphor (14). 3-Bromocamphor (0.48 g, 2.05 mmol) in THF (4.5 mL) was treated successively with lithium hexamethyldisilazide (1.1 equiv) in THF (4.5 mL), *t*-BuLi (3.5 equiv) and bis(2,2,2-trifluoroethyl) chlorophosphate (1 equiv) in a manner analogous to the general procedure described above. Normal workup produced an orange liquid (1.2 g) shown by GC to consist of camphor, starting material, and a new product. The latter was separated by radial chromatography (silica gel, 85% petroleum ether, 15% EtOAc) and found to be the enol phosphate of camphor (32% based on consumed starting material): ^1H NMR δ 5.38 (d, 1, *J* = 2.8 Hz, olefin H), 4.46–4.36 (m, 4, $P(O)(OCH_2CF_3)_2$), 2.36 (t, 1, *J* = 3.6 Hz, CH), 1.92–1.09 (m, 4, CH_2), 0.98 (s, 3, CH_3), 0.90 (s, 3, CH_3), 0.77 (s, 3, CH_3); GC/MS, *m/z* (relative intensity) 396 (M^+, 2), 368 (2), 263 (1), 163 (7), 134 (24), 119 (100), 106 (97), 91 (99), 83 (32), 77 (38); HR MS calcd for $C_{14}H_{19}F_6O_4P$ 396.0925, found 396.0920.

Preparation of the *C*-Silyl *O*-Phosphate 16. To a solution of lithium hexamethyldisilazide (1.45 mmol) in anhydrous THF (2 mL) at −78 °C was added a solution of α-bromoacetophenone (278 mg, 1.40 mmol) in THF (6 mL). After stirring for 15 min, chlorotrimethylsilane (0.18 mL, 1.40 mmol) was added, and the pale yellow solution was allowed to warm to room temperature. After being stirred for 1.5 h, the solution was cooled to −78 °C, and *n*-BuLi (2.9 mmol) was added. The resulting orange solution was stirred for 10 min, and then diethyl chlorophosphate (0.41 mL, 2.8 mmol) was added slowly. After the mixture was allowed to warm to room temperature and was stirred for 1 h, 2 M HCl (10 mL) was added and the solution partitioned between ether (30 mL) and water (30 mL). The aqueous layer was extracted with ether (10 mL) and the combined ethereal layers were washed with water (25 mL) and brine (25 mL) and dried ($MgSO_4$). Concentration in vacuo gave an orange oil (429 mg) which was purified by flash chromatography (35% EtOAc, 65% hexane) to afford the *O*-phosphate *C*-silane **16** as a colorless oil (256 mg, 55%): ^1H NMR δ 7.5–7.2 (m, 5, Ar H's), 5.38 (s, 1, olefinic H), 3.97 (q, 4, $P(O)(OCH_2CH_3)_2$), 1.12 (m, 6, $P(O)(OCH_2CH_3)_2$), 0.18 (s, 9, $Si(CH_3)_3$); ^{31}P NMR δ −6.91; MS, *m/z* (relative intensity) 313 (M^+ − 15, 5), 241 (4), 211 (49), 183 (24), 174 (4), 159 (24), 155 (100), 77 (12). Anal. Calcd for $C_{15}H_{25}O_4PSi$: C, 53.88; H, 7.54. Found: C, 53.93; H, 7.22.

