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The Synthesis of 3-Trimethylsilyl-4-dimethyl(phenyl)silyl-but-3-en-2-one, a β-Functionalised Michael Acceptor

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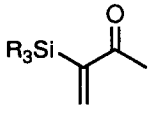
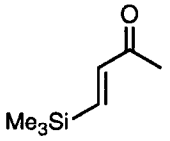
Abstract: The title compound **3** has been prepared by silyl-cupration of trimethylsilylacetylene followed by acetylation. The phenyldimethylsilyl group can be removed selectively in a three-step procedure to give 3-trimethylsilylbut-3-ene-2-one **1b**. The enone **3** and cyclohexanone can be used in an annelation reaction to make 5-dimethyl(phenyl)silylbicyclo[4.4.0]decan-3-one **20** and hence to make 2-vinylcyclohexylacetic acid **23**.

INTRODUCTION

In one of the earliest applications of organosilicon chemistry to organic synthesis, Stork[1] and Boeckman[2] introduced, respectively, the α-triethylsilyl version **1a** and the α-trimethylsilyl version **1b** of methyl vinyl ketone as substrates for aprotic Michael reactions. The α-silyl group stabilises the enolate produced by conjugate addition, and, in consequence, probably increases the electrophilicity of the double bond. In contrast, we found that the β-silyl group in the regioisomeric methyl vinyl ketone **2** reduced the electrophilicity of the double bond, and that, although this ketone reacted with cuprates, it did not react easily or usefully with simple enolates, enamines or silyl enol ethers.[3] We considered that the doubly silylated version **3** of methyl vinyl ketone might



1a R = Et
1b R = Me



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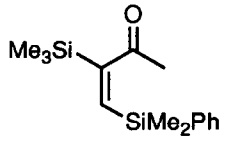

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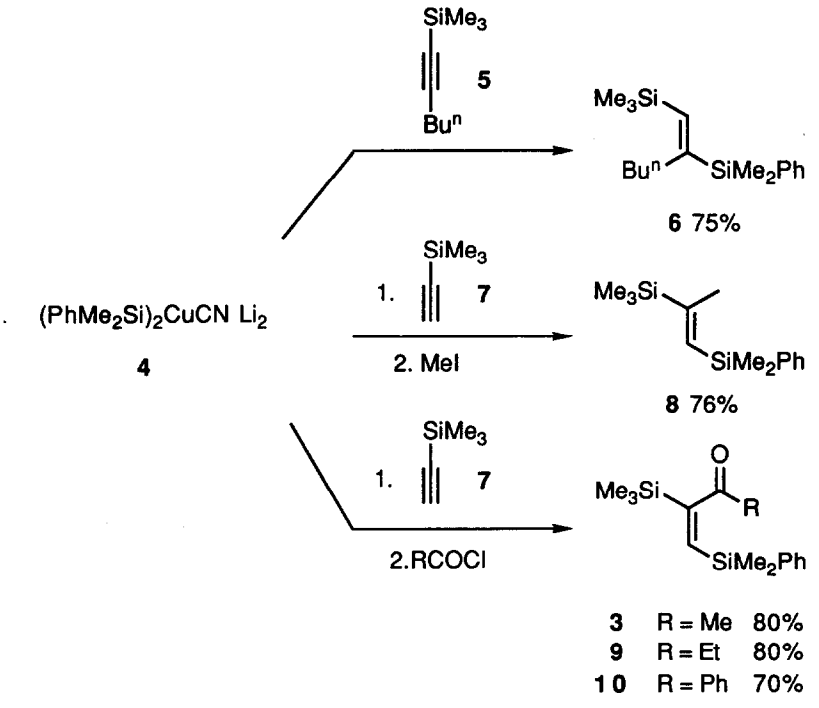
therefore combine the properties of Stork's enone and ours. The α-silyl group should make it more electrophilic, and the β-functionality might be useful in the same way that it was in our earlier work, where we used it to restore αβ-unsaturation regiospecifically after the cuprate additions. Since that time, we have learned how to convert a phenyldimethylsilyl group into a hydroxyl group,[4] and have thereby increased the potential usefulness of β-silylated enone systems, hence our choice of the β-phenyldimethylsilyl ketone **3** as our target rather than the corresponding β-trimethylsilyl ketone. In this paper we record our synthesis of this ketone, our attempts to use it to simplify the syntheses[5] of Boeckman's ketone **1b**, and we hint at one of the possibilities in synthesis for which it might be useful.

RESULTS AND DISCUSSION

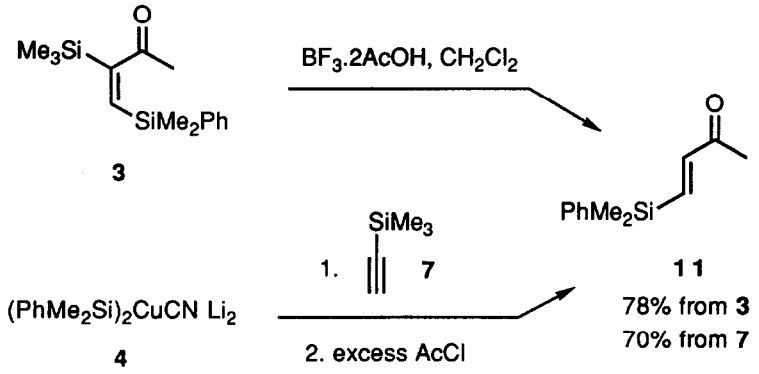
We already knew that terminal acetylenes reacted with our phenyldimethylsilyl-cuprate reagent **4** to give, *syn* stereospecifically, vinyl-cuprates in which the silyl group was exclusively at the terminus and the copper was

