Phosphonamide Stabilized Allylic Carbanions. New Homoenolate Anion Equivalents

David A. Evans,* James M. Takacs, and Kenneth M. Hurst

Contribution No. 5815 from the Laboratories of Chemistry, California Institute of Technology, Pasadena, California 91125. *Received June 23, 1978*

Abstract: The chemistry of phosphonamide stabilized allylic carbanions derived from the 1,2-addition of tervalent phosphorus siloxanes with α,β-unsaturated aldehydes has been studied. An in situ synthesis of allylic α-silyloxyphosphonamides, followed by metalation and regioselective γ-alkylation of the allylic carbanion, yields a versatile "active ester". Transesterification under mild conditions gives esters and lactones and defines a new homoenolate equivalency.

Introduction

Over the last few years intense activity has been directed toward the development of "reversed polarity" equivalents such as carbonyl[1,2] and homoenolate anion synthons.[3,4] In con-

1 2

junction with such objectives we have engaged in a detailed study of the carbonyl addition reactions of organosilanes R'_3SiA (eq 1, 2) where A is a suitable carbanion-stabilizing

(1)

3

(2)

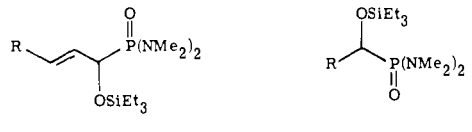
4

function such as $-C{\equiv}N$,[5] $-P(=O)R_2$,[6] or $-SR$.[7] Metalation of such carbonyl adducts should provide carbanions which might serve as practical equivalents to both carbonyl and homoenolate anions **1** and **2**. Reversed polarity equivalents derived from the adduct **4** serve to illustrate the synthetic capabilities of such carbanions (Scheme I). The α and γ reactivity modes of **5** with electrophiles lead to either adducts **6** or **9**, respectively. Carbonyl unmasking and polar disconnection afford an equivalency between carbanion **5** and synthons **8** or **11**. In the present illustration, the regiochemistry of the electrophilic substitution defines the specific equivalency.

The arbitrary criteria which we have applied in the selection of suitable organosilanes, R'_3SiA, for this study were as follows: (1) Carbonyl addition (eq 1, 2) should proceed readily under neutral conditions (Et_2O, THF) so that in situ metalation could be effected. (2) The choice of activating function, A, should provide sufficient activation for subsequent metalation. (3) Carbonyl unmasking (cf. **6** → **7**, **9** → **10**) should be possible under mild conditions.

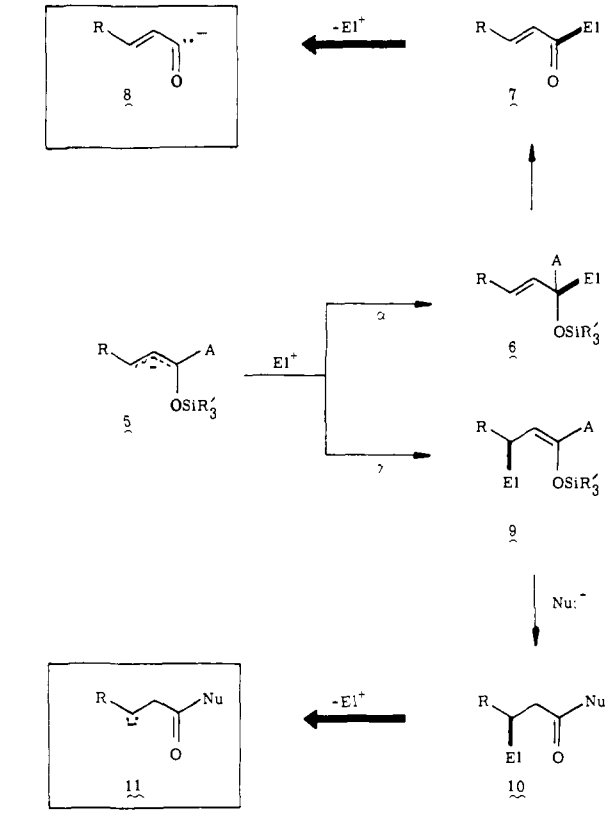
We have found that the phosphorodiamidite **12** satisfies

12



13 14

Scheme I



nearly all of our predefined criteria. This reagent demonstrates exceptional reactivity toward both unsaturated and saturated aldehydes. These reactions may be carried out in ethereal solvents (0–25 °C) in high yield (90–95%) to give adducts **13** and **14**.[6a,b] In most cases, in situ metalation of these adducts is readily accomplished with alkyllithium bases. The selection of the appropriate trialkylsilyl ligands was found to be critical to the present study. It is well known that trialkylsilyl groups have a propensity to participate in anionic sigmatropic rearrangements.[8] We have found that such difficulties are inherent in the design of silicon-substituted carbanions. However, since such rearrangements appear to be subject to steric constraints at silicon, these abortive reactions can be effectively suppressed. The following example serves to illustrate this point. Both allylic phosphonates **15a** and **15b**[6a] were readily metalated at −65 °C (*n*-BuLi, THF). However, whereas **16a** was stable for at least 30 min at these temperatures, **16b** rearranged within 5 min to an equilibrium mixture of **16b** and **17** ($k_{eq} \simeq 13$).[9]

The requisite α-silyloxyphosphonamides employed in the present study are shown in Table I. The preparation of

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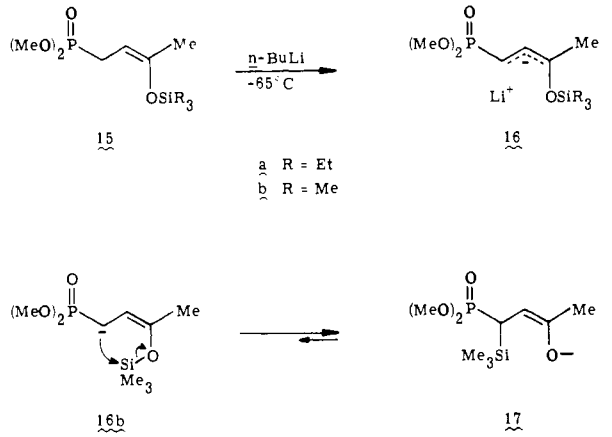
Table I. α-Silyloxy Phosphonamide Substrates[a]

Adduct		Yield, %
PhCH=CHCH(OSiEt$_3$)P(NMe$_2$)$_2$	13a	93
CH$_3$CH=CHCH(OSiEt$_3$)P(NMe$_2$)$_2$	13b	95
CH$_2$=CHCH(OSiEt$_3$)P(NMe$_2$)$_2$	13c	90
PhCH(OSiEt$_3$)P(NMe$_2$)$_2$	14a	92
(CH$_3$)$_2$CHCH(OSiEt$_3$)P(NMe$_2$)$_2$	14b	90

[a] See ref 6a for experimental details.