General Procedure for the Preparation of α-Trialkylsilyl Ketones from α-Bromo Ketones. α-(Trimethylsilyl)pinacolone (17). A solution of α-bromopinacolone (0.69 mL, 5.13 mmol) in anhydrous THF (10 mL) was added dropwise to a THF solution of lithium hexamethyldisilazide (generated at 78 °C from hexamethyldisilazane (1.16 mL, 5.5 mmol) and *n*-BuLi (5.27 mmol) in THF (10 mL)) at −78 °C and under nitrogen. The yellow solution was stirred for 30 min and then chlorotrimethylsilane (0.66 mL, 5.13 mmol, 1 equiv) was added in one portion. After being stirred for 5 min the solution was allowed to warm to room temperature. After 30 min at room temperature, the solution was recooled to −78 °C, and *n*-butyllithium (7.3 mL of 1.55 M solution in hexanes, 11.7 mmol) was added over 1 min. The orange/red solution was stirred at −78 °C for 30 min, allowed to warm to room temperature, and then quenched with saturated aqueous NH_4Cl (50 mL). Ether (50 mL) was added, the layers were separated, the aqueous layer was extracted with ether (2 × 20 mL), and the combined organic layers were washed with water (30 mL) and brine (30 mL) and dried (Na_2SO_4) overnight. Concentration in vacuo was followed by distillation to obtain the analytically pure product (0.59 g, 68%): bp 55 °C (8 mm); ^1H NMR δ 2.16 (s, 2, CH_2), 1.07 (s, 9, $(CH_3)_3$), 0.06 (s, 9, $(CH_3)_3Si$); MS, *m/z* (relative intensity) 172 (M^+, 2), 157 (16), 141 (0.4), 117 (4), 116 (12), 115 (100), 99 (2), 75 (36), 73 (79), 57 (3); HR MS calcd for $C_9H_{20}OSi$ 172.1284, found 172.1281.

α-(Triethylsilyl)pinacolone (18). The triethylsilyl ketone was prepared by a sequence analogous to that described above for the trimethylsilyl compound, using chlorotriethylsilane (0.86

mL, 5.13 mmol). Workup in the usual manner and vacuum distillation gave compound **18** (0.72 g 67%): ^{1}H NMR δ 2.16 (s, 2, CH_2), 1.12 (s, 9, $(CH_3)_3$), 1.08–0.75 (m, 9, $(CH_3CH_2)_3Si$)), 0.65 (m, 6, $(CH_3CH_2)_3Si$)); GC MS, *m/z* (relative intensity) 199 ($M^+ - CH_3$, 1), 186 (9), 185 (55), 171 (2), 157 (80), 115 (100), 103 (79), 87 (38), 75 (43), 59 (13); HR MS calcd for $C_{10}H_{21}OSi$ ($M^+ - C_2H_5$) 185.1362, found 185.1364.

α-(Trimethylsilyl)acetophenone (19).[10] Treatment of α-bromoacetophenone (1.02 g, 5.13 mmol) with lithium hexamethyldisilazide, chlorotrimethylsilane, and *n*-BuLi as described above gave, after standard workup and vacuum distillation, the expected trimethylsilyl ketone (0.50 g, 51%): bp 47–50 °C (0.15 mm); ^{1}H NMR δ 8.0–7.6 (m, 2, Ar H's), 7.5–7.2 (m, 3, Ar H's), 2.73 (s, 2, CH_2), 0.07 (s, 9, $(CH_3)_3Si$); GC/MS, *m/z* (relative intensity) 192 (M^+, 25), 191 (75), 178 (16), 177 (100), 135 (54), 105 (13), 103 (13), 77 (28), 75 (76), 73 (23).

α-(Triethylsilyl)acetophenone (20). Treatment of α-bromoacetophenone (1.02 g, 5.13 mmol) with base, chlorotriethylsilane (0.86 mL, 5.13 mmol), and *n*-BuLi as described above gave the crude product. Purification by flash chromatography gave pure compound **20** (0.75 g, 62%): ^{1}H NMR δ 7.9–7.6 (m, 2, Ar H's), 7.45–7.15 (m, 3, Ar H's), 2.72 (s, 2, CH_2), 1.10–0.75 (m, 9, $(CH_3CH_2)_3Si$)), 0.61 (m, 6, $(CH_3CH_2)_3Si$)); GC/MS, *m/z* (relative intensity) 234 (M^+, 0.7), 219 (3), 206 (19), 205 (100), 177 (5), 163 (10), 135 (19), 103 (40), 77 (14), 75 (39); HR MS calcd for $C_{12}H_{17}$)OSi ($M^+ - C_2H_5$), 205.1049, found 205.1053.