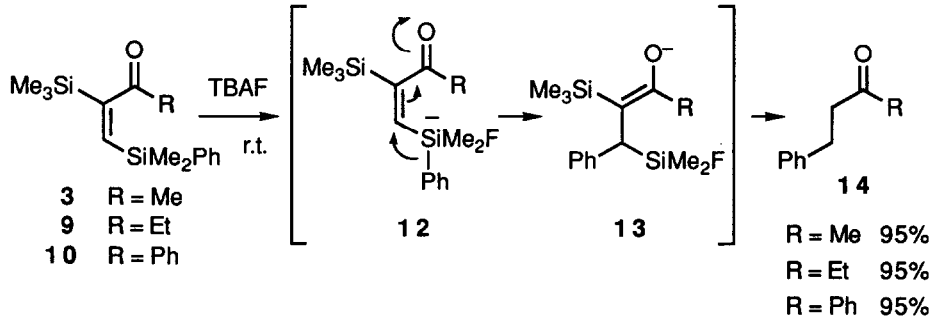
inside.[6] Subsequent reaction with electrophiles gave a wide range of vinylsilanes with the overall regiochemistry opposite to that found for alkyl-cuprates in comparable reactions. Although we found that the regiochemistry was unchanged when the acetylene was first metallated with butyl-lithium to give a lithium acetylide, we now report that the regiochemistry *is* inverted when a trimethylsilyl group occupies the terminal position rather than a hydrogen or a lithium atom. The hexynylsilane **5** gave the vinyldisilane **6** with the phenyldimethylsilyl group occupying the internal position. With this precedent, it seemed more than likely that the phenyldimethylsilyl-cuprate reagent **4** would react cleanly with the monosilylated acetylene **7**,[7] and so it does, giving, after treatment with methyl iodide or an acid chloride, the differentially disilylated vinyldisilane **8** and the enones **3**, **9** and **10**.



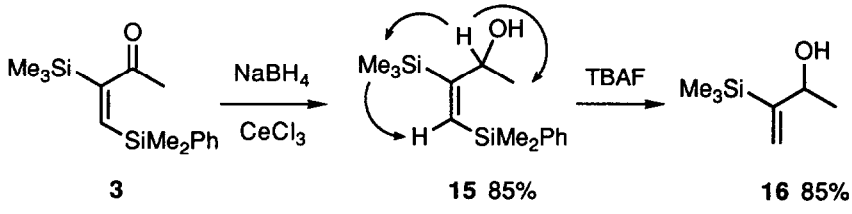
We considered that there was some possibility of selectively removing the phenyldimethylsilyl group of the enone **3**, and hence of shortening the existing, four-step synthesis of Stork's and Boeckman's enones **1**. Hudrlik has shown that terminal silyl groups in vinylsilanes are more susceptible to acid-catalysed protodesilylation than internal silyl groups,[8] but the reason for this selectivity—the relative stabilities of the intermediate cations—cannot be expected to extend to the present situation, where the acetyl group will slow down acid-catalysed protodesilylation of the terminal silyl group. And so it proved, for treating the enone **3** with acid gave the product **11**, in which the trimethylsilyl group had been cleanly removed, presumably by way of the allenol. This product could also be made in one step by repeating the reaction between the silyl-cuprate reagent **4** and the acetylene **7**, and adding a large excess of acetyl chloride instead of one equivalent. The alternative approach for removing the silyl group, using fluoride ion, seemed more hopeful, for there is a report of the selective removal of a phenyldimethylsilyl group in a vinylsilane using fluoride ion, when the corresponding trimethylsilyl group was untouched.[9] However, treating the enones **3**, **9** and **10** with tetrabutylammonium fluoride set off a remarkable rearrangement to give the ketones **14**, in which altogether too much had happened. Fluoride ion attack on the phenyldimethylsilyl group will give the pentacovalent silyl anion **12**, from which the phenyl group can migrate to the β-position of the enone system to give the enolate **13**. Migration of groups from silicon to neighbouring electrophilic sites is known when the electrophilic site is a carbon atom carrying a good

nucleofugal group such as a halide[10] or triflate group[11] or is an epoxide,[12] or carbonyl group.[13] It is also known for an oxygen atom carrying another oxygen atom as a leaving group,[3,14] but this is the first example of migration to an enone, although there is a near analogy in an iron complex, in which an iron-carbene double bond acts as the equivalent of the carbonyl group of an enone.[15] The enolate **13** can acquire a proton, and thereafter the loss of the silyl groups, both that α to the ketone[16] and that from the benzylic position,[17] is unremarkable.





Thus we were unable to remove selectively the phenyldimethylsilyl group from the enone **3**, and resorted instead to reducing the ketone first to the alcohol **15** using Luche's conditions.[18] This compound gave us an opportunity to prove the stereochemistry of our products, which up to this point we had simply assumed to be those of *syn* addition, by analogy with our earlier work. Irradiation at the resonance frequency of the trimethylsilyl protons caused an NOE enhancement in the signal from the olefinic proton, whereas irradiation at



the frequency of the allylic proton gave NOE enhancements only to the signals from the trimethylsilyl and the *C*-methyl protons. There is good precedent for the relatively easy removal of a silyl group from the α-position, occupied by the trimethylsilyl group in this allylic alcohol, using tetrabutylammonium fluoride,[9,19,20] but there is

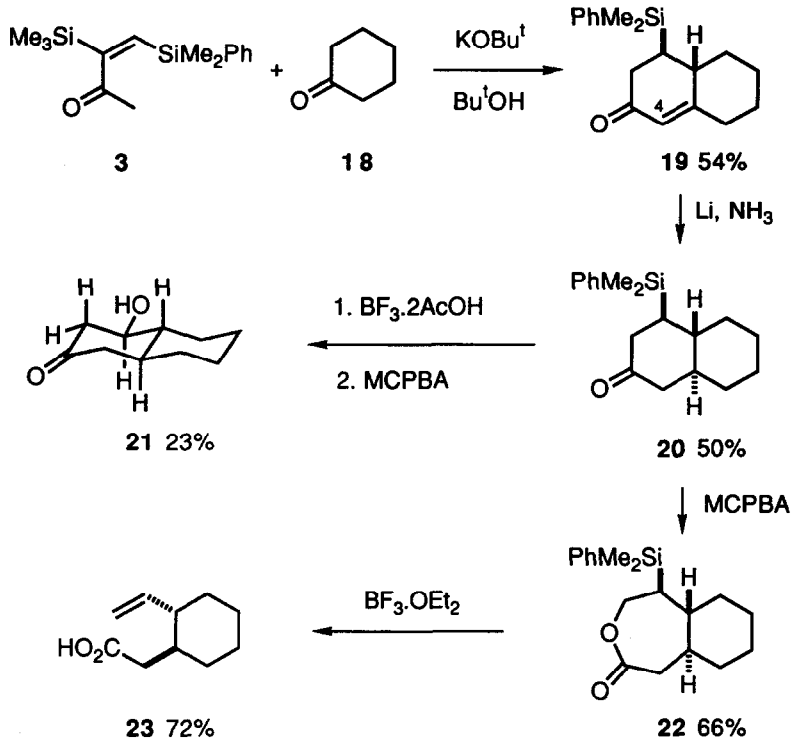
little precedent for the removal of a silyl group from the β-position, occupied by the phenyldimethylsilyl group. There is one example of the phenyl group being displaced intramolecularly from a phenyldimethylsilyl group in this position,[9] but the complete removal of a silyl group from the β position of an allylic double bond has only been reported for one compound in a thesis from this laboratory, and in that compound the β silyl group was *trans* to the hydroxymethyl group, and intramolecular assistance was impossible.[21] There is one case of an allylic alcohol having both an α-phenyldimethylsilyl group and a β-trimethylsilyl group losing only the α-silyl group, but in that compound, the β-silyl group is also *trans* to the hydroxymethyl group.[20] It is, therefore, not clear which silyl group in the case in hand **15** can be expected to go first. In the event, boiling aqueous acetic acid gave only the acetate of the alcohol **15**, with no loss of either silyl group, but treatment with tetrabutylammonium fluoride selectively removed the phenyldimethylsilyl group to give the alcohol **16**, which is the penultimate intermediate in Boeckman's synthesis. When we used less than a full equivalent of tetrabutylammonium fluoride, we obtained the cyclic silyl ether from displacement of the phenyl group, as in the earlier precedent.[9]