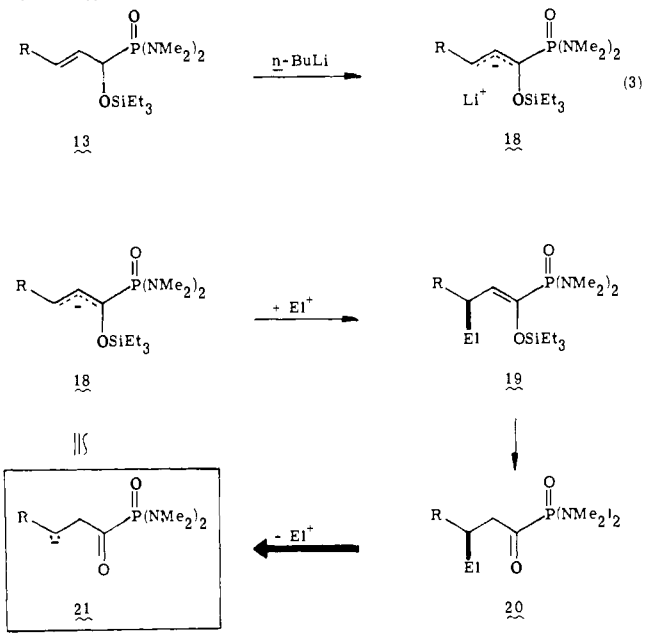
triethylsilyl *N,N,N'N'*-tetramethylphosphorodiamidite (**12**) as well as adducts **13** and **14** have been described by us in detail elsewhere.[6a]



Discussion

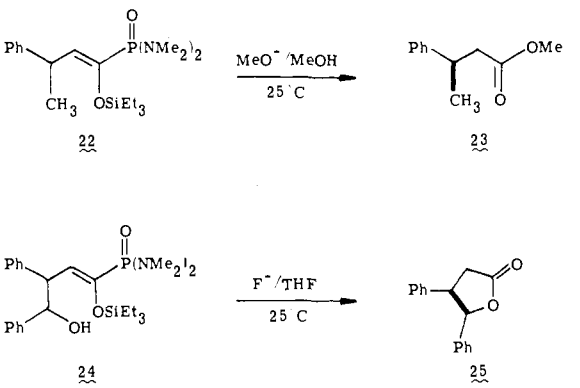
Homoenolate Anion Equivalents. With a simple in situ synthesis of α-silyloxyphosphonamides **13** in hand, it was anticipated that the derived allylic carbanions could be induced to undergo regioselective electrophilic substitution. The γ adducts **19,** upon desilylation, should reveal the acyl phosphonamide **20,** which is a highly versatile "active ester" useful in the subsequent construction of esters and amides (Scheme II). The illustrated γ-reactivity mode defines the equivalency between **18** and the homoenolate synthon **21.** The α-silyloxyphosphonamides **13a–c,** prepared in situ from 1 equiv each of aldehyde and **12** in either ether or THF, were cooled to −78 °C and treated with 1–1.2 equiv of *n*-butyllithium (hexane). Within 5 min complete metalation had occurred (eq 3). Upon quenching **18a** with methyl iodide or benzaldehyde, the γ-alkylated enol phosphonamides **22** and **24** were obtained as the exclusive products. Careful analysis of the crude reaction mixtures in each instance afforded no indication of the presence of any α-alkylation products. Without purification, treatment of the enol phosphonamide **22** with methanolic sodium methoxide (25 °C, 1 h) gave the methyl ester **23** in an overall yield of 75% based upon cinnamaldehyde. Under suitable conditions for lactone formation, enol phosphonamide **24** was treated with tetra-*n*-butylammonium fluoride[10] in THF (25 °C, 4 h) to give

Scheme II



a, R = Ph; b, R = CH$_3$; c, R = H

the butyrolactone **25** as an 85:15 mixture of diastereoisomers in 71% yield (based upon cinnamaldehyde). It is assumed that,



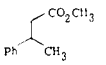
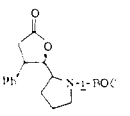
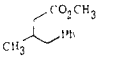
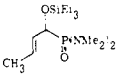
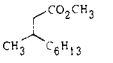
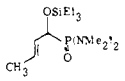
in both of the above esterification reactions, α-acyl phosphonamides (cf. **20,** Scheme II) are intermediates. The generality of the above transformations is affirmed by the representative examples in Table II. Except where noted, the α,β-unsaturated aldehydes were transformed without purification to either ester or lactone products according to the general bond construction shown below (eq 4). In contrast to the phosphonamide-derived

a, 12; b, n-BuLi; c, El$^+$; d, R′O$^\ominus$

carbanion **18c,** the other allylic carbanions (**18a** and **18b**) exhibited good low-temperature stability. Carbanion **18c** is apparently only marginally stable at −78 °C. The yields of carbonyl addition and alkylation in this instance (entries 9, 10) were based upon the electrophile used. Thus, this methodology seems of limited applicability in the acrolein case.

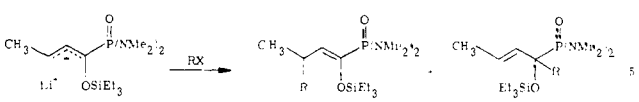
During the course of these studies we encountered *one* instance where only modest regioselectivity was observed in allylic carbanion alkylation. At −78 °C the alkylation of **18b** with methyl iodide in THF revealed for the first time a significant amount of α-alkylation (**26γ:26α** = 70:30). This

Table II. General Synthesis of Esters and Lactones from α,β-Unsaturated Aldehydes (eq 4)

Entry	Substrate[a]	Electrophile	Product	Yield, %
1		CH_3I		75
2		PhCHO		71[b]
3		i-PrCHO		65[b]
4				63
5				66
6		$PhCH_2Cl$		50
7		$C_6H_{13}Br$		59
8		PhCHO		67[d, e]
9		PhCHO		55[e, f, g]
10		$C_6H_{13}Br$	$C_8H_{17}CO_2CH_3$	22[e, f, g]

[a] All reactions run in THF unless otherwise noted. [b] 85:15 mixture of diastereoisomers. [c] 60:40 mixture of diastereoisomers. [d] 65:35 cis:trans mixture of diastereoisomers. [e] Reaction run in ether. [f] Two equivalents of acrolein adduct used. [g] Anion unstable.

system was chosen to examine the effects of solvent and temperature on the ratio of **26**γ:**26**α (R = CH_3). At −78 °C the



18b 26 26

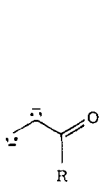
following trend in γ:α was observed: THF (70:30), DME (74:26), Et_2O (86:14), hexane (>90:10). At −100 °C in Et_2O the ratio of **26**γ:**26**α was greater than 97:3. *Of all the electrophiles examined in this study, methyl iodide was the least regioselective electrophile encountered.* As summarized in Table III, the alkylation of **18b** with those alkyl halides imposing *greater* steric constraints on the substitution process reveals significantly improved regioselectivity even in THF. Based upon the solvent trends observed above, it is concluded that the γ:α (THF) ratios shown in Table III would be markedly improved if the analogous reactions were carried out in diethyl ether. Subsequent to the present study we have observed that diethyl ether is the solvent of choice for these and related

Table III. Reaction of **18b** with Electrophiles at −78 °C in Tetrahydrofuran (eq 5)

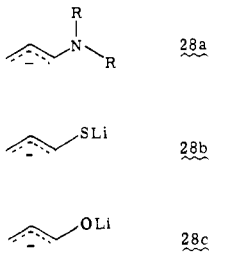
Electrophile	Ratio **26**γ:**26**α	Electrophile	Ratio **26**γ:**26**α
MeI	70:30	n-$C_6H_{13}Br$	>90:10
EtI	89:11	$PhCH_2Cl$	>88:12
n-$C_6H_{13}I$	>95:5	PhCHO	>99:1

alkylation reactions. In a related study we have also examined the relationship between the nature of the phosphorus activating group and the observed α:γ ratio. In comparing $-P(O)(NMe_2)_2$ with $-P(O)(OMe)_2$ with an otherwise identical set of substituents on the allylic carbanion (cf. **18b**) we have found the latter activating group to be *less* regioselective. For example, the carbanion derived from $CH_3CH{=}CHCH(OSiEt_3)P(O)(OMe)_2$ in THF (−78 °C) afforded a γ:α ratio of 67:33 with methyl iodide and 75:25 with n-hexyl iodide (cf. Table III). The modest differences in product ratios in these two systems could be attributable to nothing more than steric factors.[11]

Binucleophilic Homoenolate Anions. The successful design of an equivalent to the binucleophilic synthon **27** would be a