Attempted Preparation of α-(Trialkylsilyl)propiophenones. The general procedure described above was applied to α-bromopropiophenone (0.78 mL, 5.10 mmol), first using chlorotrimethylsilane (0.66 mL, 5.13 mmol). After workup in the usual manner, concentration in vacuo afforded an orange oil, which was shown by GC and GC/MS to contain 1-phenylpropyne [80–83%; GC/MS, *m/z* (relative intensity) 116 (M^+, 68), 115 (100), 103 (8), 89 (7), 75 (7), 63 (6), 57 (3), 51 (2), 45 (2)] and only a trace of the desired α-(trimethylsilyl)propiophenone **21** [6–8% by GC; GC/MS, *m/z* (relative intensity) 206 (M^+, 24), 205 (71), 191 (23), 177 (44), 135 (24), 117 (30), 105 (28), 77 (27), 75 (100), 73 (63)]. With α-bromopropiophenone and chlorotriethylsilane (0.86 mL, 5.13 mmol), the analogous procedure gave primarily 1-phenylpropyne (80% by GC analysis) and only a trace of the triethylsilyl ketone **23** [(8% by GC; GC/MS, *m/z* (relative intensity) 248 (M^+, 4), 220 (5), 219 (23), 186 (20), 171 (7), 143 (34), 129 (100), 115 (29), 91 (18), 77 (7)].

Preparation of α-(Trialkylsilyl)camphors. Utilization of the general procedure given above resulted in formation of the isomeric silyl enol ether products. However, if, after addition of *n*-butyllithium to the siloxyvinyl bromide intermediate, the orange solution was stirred at room temperature for 24 h, employment of the same workup and purification conditions afforded good yields of the desired α-(trialkylsilyl)camphors as mixtures of exo and endo isomers.

α-(Trimethylsilyl)camphor (24).[10] The epimeric trimethylsilyl ketones were purified by distillation but could not be readily separated from each other: yield, 0.92 g (80%); bp 48–50 °C (0.25 mm); ^{1}H NMR (as a 1:1 mixture of epimers) δ 2.04 (d, 1)/2.00 (m, 1), 1.91 (m, 1)/1.79 (m, 1), 1.63–1.15 (m, 4), 0.84, 0.80, 0.76, 0.75, 0.73, 0.67 (all s, 3 each, CH_3's); ^{13}C NMR (as a 1:1 mixture of epimers) δ 219.0/218.6 (C-2), 57.8/57.2 (C-1), 48.3/45.9/44.7 (C-3, C-4, and C-7), 30.8/30.1/29.4/24.7 (C-5 and C-6), 20.8/19.8/19.2/18.9 (C-9 and C-10), 9.3/9.0 (C-8), −0.4/−1.3 ($Si(CH_3)_3$); GC/MS, [longer GC retention time epimer] *m/z* (relative intensity) 209 ($M^+ - CH_3$, 30), 196 (100), 195 (8), 165 (17), 154 (14), 123 (11), 108 (14), 95 (73), 73 (88), [shorter GC retention time epimer] 224 (M^+, 11), 209 (39), 197 (18), 196 (66), 181 (44), 165 (25), 119 (19), 108 (57), 95 (72), 73 (100).[10]