Our route to the ketone **1b** is therefore also a four-step sequence, and hence no improvement over the existing synthesis,[5] unless starting with the acetylene **7** can be regarded as an advantage over starting with vinyltrimethylsilane. Our overall yield to the alcohol **16** is 58%, which is probably comparable to that reported, but exact comparisons are not possible because the yield of the alcohol **16** is not reported—the crude material was simply used in the next step. One hope remained for reducing our sequence to three steps—to trap the intermediate cuprate with acetaldehyde instead of acetyl chloride—but this led only to the vinyldisilane **17**, whether or not we added ceric salts or HMPA to the intermediate.

17 85%

One use for which we had prepared the enone **3** was as a component in a Robinson annelation, for which the enone **2** had proved inadequate. We find that the enone **3** is indeed a better substrate, giving, with cyclohexanone **18** in the presence of potassium t-butoxide, the unsaturated ketone **19** as the only identifiable product, although not in high yield. We obtained the same product, but in no better yield, when we used the preformed lithium enolate of cyclohexanone and followed the aprotic Michael step by treating the crude product with sodium methoxide in methanol to complete the annelation. A similar reaction with the enone **9** in place of the enone **3** gave the corresponding C-4 methylated (steroid numbering) version of the enone **19**. Reduction of the enone **19** with lithium in liquid ammonia gave the decalone **20**, from which we could prepare the β-hydroxyketone **21** by converting the phenyldimethylsilyl group into a hydroxyl group.[4] The ^{1}H-NMR spectrum of the alcohol **21** enabled us to assign stereochemistry to the annelation product **19**, since the axial proton adjacent to the hydroxyl group, a well-resolved double double doublet, had two large coupling constants, appropriate for *trans*-diaxial relationships, and one smaller coupling constant to the vicinal equatorial hydrogen. That the stereochemistry should have the silyl group *cis* to the bridgehead hydrogen is reasonable for a reaction that is likely to have been thermodynamically controlled. We assume that the lithium-in-ammonia reduction of the enone **19** is normal in giving a *trans* decalone, but we have no evidence on this point.[22]

Another use for the intermediate **20** is to give the fragmentation product **23**, using Hudrlik's silicon-directed Baeyer-Villiger reaction,[23] which worked well to give regioselectively the lactone **22**.



EXPERIMENTAL

(E)-2-*Dimethyl(phenyl)silyl-1-trimethylsilylhexene* **6**.—1-Trimethylsilylhexyne[24] (240 mg, 1.56 mmol) was kept with the silyl-cuprate reagent[6] (1.56 mmol) under argon at 0 °C for 20 min. Saturated ammonium chloride solution (1 ml) was added and the mixture extracted with light petroleum (b.p. 40-60 °C). The organic layer was washed with ammonium chloride solution and brine, dried ($MgSO_4$) and evaporated under reduced pressure. Chromatography [SiO2, light petroleum (b.p. 40-60 °C)-Et_2O, 19:1] gave the *vinyldisilane* (340 mg, 75%); R_f[light petroleum (b.p. 40-60 °C)-Et_2O, 19:1] 0.69; $\nu_{max}(CCl_4)/cm^{-1}$ 1570 (C=C), 1251 (SiMe), 1433 and 1116 (SiPh); δ_H(90 MHz; CCl_4) 7.7-7.3 (5H, m, Ph), 6.15 (1H, s, C=CH), 2.26 (2 H, br t, *J* 7, $C{=}CCH_2$), 1.45-1.10 (4 H, m, CH_2CH_2), 0.78 (3 H, t, *J* 7, Me), 0.33 (6 H, s, $SiMe_2Ph$) and 0.11 (9 H, s, $SiMe_3$); *m/z* 290 (10%, M^+), 277 (22%, M – Me), 135 (100, $SiMe_2Ph$) and 73 (60, $SiMe_3$)(Found: M^+, 290.1910. $C_{17}H_{30}Si_2$ requires M, 290.1886).

(E)-1-*Dimethyl(phenyl)silyl-2-trimethylsilylpropene* **8**.—Dimethyl(phenyl)silyl-cuprate (1.33 mmol) and trimethylsilylacetylene[7] (392 mg, 1.33 mmol) were mixed at 0 °C. After 3 h, methyl iodide (1 ml) was added and the mixture kept at 0 °C for 1 h. The mixture was quenched with saturated ammonium chloride solution (1 ml) and worked up as above to give the *vinyldisilane* (0.251 g, 76%); R_f[light petroleum (b.p. 40-60 °C)-Et_2O, 19:1] 0.65; $\nu_{max}(CCl_4)/cm^{-1}$ 1581 (C=C), 1250 (SiMe), 1430 and 1113 (SiPh); δ_H(90 MHz; CCl_4) 7.7-7.3 (5H, m, Ph), 6.18 (1H, br s, C=CH), 1.84 (3 H, s, Me), 0.38 (6 H, s, $SiMe_2Ph$) and 0.09 (9 H, s, $SiMe_3$); *m/z* 248 (7%, M^+), 233 (28%, M – Me), 175 (42, M – SiMe3), 135 (100, $SiMe_2Ph$) and 73 (57, $SiMe_3$)(Found: M^+, 248.1433. $C_{14}H_{24}Si_2$ requires M, 248.1416).