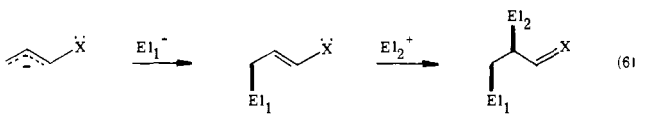


27



28a 28b 28c

significant accomplishment. The utility of **27** in annelation reactions could prove to be substantial (eq 6). Currently, me-



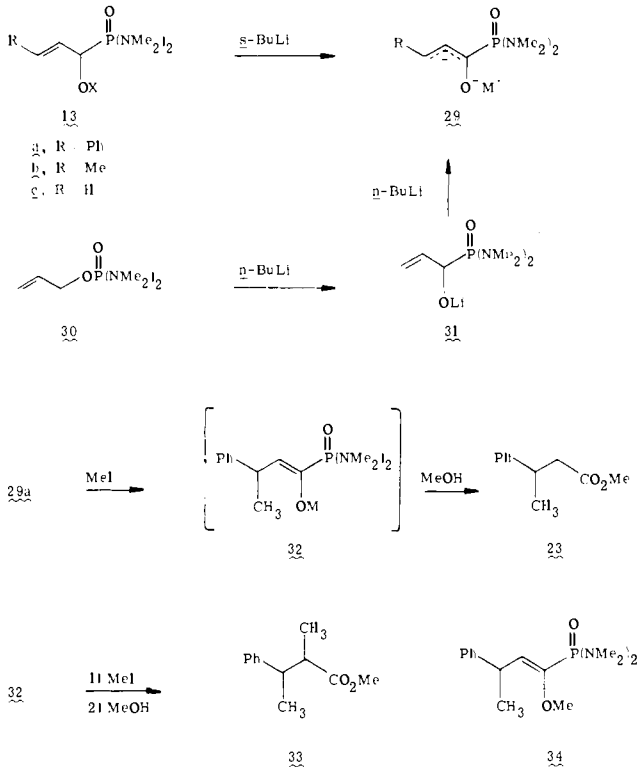
(6)

talated enamines **28a**[12] most closely approximate synthon **27**. These carbanions undergo regioselective γ-alkylation establishing an enamine which exhibits modest nucleophilic reactivity. The attainment of *more* nucleophilic enolate equivalents would be desirable. Unfortunately, although allyl mercaptide **28b** demonstrates the proper regiochemistry in the primary alkylation step, the resultant thioenolate alkylates exclusively on sulfur rather than carbon.[13] Finally, a *general* synthesis of alkoxide-substituted allylic anions **28c** has thus far proved to be elusive.[14]

In an effort to examine the capabilities of constructing suitable alkoxide-substituted allylic carbanions related to **28c** the bismetalation of hydroxyphosphonamide **13a** (X = H) was investigated (Scheme III). Treatment of **13a** (X = H) with 2 equiv of *sec*-butyllithium (DME, −50 °C) afforded the dianion **29a** (M = Li). Subsequent alkylation with 1 equiv of methyl iodide followed by methanolysis afforded methyl 4-phenylbutyrate (**23**) in 74% yield. It was concluded that **29a** was thus formed in good yield using the stated conditions.[15] Sturtz and Corbel have recently reported an alternate entry to **29c** via the bismetalation of **30**.[16] They report that methylation of dianion **29c** derived from **30** and subsequent hydrolysis afforded butyric acid in only 45% yield.[16] The restricted use of only substrate **30** and modest yields of dianion formation via this approach are limiting constraints for this process.

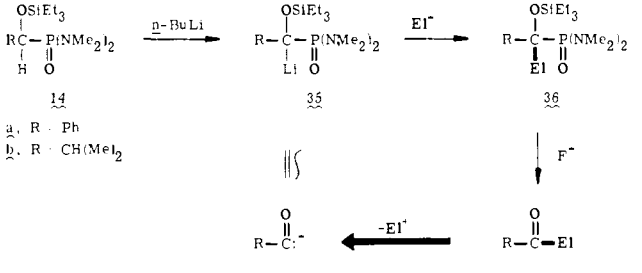
Attempts to regiospecifically bisalkylate dianion **29** (M = Li) have revealed some intrinsic problems associated with

Scheme III

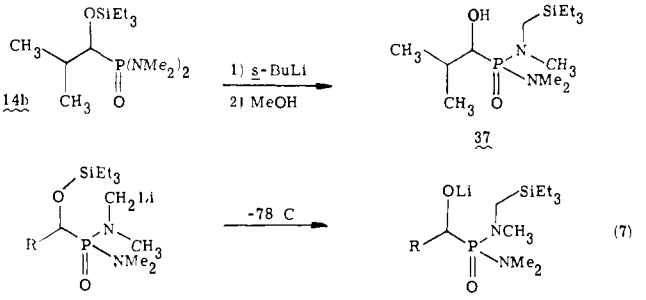


α-acyl phosphonamide derived enolates such as **32**. Generation of **29a** (M = Li) from **13a** (X = H) followed by the addition of excess methyl iodide and subsequent methanolysis afforded **33** and **34** in a 17:83 ratio. This observation clearly points out the problem of competing O-alkylation in enolates such as **32**. Reports suggest that tetra-*n*-butylammonium enolates generally afford improved yields of C-alkylation.[17] Accordingly, treatment of **32** (M = $SiEt_3$) with tetra-*n*-butylammonium fluoride followed by methylation afforded an improved, although still inadequate, C:O-alkylation ratio (**33**:**34** = 57:43). It is thus apparent that the efficient bis-carbon alkylation of dianions such as **29** is thwarted by competing reactivity modes, a problem shared with the dianion derived from allyl mercaptan **28b**.[13]

Carbonyl Anion Equivalents. We have briefly examined the carbanions derived from α-silyloxyphosphonamides **14a,b** as potential carbonyl anion equivalents. Benzaldehyde adduct **14a**,[6a] generated in situ, was readily metalated by *n*-butyllithium (−78 °C) in ethereal solvents. Upon quenching with methyl iodide, **36** (El = Me) was obtained in good yield. It was



found that silyloxyphosphonamides such as **36** could be efficiently converted to carbonyl substrates upon treatment with tetra-*n*-butylammonium fluoride (20 h, 25 °C). In the present instance benzaldehyde was transformed to acetophenone without intermediate purification steps in 72% yield. This methodology complements a related procedure recently reported by Hata and co-workers.[18] Intrinsic problems associated with silicon migration were encountered with the less highly stabilized carbanion derived from phosphonamide **14b**. Metalation of **14b** with *sec*-butyllithium followed by a methanol quench afforded, in addition to starting material, the hydroxyphosphonamide **37**. The simplest explanation for this observation is shown in eq 7. This undesired metalation, which



(7)

has precedent in the reaction of alkyllithium reagents with HMPA,[19] could possibly be suppressed by simple substrate modification (NMe → NEt).

Conclusions

A wealth of practical synthetic methods have evolved around the use of phosphorus-stabilized carbanions in carbon-carbon bond construction.[20] The present study further extends this area and provides practical constraints on the design of such carbanions incorporating potentially labile silicon substituents.

Experimental Section

Infrared spectra were recorded on a Beckman 4210 spectrophotometer. ^1H magnetic resonance spectra were recorded on Varian Associates A-60A (60 MHz) and EM-390 (90 MHz) spectrometers and are reported in parts per million from internal tetramethylsilane on the δ scale. Data are reported as follows: chemical shift, multiplicity (s = singlet, d = doublet, t = triplet, q = quartet, m = multiplet, br = broad), integration, coupling constant (Hz), and interpretation. ^{13}C magnetic resonance spectra were recorded on a Varian Associates XL-100 (25.2 MHz) spectrometer and are reported in parts per million from tetramethylsilane on the δ scale. Mass spectra were recorded on a Du Pont 21-492 B spectrometer. Mass spectral and combustion analyses were performed by the California Institute of Technology Microanalytical Laboratory. Melting points were determined with a Büchi SMP-20 melting point apparatus and are uncorrected. Molecular distillations were accomplished using a Büchi GKR-50 Kugelrohrapperat.