α-(Triethylsilyl)camphor (25). The epimeric triethylsilyl ketones were obtained in good yield (1.07 g, 78% from a 5-mmol scale reaction) and were separated by flash chromatography. Major epimer (longer retention time): ^{1}H NMR δ 2.14 (d, 1, J = 3.6 Hz), 2.02 (m, 1), 1.66–1.16 (m, 4), 0.92 (t, 9, J = 7.8 Hz, $(CH_3CH_2)_3Si$)), 0.87 (s, 3, CH_3), 0.84 (s, 3, CH_3), 0.75 (s, 3, CH_3), 0.61 (m, 6, $(CH_3CH_2)_3Si$)); ^{13}C NMR δ 219.9 (C-2), 57.6 (C-1), 46.1 (C-3, C-4, and C-8), 31.3 (C-5 or C-6), 30.5 (C-6 or C-5), 21.0 (C-9 or C-10), 20.2 (C-10 or C-9), 9.4 (C-8), 7.4 ($Si(CH_2CH_3)_3$), 4.3 ($Si(CH_2CH_3)_3$); GC/MS, *m/z* (relative intensity) 251 ($M^+ - CH_3$, 16), 239 (27), 238 (100), 237 (97), 223 (32), 135 (23), 115 (50), 103 (98), 87 (91), 75 (44). Anal. Calcd for $C_{16}H_{30}OSi$, C, 72.11; H, 11.35. Found, C, 71.82; H, 11.49. Minor epimer (shorter GC retention time): ^{1}H NMR δ 2.09 (m, 1), 1.91 (m, 1), 1.72–1.23 (m, 4), 0.98 (t, 9, J = 7.9 Hz, $(CH_3CH_2)_3Si$)), 0.95 (s, 3, CH_3), 0.87 (s, 3, CH_3), 0.83 (s, 3, CH_3), 0.68 (m, 6, $(CH_3CH_2)_3Si$)); ^{13}C NMR δ 220.3 (C-2), 58.3 (C-1), 49.0/46.4/42.5 (C-3, C-4, and C-7), 29.7 (C-5 or C-6), 25.7 (C-6 or C-5), 19.6 (C-9 or C-10), 19.3 (C-10 or C-9), 9.6 (C-8), 7.5 ($Si(CH_2CH_3)_3$), 4.1 ($Si(CH_2CH_3)_3$); GC/MS, *m/z* (relative intensity) 238 ($M^+ - C_2H_4$, 42), 237 (100), 223 (19), 135 (18), 115 (29), 103 (88), 87 (56), 75 (33), 59 (36).

Acknowledgment. We thank the Alfred P. Sloan Foundation and the National Institutes of Health (CA-33743) for their financial support.

Registry No. **6**, 3453-00-7; **7**, 10409-56-0; **8**, 814-16-4; **9**, 85234-36-2; **10**, 104464-23-5; **11**, 104464-24-6; **12**, 104487-43-6; **13**, 104464-25-7; **14**, 104464-26-8; **16**, 104464-28-0; **17**, 103230-42-8; **18**, 103230-43-9; **19**, 13735-78-9; **20**, 17718-97-7; **21**, 88257-40-3; **22**, 673-32-5; **23**, 103230-44-0; **24**, 104464-29-1; **25**, 104464-30-4; $PhCOCH_2Br$, 70-11-1; $PhCOCH(CH_3)Br$, 2114-00-3; $(CH_3)_3CCOCH_2Br$, 5469-26-1; CF_3COCH_2Br, 431-35-6; $(EtO)_2POCl$, 814-49-3; $(CF_3CH_2O)_2POCl$, 381-44-2; 3-bromocamphor, 76-29-9; camphor, 76-22-2; chlorotrimethylsilane, 75-77-4; chlorotriethylsilane, 994-30-9; camphor (trifluoroethyl enol phosphate), 104464-27-9.

Quassinoids. 2. A New Approach to the BCD Ring System

Robert V. Stevens,† Steven R. Angle, Ken Kloc,* Kok F. Mak, Kenneth N. Trueblood, and You-Xi Liu

Department of Chemistry and Biochemistry, University of California, Los Angeles, California 90024

Received September 23, 1985

Diels-Alder reaction of 2,6-disubstituted quinones **4** and simple dienes **5** furnished cis adducts **3** in good yields. Basic isomerization provided the *trans*-decalins **11** which were converted into the lactones **2** which are models of the BCD ring system of quassinoids.

Quassinoids are a group of related compounds isolated from plants and trees belonging to the Simaroubacae family.[1] A broad range of biological activity including antileukemic, antineoplastic, insecticidal, and antifeedant properties has led to a keen interest in these compounds and numerous accounts of synthetic efforts have been documented.[2] We have previously proposed[2a] synthetic

†Deceased March 9, 1984. Address all correspondence to Dr. Michael E. Jung, Department of Chemistry and Biochemistry, University of California, Los Angeles, CA 90024.

(1) Polonsky, J. *Fortschr. Chem. Org. Naturst.* **1973**, *30*, 101.

0022-3263/86/1951-4347$01.50/0 © 1986 American Chemical Society