Silylcupration-Acylation of Trimethylsilylethyne **7**.—Typically, dimethyl(phenyl)silyllithium (42 ml of a 0.87 M solution in THF, 36.55 mmol) was added to a slurry of copper(I) cyanide (1.64 g, 18.3 mmol) in dry THF (20 ml) under argon at 0 °C, and the mixture stirred for 0.5 h, and cooled to –78 °C. Trimethylsilylacetylene[7] (15 ml of a 1.3 M solution in THF, 18.3 mmol) was added, and, after 3 h, acetyl chloride (3 ml, 20 mmol) was added. After 0.5 h at –78 °C the mixture was kept at 0 °C for 4 h, then quenched with saturated ammonium chloride solution and extracted with ether. The ether was washed with saturated ammonium chloride solution and brine, dried ($MgSO_4$) and evaporated under reduced pressure. The residue was chromatographed (SiO_2, CH_2Cl_2) to give the following ketones:

(E)-3-*Trimethylsilyl*-4-*dimethyl*(*phenyl*)*silylbut*-3-*en*-2-*one* (**3**)(80%); R_f(CH_2Cl_2) 0.63; ν_{max}($CHCl_3$)/cm^{-1} 1680 (C=O), 1251 (SiMe) and 1176 (SiPh); δ_H(250 MHz; $CDCl_3$) 7.55-7.32 (5H, m, Ph), 6.32 (1H, s, C=CH), 2.00 (3 H, s, COMe), 0.43 (6 H, s, $SiMe_2Ph$) and 0.17 (9 H, s, $SiMe_3$); *m/z* 276 (27%, M^+), 261 (76%, M – Me), 135 (100, $SiMe_2Ph$) and 73 (55, $SiMe_3$)(Found: M^+, 276.1366. $C_{15}H_{24}OSi_2$ requires M, 276.1365).

(E)-4-*Trimethylsilyl*-5-*dimethyl*(*phenyl*)*silylpent*-4-*en*-3-*one* **9** (80%); R_f(CH_2Cl_2) 0.77; ν_{max}($CHCl_3$)/cm^{-1} 1680 (C=O), 1251 (SiMe) and 1113 (SiPh); δ_H(250 MHz; $CDCl_3$) 7.55-7.32 (5 H, m, Ph), 6.35 (1H, s), 2.30 (2 H, q, *J* 7.5), 0.95 (3 H, t, *J* 7.5), 0.35(6 H, s, $SiMe_2Ph$) and 0.17 (9 H, s, $SiMe_3$); *m/z* 290 (15%, M^+), 275 (55, M – Me), 275 (18, M-Et), 154 (90, M – $SiMe_2Ph$) 135 (100, $SiMe_2Ph$) and 73 (55, $SiMe_3$)(Found: M^+ 275.1280. $C_{16}H_{26}OSi$ requires M, 276.1287).

(E)-1-*Phenyl*-2-*trimethylsilyl*-3-*dimethyl*(*phenyl*)*silylprop*-2-*enone* **10** (70%); R_f(hexane-EtOAc, 4:1) 0.72; ν_{max}($CHCl_3$)/cm^{-1} 1680 (C=O), 1251 (SiMe) and 1113 (SiPh); δ_H(250 MHz; $CDCl_3$) 8.01-7.32 (10 H, m, Ph), 6.62 (1 H, s), 0.23 (6 H, s, $SiMe_2Ph$) and 0.10 (9 H, s, $SiMe_3$); *m/z* 238 (10%, M^+), 323 (60, M – 15), 261 (18, M – Ph), 135 (100, $SiMe_2Ph$) and 73 (55, $SiMe_3$)(Found: M^+ 238.1524. $C_{20}H_{26}OSi_2$ requires M, 238.1522).

1-*Dimethyl*(*phenyl*)*silyl*-2-*trimethylsilylethylene* **17**[25] using acetaldehyde in place of acetyl chloride (85%); R_f(hexane-EtOAc, 4:1) 0.78; ν_{max}($CHCl_3$)/cm^{-1} 1266 (SiMe) and 1113 (SiPh); δ_H(250 MHz; $CDCl_3$) 7.54-7.39 (5 H, m, Ph), 6.74-6.70 (2 H, m, C*H* =C*H*), 0.34 (6 H, s, $SiMe_2Ph$) and 0.10 (9 H, s, $SiMe_3$); *m/z* 234 (80%, M – Me), 135 (100, $SiMe_2Ph$) and 73 (55, $SiMe_3$).

(E)-4-*Dimethyl*(*phenyl*)*silylbut*-3-*en*-2-*one* **11**.—The enone **3** (0.36 mmol) was stirred with the boron trifluoride-acetic acid complex (0.36 mmol) in dichloromethane at room temperature for 8 h. Sodium bicarbonate solution was added and the mixture extracted with ether (2 × 30 ml). The ether was dried ($MgSO_4$) and evaporated under reduced pressure to give the *ketone* (78%); R_f(hexane-EtOAc, 4:1) 0.56; ν_{max}($CHCl_3$)/cm^{-1} 1672 (C=O), 1216 (SiMe) and 1114 (SiPh); δ_H(250 MHz; $CDCl_3$) 7.55-7.32 (5 H, m, Ph), 7.11 (H, d, *J* 19.2, CH=C*H*CO), 6.48 (H, d, *J* 19.2 CH=C*H*Si), 2.28 (3H, s, COMe) and 0.43 (6 H, s, $SiMe_3$)(Found: M^+, 204.0959. $C_{12}H_{16}OSi$ requires *M*, 204.0966).This compound was also obtained (70%) by following the general procedure described above for the silyl-cupration of trimethylsilylacetylene and quenching with acetyl chloride (10 equivalents).

Preparation of the Ketones **14**.—Typically, tetrabutylammonium fluoride in THF (0.36 ml, 1 M, 0.36 mmol) was stirred with the ketone **3**, **9** or **10** (0.36 mmol) in THF (5 ml) at room temperature for 8 h under argon. Ethyl acetate (20 ml) was added, and the organic layer washed with brine, dried ($MgSO_4$) and evaporated under reduced pressure. The residue was chromatographed (SiO_2, CH_2Cl_2) to give the following ketones:

4-Phenylbutan-2-one **14** (R = Me) (95%); R_f(CH_2Cl_2) 0.80; ν_{max}($CHCl_3$)/cm^{-1} 1714 (C=O) and 1358 (MeCO); δ_H(250 MHz; $CDCl_3$) 7.31-7.16 (5 H, m, Ph), 2.93-2.86 (2 H, t, *J* 7.1, CH_2CH_2), 2.78-2.72 (2 H, t, *J* 8.0, CH_2CH_2) and 2.13 (3 H, s, COMe) identical with the published spectrum;[26] *m/z* 148 (100%, M^+) and 105 (80, M – Ac)(Found: M^+, 148.1066. $C_{10}H_{12}O$ requires *M*, 148.0888).