Analytical gas-liquid chromatography was carried out on a Varian Aerograph Model 1400 gas chromatograph equipped with a flame ionization detector using 2 ft by 0.25 in. stainless steel columns packed with 10% SE-30 on DMCS Chromosorb W. Medium-pressure chromatography (MPLC) was performed using EM Laboratories LoBar silica gel 60 prepacked columns on a Chromatronix MPLC apparatus equipped with a Fluid Metering Inc. Model RP lab pump.

High-pressure liquid chromatography (HPLC) was performed using a Waters Associates liquid chromatograph or a Waters Associates Prep LC/System 500.

Diethyl ether, tetrahydrofuran (THF), and dimethoxyethane (DME) were dried by distillation from benzophenone ketyl. Dichloromethane and alkyl halides were passed through a column of activity I alumina prior to use. Aldehydes and ketones were freshly distilled. Hexamethylphosphoric triamide (HMPA), tetramethylethylenediamine (TMEDA), and dimethylformamide (DMF) were distilled from calcium hydride and stored over molecular sieves.

Unless otherwise specified, all reactions were carried out under an atmosphere of nitrogen with rigid exclusion of moisture from reagents and glassware.

***N,N,N',N'*-Tetramethyl-*P*-1-(triethylsilyloxy)isobutylphosphonic Diamide (14b).** To 3.40 g (13.5 mmol) of **12** (0 °C) was added 1.27 mL (1.00 g, 14.0 mmol) of isobutyraldehyde dropwise. The resulting mixture was stirred at 0 °C for 30 min and evaporatively distilled (155 °C, 0.02 mm) yielding 3.91 g (90%) of **14b** as a colorless liquid: IR (CCl_4) 1198 (P=O), 1055 (SiO), 993 cm^{-1} (P-N); NMR (CCl_4) δ 3.97 (d of d, 1, J_{HH} = 4, J_{PH} = 7 Hz, HCP), 2.63 (d, 6, J_{PH} = 7 Hz,

$PNMe_2$), 2.52 (d, 6, J_{PH} = 11 Hz, $PNMe_2$), 2.27-1.83 (m, 1, methine), and 1.22-0.44 (m, 21, Et_3Si) ppm; ^{13}C NMR (C_6D_6) δ 75.09 (d, J = 141.2 Hz, CP), 37.05-36.54 (m, NCH_3), 32.47 (d, J = 3.8 Hz, $(CH_3)_2C$), 20.95-18.17 (d of d, CH_3CH), 7.58-5.88 (m, $SiEt_3$) ppm.

Exact mass (15 eV). Calcd for $C_{14}H_{35}N_2O_2PSi$: *m/e* 322.221. Found: 322.223.

Methyl 3-Phenylbutyrate (23).[21] To a cooled (0 °C) solution of 0.845 g (3.38 mmol) of **12** in 35 mL of THF was added 0.413 g (3.13 mmol) of cinnamaldehyde. The resulting solution was warmed to room temperature and stirred for 12 h, then cooled to −78 °C followed by addition of 1.7 mL (3.76 mmol) of a 2.21 M solution of *n*-butyllithium in hexane. The resulting red-orange solution was stirred at −78 °C for 2-3 min, then 0.4 mL (6.4 mmol) of methyl iodide was added with loss of color. The yellow solution was slowly warmed to room temperature, added to 60 mL of brine, and extracted with two 20-mL portions of ether. The combined extracts were dried ($MgSO_4$) and concentrated yielding 1.316 g of a yellow oil. The oil was dissolved in 30 mL of methanol and cooled to 0 °C, and 0.8 g (14.8 mmol) of sodium methoxide was added. The resulting solution was warmed to room temperature and stirred for 1 h, then added to 60 mL of brine and extracted with three 20-mL portions of ether. The combined extracts were dried ($MgSO_4$) and concentrated giving an amber liquid. Chromatography on 50 g of silica gel (methylene chloride) yielded 0.418 g (75%) of methyl 3-phenylbutyrate (**23**) as a clear yellow liquid: IR (neat) 1728, 1163, 695 cm^{-1}; NMR (CCl_4) δ 7.18 (s, 5, Ar), 3.50 (s, 3, OCH_3), 3.19 (m, 1, methine), 2.51 (d, 1, J = 6.8 Hz, CH_2), 2.50 (d, 1, J = 7.3 Hz, CH_2), 1.25 (d, 3, J = 7 Hz, CH_3) ppm.

β,γ-Diphenyl-γ-butyrolactone.[22] To a solution of 1.067 g (4.27 mmol) of **12** in 35 mL of THF was added 0.540 g (4.09 mmol) of cinnamaldehyde. The resulting solution was stirred at room temperature for 12 h, then cooled to −78 °C followed by addition of 1.90 mL (4.20 mmol) of a 2.21 M solution of *n*-butyllithium in hexane, yielding at first a deep red solution which rapidly turns orange. The resultant mixture was stirred at −78 °C for 5 min, then 0.44 mL (0.46 g, 4.32 mmol) of benzaldehyde was added with rapid loss of color. The resulting yellow solution was warmed to room temperature, added to 50 mL of brine, and extracted with three 20-mL portions of ether. The combined extracts were dried ($MgSO_4$) and concentrated giving 2.205 g of a clear yellow oil. The oil was dissolved in 70 mL of THF and cooled to 0 °C, and 1.60 g (6.13 mmol) of tetra-*n*-butylammonium fluoride was added. The resulting deep orange solution was warmed to room temperature and stirred for 4 h, then worked up as above yielding 1.897 g of a mixture of clear liquid and yellow oil. Chromatography on 50 g of silica gel (methylene chloride) yields 0.691 g (71%) of β,γ-diphenyl-γ-butyrolactone as a white solid: mp 97-106 °C; IR ($CHCl_3$) 1782, 1178, 1146, 700 cm^{-1}; NMR ($CDCl_3$) δ 7.23-6.57 (m, 10, Ar), 5.70 (d, 0.85, J = 7 Hz, -OCH), 5.30 (d, 0.15, J = 8 Hz, -OCH), 3.95 (d of t, 1, J_1 = 7, J_2 = 7 Hz, methine), 2.85 (br d, 2, J = 6 Hz, CH_2) ppm. VPC analysis (SE-30, 170-220 °C, at 8 °C/min) showed peaks at 4.5 (84.7%) and 4.8 min (15.3% of the peak area).

γ-Isopropyl-β-phenyl-γ-butyrolactone. To a solution of 1.135 g (4.54 mmol) of **12** in 35 mL of THF was added 0.545 g (4.12 mmol) of cinnamaldehyde. The resulting solution was stirred at room temperature for 12 h, then cooled to −78 °C, followed by addition of 1.9 mL (4.20 mmol) of a 2.21 M solution of *n*-butyllithium in hexane. The resulting orange solution was stirred at −78 °C for 2-3 min, then 0.40 mL (0.32 g, 4.40 mmol) of isobutyraldehyde was added with gradual loss of color. The resulting mixture was stirred at −78 °C for 1.5 h, then warmed to room temperature, added to 50 mL of brine, and extracted with three 20-mL portions of ether. The combined extracts were dried ($MgSO_4$) and concentrated giving 1.944 g of a yellow oil. The oil was dissolved in 60 mL of THF and cooled to 0 °C and 1.7 g (6.5 mmol) of tetra-*n*-butylammonium fluoride was added. The reaction mixture was slowly warmed to room temperature, stirred for 12 h, then worked up as above to give 1.475 g of a yellow solid and oil. Chromatography on 80 g of silica gel (methylene chloride) yielded 0.549 g (65%) of γ-isopropyl-β-phenyl-γ-butyrolactone as a white solid: mp 94-102 °C; IR (CCl_4) 1777, 1193, 1168, 1132, 1002, 996, 696 cm^{-1}; NMR ($CDCl_3$) δ 7.22 (br s, 5, Ar), 4.27 (overlapping d of d, 1, OCH), 3.82-3.27 (m, 1, ArCH), 3.07-2.3 (m, 2 CH_2), 1.20 (d, 3.5, J = 6 Hz, CH_3), 0.92 (d, 2.3, J = 6.5 Hz, CH_3) ppm.