1-Phenylpentan-3-one[27] **14** (R = Et) (95%); R_f (CH_2Cl_2) 0.85; ν_{max}($CHCl_3$)/cm^{-1} 1714 (C=O) and 1358 (MeCO); δ_H(250 MHz; $CDCl_3$) 7.30-7.15 (5 H, m, Ph), 2.89 (4 H, t, *J* 7.4, CH_2Ph), 2.77-2.69 (2 H, t, *J* 7.5, CH_2Ph), 2.40 (2 H, q, *J* 7.5, CH_2Me) and 1.03 (3 H, t, *J* 7.5, CH_2Me).
1,3-Diphenylpropan-3-one **14** (R = Ph) (95%); R_f(CH_2Cl_2) 0.70; ν_{max}($CHCl_3$)/cm^{-1} 1714 (C=O); δ_H(250 MHz; $CDCl_3$) 8.01-7.16 (10 H, m, Ph), 3.30 (2 H, t, *J* 7.4, CH_2CH_2Ph), and 3.06 (2 H t, *J* 7.9, CH_2CH_2CO) identical with the published spectrum.[28]

(E)-4-*Dimethyl(phenyl)silyl*-3-*trimethylsilylbut*-3-*en*-2-*ol* **15**.—Sodium borohydride (2.72 g, 72 mmol) was added to a stirred solution of the enone **3** (2 g, 7.2 mmol) and cerium(III) chloride (17.7 g, 72 mmol) in dry methanol (40 ml) at 0 °C. A vigorous evolution of gas occurred, together with an increase in temperature (35-40 °C).The mixture was stirred for 1 h at 0 °C, then quenched with a saturated solution of ammonium chloride and extracted with ether (2 × 50 ml). The extract was washed with brine, dried ($MgSO_4$) and evaporated under reduced pressure. The residue was chromatographed (SiO_2, CH_2Cl_2) to give the *alcohol* (1.9 g, 85%); R_f(CH_2Cl_2) 0.55; ν_{max}($CHCl_3$)/cm^{-1} 3611 (OH), 1559 (C=C), 1249 (SiMe) and 1112 (SiPh); δ_H(250 MHz; $CDCl_3$) 7.53-7.32 (5 H, m, Ph), 6.18 (1 H, s, =C*H*SiMe$_2$Ph), 4.63 (1 H, q, *J* 7.5, C*H* OH), 1.45 (1 H, br s, OH), 1.15 (3 H, d, *J* 7.5, Me), 0.43 (3 H, s, Si*Me*$_A$Me$_B$), 0.39 (3 H, s, SiMe$_A$*Me*$_B$) and 0.16 (9 H, s, SiMe$_3$); *m/z* 278 (58%, M^+), 260 (50, M – H_2O), 135 (100, SiMe$_2$Ph) and 73 (40, SiMe$_3$)(Found: M^+, 278.1522. $C_{15}H_{26}OSi_2$ requires *M*, 278.1522).

3-*Trimethylsilylbut*-3-*en*-2-*ol* **16**.—Tetrabutylammonium fluoride in THF (0.36 ml, 1 M, 0.36 mmol) was stirred with **15** (100 mg, 0.36 mmol) in THF (5 ml) under argon at room temperature for 8 h. The mixture was diluted with ethyl acetate (20 ml), washed with brine, dried ($MgSO_4$) and evaporated under reduced pressure. The residue was chromatographed (SiO_2, CH_2Cl_2) to give the alcohol (45 mg, 85%); R_f(CH_2Cl_2) 0.22; ν_{max}($CHCl_3$)/cm^{-1} 3690-3605 (OH), 1600 (C=C) and 1250(SiMe); δ_H(250 MHz; $CDCl_3$) 5.79 (1 H, m, =C*H*$_A$H$_B$), 5.36 (1 H, m, =CH$_A$*H*$_B$),4.48 (1 H, q, *J* 6.45, C*H* OH), 1.54 (1 H, br s, OH), 1.29 (3 H, d, *J* 6.45, Me) and 0.13 (9 H, s, SiMe$_3$); *m/z* 144 (20%, M^+) and 73 (50, SiMe$_3$). A similar experiment, but using only one-third of an equivalent of fluoride, gave the cyclic ether 2,2,5-*trimethyl*-3-*trimethylsilyl*-2-*sila*-2,5-*dihydrofuran* (60%) from displacement of the phenyl group; R_f(CH_2Cl_2) 0.22; ν_{max}($CHCl_3$)/cm^{-1} 1560 (C=C), 1251(SiMe), and 1216 (SiO-C); δ_H(250 MHz; $CDCl_3$) 6.37 (1 H, d, *J* 1.9, =C*H*SiMe$_2$O), 4.90 (1 H, dq, *J* 6.6 and 1.9, MeC*H*O), 1.30 (3 H, d, *J* 6.6, *Me*CHO), 0.24 (3 H, s, OSi*Me*$_A$Me$_B$Ph), 0.19 (3 H, s, OSiMe$_A$*Me*$_B$Ph) and 0.13 (9 H, s, SiMe$_3$); *m/z* 200 (60%, M^+) and 73 (50%, SiMe$_3$).

(E)-2-*Acetoxy*--4-*dimethyl(phenyl)silyl*-3-*trimethylsilylbut*-3-*ene*.—The alcohol **15** (100 mg, 0.36 mmol) was heated at 110 °C for 48 h in glacial acetic acid (1 ml) and water (0.05 ml). The mixture was cooled and quenched with saturated sodium bicarbonate solution (10 ml) and the mixture was extracted with ether. The ether extract was washed with brine, dried ($MgSO_4$) and evaporated under reduced pressure. The residue was chromatographed (SiO_2, CH_2Cl_2) to give the acetate (110 mg, 90%); R_f(CH_2Cl_2) 0.75; ν_{max}($CHCl_3$)/cm^{-1} 1728 (C=O), 1527 (C=C), 1250 (SiMe), 1216 (C-O-C) and 1112 (SiPh); δ_H(250 MHz; $CDCl_3$) 7.55-7.33 (5 H, m, Ph), 6.23 (1 H, s, =C*H*SiMe$_2$Ph), 5.71 (1 H, q, *J* 6.7, C*H*MeOAc), 2.05 (3 H, s, COMe), 1.12 (3 H, d, *J* 6.7, Me), 0.48 (3 H, s, Si*Me*$_A$Me$_B$), 0.45 (3 H, s, SiMe$_A$*Me* $_B$) and 0.16 (9 H, s, SiMe$_3$).

(5RS,6RS)-5-*Dimethyl(phenyl)silylbicyclo*[*4.4.0*]*dec*-1-*en*-3-*one* **19**.—Method A: Cyclohexanone (0.19 ml, 1.81 mmol) was added to LDA [prepared from butyl-lithium (1.30 ml of a 1.5 M solution in hexane) and diisopropylamine (0.27 ml, 1.9 mmol) in THF (5 ml)], the mixture kept at –20 °C for 0.5 h, and then cooled to –78 °C. Ketone **3** (0.5 g, 1.81 mmol) was added, the solution was allowed to warm to room temperature and kept for 24 h. The mixture was quenched with a saturated ammonium chloride solution and extracted with ether (2 × 50 ml). The extract was washed with brine, dried ($MgSO_4$) and evaporated under reduced pressure. The residue was chromatographed (SiO_2, hexane-EtOAc, 4:1) to give the *octalone* (0.25 g, 50%); R_f(hexane-EtOAc, 4:1)

0.42; $\nu_{max}(CHCl_3)/cm^{-1}$ 1657 (C=O), 1559 (C=C) and 1112 (SiPh); δ_H(250 MHz; $CDCl_3$) 7.53-7.32 (5 H, m, Ph), 5.76 (1 H, s, =C*H*), 2.5-1.10 (12 H, m), 0.34 (3 H, s, Si*Me*$_A$Me$_B$Ph) and 0.29 (3 H, s, SiMe$_A$*Me*$_B$Ph); *m/z* 284 (65%, M^+), 149 (50, M – $SiMe_2Ph$) and 135 (100, $SiMe_2Ph$)(Found: M^+, 284.1603. $C_{18}H_{24}OSi$ requires *M*, 284.1596). Method B: Cyclohexanone (1.2 ml, 10.5 mmol) and the enone **3** (2.9g, 10.5 mmol) in t-butanol (5 ml) were added to potassium t-butoxide (2.6g, 21 mmol) in t-butanol (15 ml) under argon at 35°C, and the mixture stirred at 35°C for 0.75 h. The mixture was cooled to room temperature and extracted with ether (50 ml). The ether layer was washed with brine, dried ($MgSO_4$) and evaporated under reduced pressure. The residue was chromatographed (SiO_2, EtOAc-hexane, 15:85) to give the octalone (1.6 g, 54%) identical (^{1}H-NMR, IR, TLC) with the earlier sample. Method C: Methyllithium (1.26 ml of a 1.4 mol dm^{-3} solution in hexane) was added dropwise to a solution of the silyl enol ether[29] (0.3g, 1.76 mmol) in ether (5 ml). The mixture was stirred for 0.25 h at room temperature and evaporated to dryness. The enone **3** (0.35 g, 1.27 mmol) in THF (3 ml) was added dropwise at 0 °C to the residue in THF (4 ml), and the mixture stirred for 1.5 h at room temperature. The mixture was evaporated to dryness and the residue stirred with sodium methoxide in methanol (6 ml of a 0.37 mol dm^{-3} solution) for 1.25 h. The solvent was evaporated, the residue was partitioned between water and ethyl acetate and acidified with dilute hydrochloric acid. The aqueous layer was extracted into ethyl acetate, and the combined organic layers were dried ($MgSO_4$) and evaporated. Flash chromatography (SiO_2, EtOAc-hexane, 15:85) gave the octalone (150 mg 42%) identical (^{1}H-NMR, IR, TLC) with the earlier samples.

(5RS,6RS)-2-*Methyl*-5-*dimethyl*(*phenyl*)*silylbicyclo*[*4.4.0*]*dec*-1-*en*-3-*one*.—A similar reaction using cyclohexanone and the enone **9** and method A gave the corresponding *octalone* (50%); R_f(hexane-EtOAc, 4:1) 0.62; $\nu_{max}(CHCl_3)/cm^{-1}$ 1670 (C=O), 1559 (C=C) and 1112 (SiPh); δ_H(250 MHz; $CDCl_3$) 7.53-7.32 (5 H, m, Ph), 2.5-1.10 (15 H, m), 0.34 (3 H, s, Si*Me*$_A$Me$_B$Ph) and 0.29 (3 H, s, SiMe$_A$*Me*$_B$Ph). (Found: M^+, 298.1774. $C_{19}H_{26}OSi$ requires *M*, 298.1753).

(1RS,5SR,6SR)-5-*Dimethyl*(*phenyl*)*silylbicyclo*[*4.4.0*]*decan*-3-*one* **20**.—Lithium shot (0.23 g, 33 mmol) was stirred for 0.5 h in freshly distilled ammonia (60 ml) at –78 °C. The octalone **19** (5 ml of a 0.69 mol dm^{-3} solution in ether) was added and the mixture stirred at –78 °C for 3 h. The mixture was quenched with ammonium chloride (4 g) and the solvent allowed to evaporate. The residue was partitioned between ether (50 ml) and water (40 ml) and extracted with ether (2 × 50 ml). The combined ether layers were dried ($MgSO_4$) and evaporated. The residue was chromatographed (SiO_2, EtOAc-hexane, 15:85) to give the *ketone* (0.49 g, 50%). R_f(EtOAc-hexane, 30:70) 0.53; ν_{max}(film)/cm^{-1} 1720 (C=O);.δ_H(250 MHz; $CDCl_3$) 7.48-7.20.(5 H, m, Ph), 2.28-1.03 (15 H, m), 0.34 (3 H, s, Si*Me*$_A$Me$_B$) and 0.25 (3 H, s, SiMe$_A$*Me*$_B$)(Found: M^+, 286.1748. $C_{18}H_{26}OSi$ requires *M*, 286.1752).