Anal. ($C_{13}H_{16}O_2$): C, 76.60; H, 7.95.

***N*-(*tert*-Butoxycarbonyl)proline (38).** The title compound was prepared from proline and 2-(*tert*-butoxycarbonyloxyimino)-2-phenylacetonitrile in dioxane-water-triethylamine as described by Itoh[23] in 71% yield, mp 134-135 °C.

***N*-(*tert*-Butoxycarbonyl)prolinol (39).** To a cooled (0 °C) solution of 6.00 g (27.9 mmol) of acid **38** in 150 mL of THF was added 25 mL (23.5 mmol) of a 0.94 M solution of borane in THF. The resulting solution was slowly warmed to room temperature over 3.5 h, then quenched with 50 mL of methanol. The resulting mixture was stirred for 3 h, then concentrated, giving 5.74 g of pale yellow oil. Chromatography on silical gel (MPLC, 20% ethyl acetate in hexane) yielded 4.43 g (79%) of alcohol **39** as a colorless oil: IR (CCl_4) 3400 (m, OH), 1664 (s, C=O), 1397 (s), 1362 (s), 1165 (s, C-O) cm^{-1}; NMR (CCl_4) δ 4.32-4.10 (br s, 1, OH), 3.91-3.13 (m, 5, OCH_2, NCH), 1.99-1.61 (m, 4, CCH_2C), 1.43 (s, 9, *tert*-butyl) ppm.

Exact mass (75 eV). Calcd for $C_9H_{16}NO_2(PCH_3O)$: *m/e* 170.118. Found: 170.120.

***N*-(*tert*-Butoxycarbonyl)prolinal (40).** To a cooled solution of 15 mL (14.7 g, 18.6 mmol) of pyridine in 200 mL of dry methylene chloride was added 9.0 g (90 mmol) of chromium trioxide with formation of a red-brown precipitate. The resulting mixture was stirred at 0 °C for 15 min and warmed to room temperature for 0.5 h, then 3.04 g (15.1 mmol) of alcohol **39** was added with formation of a red-brown sludge. The resulting mixture was stirred for 0.5 h, filtered, and concentrated and the residue extracted with 200 mL of ether. The ether extract was filtered, washed with 50-mL portions of 10% HCl, 10% NaOH, and brine, dried ($MgSO_4$), and concentrated giving 2.34 g of a pale yellow oil. Chromatography on silica gel (MPLC, 20% EtOAc in hexanes) yields 1.68 g (56%) of aldehyde **40** as a pale yellow liquid: IR (CCl_4) 1732 (s, -CHO), 1700 (s, OC(O)N), 1388 (s), 1366 (s), 1162 (s, -OC), 1118 (s) cm^{-1}; NMR (CCl_4) δ 9.63-9.30 (m, 1, CHO), 4.16-3.59 (m, 1, methine), 3.38 (t, 2, J = 6 Hz, NCH_2), 2.19-1.96 (m, 4, $-CH_2-$), 1.41 (s, 9, *tert*-butyl) ppm.

Exact mass (75 eV). Calcd for $C_9H_{16}NO_2(PCHO)$: *m/e* 170.118. Found: 170.118.

γ-(*N*-*tert*-Butoxycarbonylpyrrolidin-2-yl)-β-phenyl-γ-butyrolactone. To a solution of 2.29 g (9.15 mmol) of **12** in 20 mL of THF was added 1.21 g (9.15 mmol) of cinnamaldehyde. The resulting mixture was stirred at room temperature for 12 h, then concentrated yielding **13a** as a pale yellow oil.

To a cooled (−78 °C) solution of 0.75 g (1.96 mmol) of **13a** in 30 mL of THF was added 0.7 mL (1.97 mmol) of a 2.82 M solution of *n*-butyllithium in hexane. The resulting mixture turns first deep red, then deep orange after 30 s. The orange solution was stirred at −78 °C for 5 min, then 0.43 g (2.16 mmol) of aldehyde **40** was added with gradual loss of color. The resulting light orange solution was stirred at −78 °C for 1 h, then added to 200 mL of brine and extracted with three 50-mL portions of ether. The combined extracts were dried ($MgSO_4$) and concentrated yielding 1.16 g of yellow oil. The oil was dissolved in 80 mL of THF and 1.25 g (4.8 mmol) of tetra-*n*-butylammonium fluoride was added. The resulting mixture was stirred for 12 h at room temperature, then worked up as above giving a yellow oil. Chromatography on silica gel (MPLC, 10% ethyl acetate in hexanes) yields 0.41 g (63%) of γ-(*N*-*tert*-butoxycarbonylpyrrolidin-2-yl)-β-phenyl-γ-butyrolactone as a pale yellow oil: IR (CCl_4) 1777, 1680, 1385, 1561, 1162, 1137, 1118, 693 cm^{-1}; NMR (CCl_4) δ 7.3-6.97 (br s, Ar), 5.11-1.56 (complex multiplets), 1.47-1.20 (m, *t*-Bu groups) ppm.

Exact mass (75 eV). Calcd for $C_{19}H_{25}NO_4$: *m/e* 331.179. Found: 331.177.

4,4-Spiro[cyclohexyl]-3-phenyl-γ-butyrolactone. To a cooled (0 °C) solution of 1.963 g (7.84 mmol) of **12** in 30 mL of THF was added 1.036 g (7.84 mmol) of cinnamaldehyde. The resulting solution was slowly warmed to room temperature, stirred for 12 h, diluted with 40 mL of THF, then cooled to −78 °C followed by addition of 3.4 mL (8.6 mmol) of a 2.54 M solution of *n*-butyllithium in hexane. The resulting red solution was stirred at −78 °C for 5 min, then 0.857 g (8.73 mmol) of cyclohexanone was added with rapid loss of color. The reaction mixture was slowly warmed to room temperature over 3 h, added to 400 mL of brine, and extracted with five 35-mL portions of ether. The combined extracts were dried ($MgSO_4$) and concentrated giving 3.848 g of yellow oil. The oil was dissolved in 70 mL of THF and cooled to 0 °C, and 9.4 mL (11.8 mmol) of a 1.26 M solution of tetra-*n*-butylammonium fluoride in THF was added. The resulting mixture was stirred at 0 °C for 2 h, warmed to room temperature for 1 h, then worked up as above giving 2.477 g of a liquid which solidifies on standing. Chromatography on silica gel (methylene chloride) yields 1.178 g (65%) of 4,4-spiro[cyclohexyl]-3-phenyl-γ-butyrolactone as

a white solid. Recrystallization (hexane) gave white crystals: mp 103.5-104.5 °C; IR (CCl_4) 2968, 1769, 1208, 1128, 957, 693 cm^{-1}; NMR (CCl_4) δ 7.42-7.03 (m, 5, Ar), 3.36 (d of d, 1, J = 9 Hz, methine), 2.88 (d, 2, J = 9 Hz, O=CCH_2-), 2.03-0.64 (m, 10, -CH_2-) ppm.

Exact mass (75 eV). Calcd for $C_{15}H_{18}O_2$: *m/e* 230.131. Found: 230.128.

Anal. ($C_{15}H_{18}O_2$): C, 77.96; H, 7.94.

Methyl 3-Methyl-4-phenylbutyrate.[24] To a solution of 1.019 g (4.07 mmol) of **12** in 35 mL of THF was added 0.294 g (4.19 mmol) of crotonaldehyde. The resulting mixture was stirred at room temperature for 12 h and cooled to −78 °C, followed by addition of 2.2 mL (4.86 mmol) of a 2.21 M solution of *n*-butyllithium in hexane. The resulting pale yellow solution was stirred at −78 °C for 5 min, then 0.66 mL (0.73 g, 5.73 mmol) of benzyl chloride was added. The reaction mixture was slowly warmed to room temperature and stirred for 12 h, added to 75 mL of brine, and extracted with three 20-mL portions of ether. The combined ether extracts were dried ($MgSO_4$) and concentrated, giving 1.698 g of yellow oil. The oil was dissolved in 25 mL of methanol and cooled to 0 °C and 0.8 g (14.8 mmol) of sodium methoxide was added. The reaction mixture was slowly warmed to room temperature and stirred for 12 h, then worked up as above giving an amber oil. Chromatography on silica gel (50% methylene chloride in hexanes) yields 0.394 g (50%) of methyl 3-methyl-4-phenylbutyrate as a clear yellow oil: IR (neat) 1730, 1447, 1431, 1203, 1156, 1148, 1005, 737, 695 cm^{-1}; NMR (CCl_4) δ 7.26-6.97 (br s, 5, Ar), 3.52 (s, 3, OCH_3), 2.7-2.0 (m, 4, -CH_2-), 1.1-0.77 (m, 4, CH_3, methine). VPC analysis (SE-30, 100-220 °C at 10 °C/min) shows one major peak at 7.1 min (>91% of the peak area).

Methyl 3-Methylnonanoate.[25] To a cooled (−78 °C) solution of 1.695 g (5.30 mmol) of adduct **13b** in 70 mL of THF was added 2.4 mL (6.1 mmol) of a 2.54 M solution of *n*-butyllithium in hexane. The resulting amber solution was stirred at −78 °C for 5 min, then 1.050 g (6.36 mmol) of hexyl bromide was added with gradual loss of color. The resulting mixture was slowly warmed to room temperature over 2 h, then added to 400 mL of brine and extracted with five 30-mL portions of ether. The combined extracts were dried ($MgSO_4$) and concentrated giving 2.350 g of oil. The oil was dissolved in 60 mL of methanol and cooled to 0 °C, and 0.8 g (14.8 mmol) of sodium methoxide was added. The reaction mixture was stirred at 0 °C for 3 h, then worked up as above giving 1.690 g of oil. Chromatography on 140 g of silica gel (40% methylene chloride in hexanes) yielded 0.578 g (59%) of methyl 3-methylnonanoate as a pale yellow liquid: IR (neat) 1737 cm^{-1}; NMR (CCl_4) δ 3.58 (s, 3, OCH_3), 2.37-1.77 (m, 2, -CH_2CO_2), 1.42-1.08 (br s, 11, methine, CH_2), 1.08-0.75 (m, 6, CH_3) ppm. VPC analysis (SE-30, 100-220 °C at 10 °C/min) shows one peak at 5.1 min.

β-Methyl-γ-phenyl-γ-butyrolactone.[26] To a cooled (−78 °C) solution of 3.41 g (10.6 mmol) of adduct **13b** in 150 mL of ether was added 6.4 mL (10.7 mmol) of a 1.67 M solution of *n*-butyllithium in hexane. The resulting solution was stirred at −78 °C for 10 min, then 1.13 g (10.6 mmol) benzaldehyde was added. The resulting mixture was stirred at −78 °C for 1 h, then added to 500 mL of brine and extracted with three 100-mL portions of ether. The combined organic layers were dried ($MgSO_4$) and concentrated giving 4.92 g of oil. The oil was dissolved in 100 mL of THF and cooled to 0 °C and 4.1 g (15.7 mmol) of tetra-*n*-butylammonium fluoride was added. The resulting solution was slowly warmed to room temperature and stirred for 3 h, then worked up as above giving 3.42 g of crude product. Chromatography on silica gel (MPLC, 30% EtOAc in hexane) gave 1.25 g (67%) of β-methyl-γ-phenyl-γ-butyrolactone as a mixture of diastereomers: IR (CCl_4) 1782 (C=O), 1151, 694 cm^{-1}; NMR (CCl_4) δ 7.27 (br s, 5, Ph), 5.43 (d, 0.65, J = 6 Hz, PhCH, cis), 4.78 (br d, 0.35, J = 8 Hz, PhCH, trans), 2.93-1.88 (m, 3, methylene, methine), 1.11 (d, 1.05, J = 6 Hz, CH_3, trans), 0.61 (d, 1.95, J = 7 Hz, CH_3, cis) ppm.

γ-Phenyl-γ-butyrolactone.[27] To a cooled (0 °C) solution of 3.52 g (14.1 mmol) of **12** in 75 mL of ether was added 0.762 g (13.6 mmol) of acrolein. The resulting solution was stirred at 0 °C for 4.5 h, then cooled to −78 °C and 4.8 mL (13.5 mmol) of a 2.82 M solution of *n*-butyllithium in hexane was added. The resulting amber solution was stirred at −78 °C for 1 min, then 0.707 g (6.67 mmol) of benzaldehyde was added with loss of color. The resulting clear yellow reaction mixture was stirred at −78 °C for 1 h, then added to 400 mL of brine and extracted with five 50-mL portions of ether. The combined extracts were dried ($MgSO_4$) and concentrated giving 4.61 g of yellow oil. The oil was dissolved in 75 mL of THF and cooled to 0 °C and 4.8 g (18.4 mmol) of tetra-*n*-butylammonium fluoride was added. The reaction mixture was slowly warmed to room temperature, stirred for 10 h, then worked up as above giving a yellow oil. Chromatography on silica gel (MPLC, 20% ethyl acetate in hexane) yielded 0.592 g (55%) of γ-phenyl-γ-butyrolactone as a colorless liquid: IR (CCl_4) 1780, 1168, 1154, 1133, 1024, 935, 693 cm^{-1}; NMR (CCl_4) δ 7.19 (s, 5, Ar), 5.23 (d of d, 1, J_1 = 7, J_2 = 7 Hz, methine), 2.66-1.77 (m, 3, -CH_2-), 1.36-0.8 (m, 1, -CH_2-) ppm. VPC analysis (SE-30, 100-220 °C at 10 °C/min) showed one peak at 7.7 min.

Methyl Nonanoate. To a solution of 3.46 g (13.8 mmol) of **12** in 65 mL of ether was added 0.77 g (13.8 mmol) of acrolein. The resulting mixture was stirred at 0 °C for 4 h and cooled to −78 °C, and 4.80 mL (13.5 mmol) of a 2.82 M solution of *n*-butyllithium in hexane was added. The resulting pale yellow solution was stirred at −78 °C for 2-3 min, then 1.97 g (9.3 mmol) of hexyl iodide was added. The resulting mixture was stirred at −78 °C for 1 h, then added to 400 mL of brine and extracted with five 50-mL portions of ether. The combined extracts were dried ($MgSO_4$) and concentrated giving 4.01 g of liquid. The liquid was dissolved in 100 mL of methanol and cooled to 0 °C, and 2.5 g of sodium methoxide was added. The reaction mixture was stirred at 0 °C for 2 h, then worked up as above giving a yellow liquid. Chromatography on silica gel (MPLC, ethyl acetate/hexanes) yielded 0.36 g (22%) of methyl nonanoate as a clear liquid: IR (CCl_4) 1729 cm^{-1}; NMR (CCl_4) δ 3.57 (s, 3, OCH_3), 2.19 (t, 2, J = 7 Hz, -CH_2CO_2), 1.8-1.12 (m, 12, -CH_2-), 1.12-0.70 (m, 3, CH_3) ppm.