(1RS,5SR,6SR)-5-*Dimethyl*(*fluoro*)*silylbicyclo*[*4.4.0*]*decan*-3-*one*.—Boron trifluoride-acetic acid complex (1.5 ml, 11.1 mmol) was stirred with the ketone **20** (320 mg 1.12 mmol) in dichloromethane (5 ml) at room temperature for 20 h. The mixture was diluted with dichloromethane (50 ml). The organic layer was washed with sodium bicarbonate solution, dried ($MgSO_4$), and evaporated. Flash chromatography (SiO_2, Et_2O-hexane, 30:70) of the residue gave the *fluorosilane* (115 mg, 46%); R_f(EtOAc-hexane, 30:70) 0.11; ν_{max}(film)/cm^{-1} 1720 (C=O), 1250 (SiMe) and 870 (SiC and SiF); δ_H(250 MHz; $CDCl_3$) 2.39-0.84 (15 H, m) and 0.17 (6 H, d, *J* 5.7, $SiMe_2$)(Found: M^+, 228.1340. $C_{12}H_{21}FOSi$ requires *M*, 228.1346).

(1RS,5SR,6SR)-5-*Hydroxybicyclo*[*4.4.0*]*decan*-3-*one* **21**.—3-Chloroperoxybenzoic acid (470 mg, 1.5 mmol), the fluorosilane (110 mg, 0.48 mmol) and potassium fluoride (102 mg, 0.96 mmol) in DMF (10 ml) were stirred at room temperature for 2 h. The mixture was diluted with dichloromethane and washed with aqueous solutions of sodium persulphate, sodium bicarbonate and brine. The organic layer was dried ($MgSO_4$), and evaporated under reduced pressure and the residue sublimed (30 °C/0.01 mmHg) to give the β-*ketoalcohol* (40 mg, 50%); ν_{max}(film)/cm^{-1} 3400 (OH) and 1700 (C=O); δ_H(400 MHz; $CDCl_3$) 3.55-3.49 (1 H, ddd, *J* 5, 9.4

and 11.4, C*H*OH), 2.75 (1 H, ddd, *J* 2.3, 5 and 13.6, H-4α), 2.41 (1 H, dd, *J* 11.4 and 13.4, H-4β), 2.28 (1 H, ddd, *J* 2.3, 3.6 and 14.1, H-2α), 2.22 (1 H, m, H-1 or H-6), 2.08 (1 H, dd, *J* 12.5 and 14.1, H-2-β), 1.85-1.73 (4 H, m) and 1.37-1.24 (5 H, m)(Found: M+, 168.1157. $C_{10}H_{16}O_2$ requires *M*, 168.1150).

(1RS,6RS,7SR)-6-*Dimethyl(phenyl)silyl*-4-*oxabicyclo[5.4.0]undecan*-3-*one* **22**.—The ketone **20** (0.2 g, 0.70 mmol) in dichloromethane (3 ml) was added dropwise to a solution of 3-chloroperoxybenzoic acid (0.44 g, 1.4 mmol) in dichloromethane (5 ml), and the mixture stirred at room temperature for 72 h. Sodium bicarbonate solution (15 ml) was added and the mixture stirred for 0.25 h. The aqueous layer was washed with dichloromethane. The combined organic layers were washed with sodium hydroxide solution and sodium bicarbonate solution, dried ($MgSO_4$), and evaporated under reduced pressure. The residue was chromatographed (TLC, SiO_2, 2 × Et_2O-hexane, 1:3) to give the *lactone* (140 mg, 66%); R_f(EtOAc-hexane, 30:70) 0.37; ν_{max}(film)/cm^{-1} 1740 (C=O), 1300, 1250 (C-O) and 840 (Si-C); δ_H(250MHz; $CDCl_3$) 7.46-7.33 (5 H, m, Ph), 4.35 (1 H, dd, *J* 1.5 and 13.1, CH_ACH$_B$O), 4.16 (1 H, dd, *J* 9.2 and 13.1, CH$_A$CH_BO), 2.67 (1 H, dd, *J* 13.8 and 10.9, CH_ACH$_B$CO), 2.29 (1 H, d, *J* 14.5, CH$_A$CH_BCO), 1.85-0.81 (11 H, m), 0.40 (3 H, s, SiMe_AMe$_B$) and 0.37 (3H, s, SiMe$_A$$Me_B$)(Found: M+, 302.1691. $C_{18}H_{26}O_2Si$ requires *M*, 302.1695).

trans-2-*Vinylcyclohexylacetic Acid* **23**.—Boron trifluoride etherate (0.17 ml, 1.38 mmol) was added to the lactone (100 mg, 0.33 mmol) in dichloromethane (5 ml) at 0 °C and the mixture kept at room temperature for 3 h. The mixture was quenched with sodium bicarbonate solution and extracted with ether. The organic layers were extracted with further portions of sodium bicarbonate solution. The combined aqueous phases were cooled in an ice bath and acidified to pH 1 with dilute sulphuric acid before being extracted into dichloromethane. The combined organic extracts were dried ($MgSO_4$) and evaporated. The residue was chromatographed (SiO_2, Et_2O-hexane, 15:85) to give the *acid* (40 mg, 72%); R_f(EtOAc-hexane, 30:70) 0.32; ν_{max}(film)/cm^{-1} 3500-2800 (C-H and CO_2H), 1710 (C=O) and 1640 (C=C); δ_H(250MHz; $CDCl_3$) 5.58 (1 H, ddd, *J* 8.6, 10.1 and 17.1, *H*C=CH$_2$), 4.99 (1 H, dd, *J* 17.1 and 2, C=CH_AH$_B$), 4.95 (1 H, dd, *J* 10.1 and 2, C=CH$_A$$H_B$), 2.58 (1 H, dd, *J* 15.4 and 3.8, CH_AH$_B$CO$_2$H), 1.97 (1 H, dd, *J* 15.4, 9.1, CH$_A$$H_BCO_2$H), 1.88-1.65 (6 H, m) and 1.29-1.21 (4 H, m)(Found: M+, 168.1151. $C_{10}H_{16}O_2$ requires *M*, 168.1150).