General Procedure for the Study of Solvent Effect on the Alkylation of Adduct 13b with Methyl Iodide. The following general procedure was used for the examples reported. To a cooled solution (−78 °C in ether, −50 °C in hexane) of 1 equiv of adduct **13b** in 10-20 mL of solvent was added 1.1-1.5 equiv of *n*-butyllithium in hexane. The resulting solution was stirred for 2-10 min and cooled to the appropriate temperature and 4-5 equiv of methyl iodide was added. The resulting mixture was stirred for at least 1 h at −78 °C, then added to 75-100 mL of brine and extracted with 20-25 mL of ether. The ether layer was dried ($MgSO_4$) and concentrated. The α:γ ratio was determined by NMR analysis of the crude reaction product, comparing the ratio of vinyl protons by NMR integration.

From one experiment the two products were separated by chromatography on silica gel (MPLC, 2% 2-propanol in chloroform). For the faster moving component γ-alkylated enol ether **26γ**: IR (CCl_4) 1780 (w), 1720 (w), 1452 (m), 1294 (m), 1275 (m), 1212 (s), 980 (s), 718 (m) cm^{-1}; NMR (CCl_4) δ 4.88 (d of d, 1, J_{HH} = 10, J_{PH} = 10 Hz, vinyl), 2.57 (d, 12 J_{PH} = 10 Hz, NCH_3), 1.13-0.37 (m, 22, methine, CH_3, $SiCH_2CH_3$) ppm.

Exact mass (70 eV). Calcd for $C_{15}H_{35}N_2O_2PSi$: *m/e* 334.221. Found: 334.220.

For the α-alkylated material **26α**: IR (CCl_4) 1451 (m), 1294 (m), 1209 (s), 1186 (m), 1129 (m), 1063 (m), 980 (s), 718 (m) cm^{-1}; NMR (CCl_4) δ 5.69-5.52 (m, 2, vinyl), 2.62 (d, 6, J_{PH} = 9 Hz, NCH_3), 2.59 (d, 6, J_{PH} = 9 Hz, NCH_3), 1.72 (t, 3, J_{PH} = 5 Hz, -CH_3), 1.45 (d, 3, J_{PH} = 15 Hz, -CH_3), 1.16-0.42 (m, 15, $SiCH_2CH_3$) ppm.

Exact mass (70 eV). Calcd for $C_{15}H_{35}N_2O_2PSi$: *m/e* 334.221. Found: 334.222.

General Procedure for the Reaction of Adduct 13b with Electrophiles. The following general procedure was used for the examples in Table III. To a cooled solution (−78 °C) of 1 equiv of adduct **13b** in 10-35 mL of THF was added 1.0-1.6 equiv of *n*-butyllithium in hexane. The resulting mixture was stirred at −78 °C, then 1.0-1.6 equiv of alkyl halide or aldehyde was added. The resulting mixture was slowly warmed to room temperature, added to brine, and extracted with ether. The ether extract was dried ($MgSO_4$) and concentrated. The α:γ ratio was determined by NMR analysis of the crude reaction product, comparing the ratio of vinyl protons.

***N,N,N′,N′*-Tetramethyl-*P*-(*Z*)-1-hydroxy-3-phenyl-2-propenylphosphonic Diamide (13a, X = H).** To 7.96 g (31.8 mmol) of **12** cooled with an ice bath was added 4.21 g (31.8 mmol) of cinnamaldehyde with evolution of heat. The resulting pale yellow solution was warmed to room temperature, stirred for 1 h, diluted with 200 mL of THF, and cooled to 0 °C, and 10.0 g (38 mmol) of tetra-*n*-butylammonium fluoride in 30 mL of THF was added. The resulting red solution was stirred at 0 °C for 20 min, then added to 750 mL of brine and extracted with two 75-mL portions of methylene chloride and with 75

mL of ether. The combined organic layers were dried ($MgSO_4$) and concentrated giving 13.9 g of yellow liquid. Chromatography on silica gel (HPLC, 5% 2-propanol in chloroform) gave 5.31 g (62%) of hydroxyphosphonamide **13a** (X = H) as white crystals: mp 128–129 °C; IR ($CHCl_3$) 3210 (br, OH), 1295 (P=O), 1188, 1157, 991 (P-N), 974 (trans -C=C) cm^{-1}; NMR ($CDCl_3$) δ 7.44–7.06 (m, 5, Ph), 6.96–6.2 (m, 2, vinyl), 4.97–4.56 (br m, 2, methine, OH), 2.69 (d, 6, J_{PH} = 10 Hz, $PNMe_2$), 2.64 (d, 6, J_{PH} = 10 Hz, $PNMe_2$) ppm.

Exact mass (75 eV). Calcd for $C_{13}H_{21}N_2O_2P$: *m/e* 268.134. Found: 268.135.

Anal. ($C_{13}H_{21}N_2O_2P$): C, 57.81; H, 7.69; N, 10.29.

Monoalkylation of Hydroxyphosphonamide 13a (X = H). To a cooled (−50 °C) solution of 0.507 g (1.89 mmol) of **13a** (X = H) in 150 mL of DME was added 3.0 mL (3.8 mmol) of a 1.27 M solution of *sec*-butyllithium in hexane rapidly.[15] The resulting deep orange solution and precipitate were stirred at −50 °C for 10 min, then 0.15 mL (0.66 g, 4.6 mmol) of methyl iodide was added. The resulting clear yellow solution was stirred at −50 °C for 20 min, then 60 mL of methanol and 0.15 g (2.8 mmol) of sodium methoxide were added. The mixture was warmed to room temperature and stirred for 1 h, then added to 400 mL of brine and extracted with three 50-mL portions of ether. The combined extracts were dried ($MgSO_4$) and concentrated giving 0.356 g of liquid. Chromatography on silica gel (MPLC, 3% EtOAc in hexane) yielded 0.250 g (74%) of methyl 3-phenylbutyrate as a clear liquid with spectral characteristics identical with those of the sample prepared from cinnamaldehyde adduct **13a** (X = $SiEt_3$).

Bisalkylation of Hydroxyphosphonamide 13a (X = H). To a cooled (−50 °C) solution of 82.6 mg (0.31 mmol) of **13a** (X = H) in 25 mL of DME was rapidly added 0.49 mL (0.62 mmol) of a 1.27 M solution of *sec*-butyllithium in hexane. The resulting red solution was stirred at −50 °C for 10 min, then 20 μL (46 mg, 0.32 mmol) of methyl iodide was added. The resulting yellow solution was stirred at −50 °C for 5 min and warmed to room temperature for 30 min, followed by addition of 100 μL (228 mg, 1.61 mmol) of methyl iodide. The reaction mixture was stirred at room temperature for 30 min, then heated to reflux for 2.5 h. From the cloudy yellow mixture ca. 10 mL was removed, added to 0.1 g of sodium methoxide in 10 mL of methanol, stirred for 1 h, then added to 100 mL of brine. The mixture was extracted with 25 mL of ether and the organic layer dried ($MgSO_4$) and concentrated. VPC analysis (SE-30, 100–240 °C at 15 °C/min) showed peaks at 3.9 (coinjects with methyl 3-phenylbutyrate), 4.3 (coinjects with authentic sample of **33** prepared from methyl 3-phenylbutyrate), and 9.8 min (enol ether **34**), the latter two in the area ratio 17:83. Chromatography on silica gel (MPLC, 3% 2-propanol in chloroform) gave pure **34:** IR (CCl_4) 1619 (C=C), 1210 (P=O), 940 (PN) cm^{-1}; NMR (CCl_4) δ 7.13 (br s, 5, Ph), 5.59 (d of d, 1, J_1 = 9, J_2 = 10 Hz, vinyl), 4.13–3.73 (m, 1, methine), 3.61 (s, 3, OCH_3), 2.6 (d, 12, J_{PH} = 10 Hz, $PNMe_2$), 1.28 (d, 3, J_{HH} = 8 Hz, CCH_3) ppm.