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REFERENCES

1. Stork, G.; Ganem, B. *J. Am. Chem. Soc.* **1973**, *95*, 6152.
2. Boeckman, R. K., Jr. *J. Am. Chem. Soc.* **1973**, *95*, 6867; Boeckman, R. K., Jr.; Blum D. M.; Ganem, B. *Org. Synth. (N.Y.)* **1978**, *58*, 158.
3. Fleming, I; Perry, D. A. *Tetrahedron*, **1981**, *37*, 4027; Wilson, S. R.; Di Grandi, M. J. *J. Org. Chem.* **1991**, *56*, 4766.
4. Fleming, I.; Henning R.; Plaut, H. *J. Chem. Soc., Chem. Commun.* **1984**, 29; Fleming, I.; Sanderson, P. E. J. *Tetrahedron Lett.* **1987**, *28*, 4229.
5. Boeckman, R. K., Jr.; Blum, D. M.; Ganem B.; Halvey, N. *Org. Synth.* **1978**, *58*, 152.
6. Fleming, I.; Newton T. W.; Roessler, F. *J. Chem. Soc. Perkin Trans. 1* **1981**, 2527.
7. Holmes, A. B.; Sporikou, C. N. *Org. Synth.* **1987**, *62*, 61.
8. Hudrlik, P. F.; Schwartz, R. H.; Hogan, J. C. *J. Org. Chem.* **1979**, *44*, 155.
9. Oda, H.; Sato, M.; Morizawa, Y.; Oshima, K.; Nozaki, H. *Tetrahedron Lett.* **1983**, *24*, 2877; Oda, H.; Sato, M.; Morizawa, Y.; Oshima, K.; Nozaki, H. *Tedrahedron* **1985**, *41*, 3257.
10. Whitmore, F. C.; Sommer, L. H.; Gold, J. *J. Am. Chem. Soc.* **1947**, *69*, 1976; Bott, R. W.; Eaborn, C.; Rushton, B. M. *J. Organomet. Chem.* **1965**, *3*, 455; Bassindale, A. R.; Brook, A. G.; Jones, P. F.; Lennon, J. M. *Can. J. Chem.* **1975**, *53*, 332; Corey, J. Y.; Chang, V. H. T. *Organometallics* **1982**, 1,

645; Damrauer, R.; Danahey, S. E.; Yost, V. E. *J. Am. Chem. Soc.* **1984**, *106*, 7633; Kreeger, R. L.; Menard, P. R.; Sans, E. A.; Schechter, H. *Tetrahedron Lett.* **1985**, *26*, 1115; Tamao, K.; Nakajima, T.; Kumada, M. *Organometallics* **1984**, *3*, 1655; Apeloig, Y.; Stanger, A. *J. Am. Chem. Soc.*, **1987**, *109*, 272; Kevill, D. N. *J. Chem. Res. (S)* **1987**, 272.
11. Hudrlik, P. F.; Kulkarni, A. K. *Tetrahedron Lett.* **1985**, *26*, 1389.
12. Matsumoto, K.; Takeyama, Y.; Oshima, K.; Utimoto, K. *Tetrahedron Lett.* **1991**, *32*, 4545.
13. Page, P. C. B.; Rosenthal, S. *J. Chem. Res. (S)* **1990**, 302.
14. Buncel, E.; Davis, A. G. *J. Chem. Soc.*, **1958**, 1550; Kumada, M.; Tamao, K.; Yoshida, J.-I. *J. Organomet. Chem.* **1982**, *239*, 115; Tamao, K. *J. Synth. Org. Chem. (Jpn.)* **1988**, *46*, 861; Tamao, K.; Hayashi, T.; Ito, Y. in *Frontiers of Organosilicon Chemistry*; Bassindale, A. R.; Gaspar, P. P. Eds.; R.S.C.; Cambridge, 1991; p. 197.
15. Landrum, B. E.; Lay, J. O.; Allison, N. T. *Organometallics* **1988**, *7*, 787.
16. A. G. Brook, *Adv. Organomet. Chem.*, **1968**, *7*, 95.
17. Bott, R. W.; Eaborn, C.; Swaddle, T. W. *J. Chem. Soc.* **1963**, 2342; Bennetau, B.; Bordeau, M.; Dunoguès, J. *Bull. Soc. Chim. Fr.* **1985**, II-90.
18. Gemal, A. L.; Luche, J. L. *J. Am. Chem. Soc.* **1981**, *103*, 5454.
19. Chan, T. H.; Mychajlowskij, W. *Tetrahedron Lett.* **1974**, 3479; Snider, B. B.; Karras, M.; Conn, R. S. E. *J. Am. Chem. Soc.* **1978**, *100*, 4624; Fristad, W. E.; Bailey, T. R.; Paquette, L. A.; Gleiter, R.; Bohm, M. C. *J. Am. Chem. Soc.* **1979**, *101*, 4420; Wrobel, J. E.; Ganem, B. *J. Org. Chem.* **1983**, *48*, 3761; Larson, G. L.; Torres, E.; Morales, C. B.; McGarvey, G. J. *Organometallics* **1986**, *5*, 2274; Jefford, C. W.; Moulin, M.-C. *Helv. Chim. Acta* **1991**, *74*, 336; Burke, S. D.; Piscopio, A. D.; Marron, B. E.; Matulenko, M. A.; Pan, G. *Tetrahedron Lett.* **1991**, *32*, 857; Krafft, M. E.; Wright, C. *Tetrahedron Lett.* **1992**, *33*, 151.
20. Wakamatsu, K.; Nonaka, T.; Okuda, Y.; Tückmantel, W.; Oshima, K.; Utimoto, K.; Nozaki, H. *Tetrahedron* **1986**, *42*, 4427.
21. Sarkar, A. K. *Allylsilanes in Organic Synthesis*, University of Cambridge, 1987.
22. Stork, G.; Darling, S. D. *J. Am. Chem. Soc.* **1964**, *80*, 1761.
23. Hudrlik, P. F.; Hudrlik, A. M.; Yimenu, T.; Zellers, E. T.; Chin, E. *J. Am. Chem. Soc.* **1980**, *102*, 6894; Hudrlik, P. F.; Hudrlik, A. M.; Yimenu, T.; Waugh, M. A.; Nagendrappa, G. *Tetrahedron* **1988**, *44*, 3791.
24. Frisch, K. C.; Young, R. B. *J. Am. Chem. Soc.* **1952**, *74*, 4853.
25. Barbero, A.; Cuadrado, P.; Fleming, I.; González, A. M.; Pulido, F. J. paper in preparation.
26. Tsuda, T.; Hayashi, T.; Satomi, H.; Kawamoto, T. *J. Org. Chem.* **1986**, *51*, 537.
27. Hewitt, L. J.; Kenyon, J. *J. Chem. Soc.* **1925**, 1094.
28. Ohta, H.; Konishi, J.; Tsuchihashi, G. *Chem. Lett. (Jpn).* **1983**, 1985.
29. Cazeau, P.; Moulines, F.; Laporte, O.; Duboudin, F. *J. Organomet. Chem.***1980**, *201*, C9.