Exact mass (75 eV). Calcd for $C_{15}H_{25}N_2O_2P$: *m/e* 296.165. Found: 296.163.

Treatment of Silyl Enol Ether 32a (M = $SiEt_3$) with Fluoride Ion and Methyl Iodide. To a cooled (−78 °C) solution of 0.23 g (0.60 mmol) of adduct **13a** in 10 mL of THF was added 0.47 mL (0.60 mmol) of a 1.27 M solution of *sec*-butyllithium in hexane. The resulting red solution was stirred at −78 °C for 10 min, then 0.15 mL (0.34 g, 2.4 mmol) of methyl iodide was added. The resulting mixture was stirred at 0 °C for 10 min, then added to 100 mL of brine and extracted with 35 mL of ether. The organic layer was dried ($MgSO_4$) and concentrated giving silyl enol ether **32a** (M = $SiEt_3$) as an oil. The oil was dissolved in 60 mL of THF and cooled to 0 °C and 0.5 g (1.9 mmol) of tetra-*n*-butylammonium fluoride was added. The resulting orange-red solution was stirred at 0 °C for 15 min, followed by addition of 0.25 mL (0.57 g, 4.0 mmol) of methyl iodide with loss of color and evolution of a gas. The resulting mixture was warmed to room temperature, stirred for 3 h, diluted with 50 mL of ether, then added to 200 mL of brine. The ether layer was dried ($MgSO_4$) and concentrated. The residue was dissolved in 50 mL of methanol, 0.15 g (2.8 mmol) of sodium methoxide was added, and the mixture was stirred at room temperature for 1 h. Workup as above gave an oil. VPC analysis (SE-30, 100–240 °C at 10 °C/min) showed among other products a 57:43 area ratio of **33:34.**

Acetophenone. To a cooled (0 °C) solution of 1.030 g (4.11 mmol) of **12** in 35 mL of THF was added 0.449 g (4.23 mmol) of benzaldehyde. The resulting solution was slowly warmed to room temperature and stirred for 12 h, then cooled to −78 °C followed by addition of 2.2 mL (4.9 mmol) of a 2.21 M solution of *n*-butyllithium in hexane. The resulting red-orange solution was stirred at −78 °C for 2–3 min, then 0.30 mL (4.82 mmol) of methyl iodide was added with rapid loss of color. The resulting yellow solution was slowly warmed to room temperature and stirred for 3 h, then added to 150 mL of brine and extracted with three 20-mL portions of ether. The combined organic extracts were dried ($MgSO_4$) and concentrated giving a pale yellow oil. The oil was dissolved in 40 mL of THF and cooled to 0 °C and 1.7 g (6.5 mmol) of tetra-*n*-butylammonium fluoride[10] was added. The resulting solution was slowly warmed to room temperature and stirred for 12 h, then worked up as above yielding 1.122 g of a yellow oil. Chromatography on 50 g of silica gel (methylene chloride) gave a pale yellow oil which was evaporatively distilled (120 °C max, 1 mm) yielding 0.356 g (72%) of acetophenone as a colorless liquid: IR (neat) 1680 cm^{-1}; NMR (CCl_4) δ 7.83–7.60 (m, 2, Ar), 7.40–7.07 (m, 3, Ar), and 2.40 (s, 3, CH_3) ppm.

Reaction of Adduct 14b with *sec*-Butyllithium. To a cooled (−78 °C) solution of 1.7 mL (2.2 mmol) of a 1.27 M solution of *sec*-butyllithium and 1.6 mL (1.23 g, 10.6 mmol) of TMEDA in 30 mL of THF was added 0.407 g (1.26 mmol) of adduct **14b.** The resulting mixture was stirred at −78 °C for 25 min, then quenched with 0.1 mL of methanol. The resulting solution was added to 200 mL of brine and extracted with 50 mL of ether. The organic layer was dried ($MgSO_4$) and concentrated giving a yellow oil. HPLC analysis (μ-Porasil, 5% methanol–47.5% ether–47.5% hexane) showed, in addition to starting material, alcohol **37.** Chromatography on silica gel gave pure **37** as a pale yellow oil: IR (CCl_4) 3215 (br, OH), 1192 (P=O), 990 (PN) cm^{-1}; NMR (CCl_4) δ 5.42–4.89 (m, 1, OH), 3.99–3.59 (br m, 1, HCP, turns to d of d upon D_2O exchange, J_{HH} = 7 J_{PH} = 7 Hz), 2.89–2.33 (m, 11, NCH_2, NCH_3), 2.11–1.67 (m, 1, methine), 1.33–0.44 (m, 21, alkyl, Et_3Si) ppm; ^{13}C NMR (C_6D_6) δ 72.22 (d, J = 123.9 Hz, C–P, off resonance decoupled spectrum gives a d of d), 36.84–36.51 (m, NCH_3), 35.09 (s, NCH_2Si), 30.92 (d, J = 4.7 Hz, CH_3C), 22.19–18.00 (m, CH_3C), 7.92 (s, CH_3CH_2Si), 4.18 (s, CH_3CH_2Si) ppm.

Exact mass (75 eV). Calcd for $C_{14}H_{35}N_2O_2PSi$: *m/e* 322.221. Found: 322.221.

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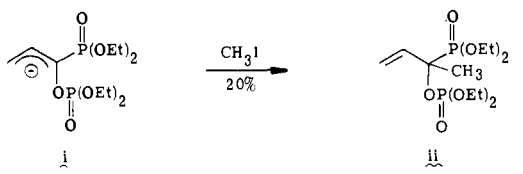

i ii

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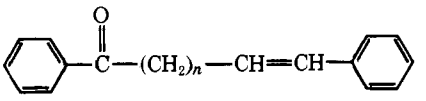
Competing Triplet Reactions in Azidoketones

Peter J. Wagner* and B. J. Scheve

Contribution from the Chemistry Department, Michigan State University, East Lansing, Michigan 48824. *Received July 18, 1978*

Abstract: The photochemistry of three α-benzoyl-ω-azidoalkanes $PhCO(CH_2)_nN_3$ has been studied. With 365-nm irradiation two competitive processes occur from the triplet ketone: γ-hydrogen abstraction to yield Norrish type II products and energy transfer to azide to yield nitrene products. The rate constant for the latter decreases an order of magnitude for each additional methylene between $n = 3$ and $n = 5$. This rate decrease is interpreted to reflect the strain in medium-sized rings. The effects of δ- and γ-azido on the rate constant for γ-hydrogen abstraction indicate a σ_I value of 0.46 for N_3 and little resonance stabilization of an adjacent carbon radical.

For years, there has been widespread interest among photochemists in bifunctional and bichromophoric compounds.[1] Nonetheless, there have been few investigations in which the positions of the two chromophores on a molecular skeleton have been varied systematically so that rate constants for interactions between the two groups can be compared to their distance apart.[2,3] One such study showed that the rate of intramolecular triplet energy transfer in ω-styrenylalkyl phenyl ketones decreases as the number of methylenes connecting the two chromophores increases from 2 to 4.[2] These energy transfer rate constants are probably controlled by rates of rotation, since the corresponding bimolecular process, being exothermic, is diffusion controlled.[4]



In this paper we report the photochemistry of three ω-azidoalkyl phenyl ketones. These compounds display the expected competition between carbonyl and azide (nitrene) photochemistry. Moreover, since energy transfer from triplet ketones to azides is two orders of magnitude slower than diffusion controlled,[5] the variation in rates of intramolecular energy transfer reflects conformational equilibrium rather than rotational kinetics.

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