Tetrahedron Vol. 45, No. 2, pp. 363 to 380, 1989
Printed in Great Britain.

0040-4020/89 $3.00+.00

REACTION OF (TRIMETHYLSTANNYL)COPPER(I) REAGENTS WITH α,β-ACETYLENIC ESTERS. STEREOCONTROLLED SYNTHESIS OF ALKYL (E)- AND (Z)-3-TRIMETHYLSTANNYL-2-ALKENOATES

Edward Piers,* J. Michael Chong, and Howard E. Morton

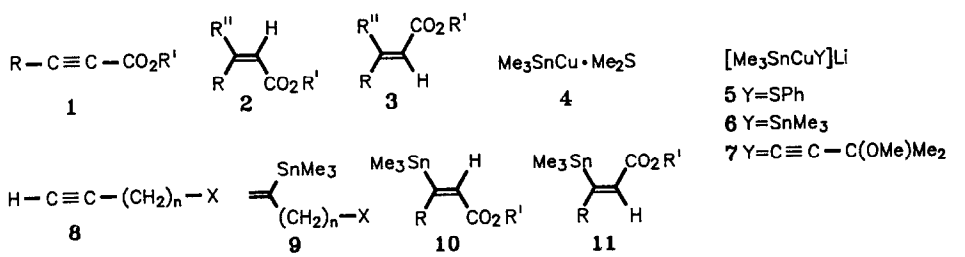
Department of Chemistry, University of British Columbia,
2036 Main Mall, University Campus, Vancouver, B.C., Canada, V6T 1Y6

(*Received in USA* 28 *April* 1988)

ABSTRACT - The reactions of α,β-actylenic esters 1 with the (trimethylstannyl)copper(I) reagents 4-7 provide good to excellent yields of the corresponding β-trimethylstannyl α,β-unsaturated esters 10 and (or) 11. In nearly all cases studied, except for the reactions involving substrate 1i, the stereochemical outcome of the transformations can be controlled by judicious choice of reagent and (or) reaction conditions. Consequently, both alkyl (E)- and (Z)-3-trimethylstannyl-2-alkenoates (10 and 11, respectively) can be produced stereoselectively. The reagents of choice for preparing the (E) isomers 10 appear to be $Me_3SnCu{\cdot}Me_2S$ (4) and $[Me_3SnCuSPh]Li$ (5), while reagent 5 must be employed for the efficient, stereoselective production of the (Z) isomers 11. Reaction of reagent (5) with substrates 1j and 1k under appropriate conditions provides good yields of methyl 2-trimethylstannyl-1-cyclopentenecarboxylate (42). However, treatment of the esters 1ℓ and 1m with 5 under similar conditions gives the "anomalous" products 44 and 45.

INTRODUCTION

Over the past couple of decades, the conjugate addition of organocopper(I) reagents to α,β-acetylenic esters 1 has seen considerable use a as method for preparing trisubstituted alkenes.[1] It has been shown that the stereoselectivity of this type of reaction varies with the nature of the reagent, the solvent, and the reaction conditions (time, temperature). Nevertheless, suitable conditions have been developed to effect the efficient, highly stereoselective conversion of 1 into α,β-unsaturated esters of general structure 2 (R″ derived from an organocopper(I) reagent). Thus, the overall cis addition of R″ and a proton across the triple bond of 1 is readily accomplished.[1] Unfortunately, reaction conditions that would allow the use of organocopper(I) reagents to effect the highly stereoselective trans addition of R″ and H across the alkyne function of 1 (to form 3) have not yet been found.[1]



Recently, we described, inter alia, the preparation of the (trimethylstannyl)copper(I) reagents 4-7 and reported that these species transfer efficiently the trimethylstannyl group to the β carbon of α,β-unsaturated carbonyl compounds.[2] Subsequently, we showed[3] that (trimethylstannyl)copper(I)·dimethyl sulfide (4) is an effective reagent for the conversion of 1-alkynes 8 (X = Cl, OH, OR) into 2-trimethylstannyl-1-alkynes 9. In connection with a continuation of our study of the chemical reactivity of reagents 4-7, along with our desire to

prepare and explore the chemistry of β-trimethylstannyl α,β-unsaturated esters, we have investigated the reactions of 4-7 with α,β-acetylenic esters 1. We were particularly interested in determining whether substances 1 could be converted, stereoselectively, into both (E) and (Z) α,β-unsaturated esters of general structures 10 and 11, respectively. We report herein the results of this study.[4]

RESULTS AND DISCUSSION

(a) Preparation of α,β-acetylenic esters. Of the 2-alkynoates 1 (see Chart 1) used for the present study, compounds 1a and 1b are commercially available. Substrates 1c and 1d were prepared as outlined in eq. [1]. Thus, reaction of the aldehydes 12 and 13[5] with $Ph_3P{=}CBr_2$ in

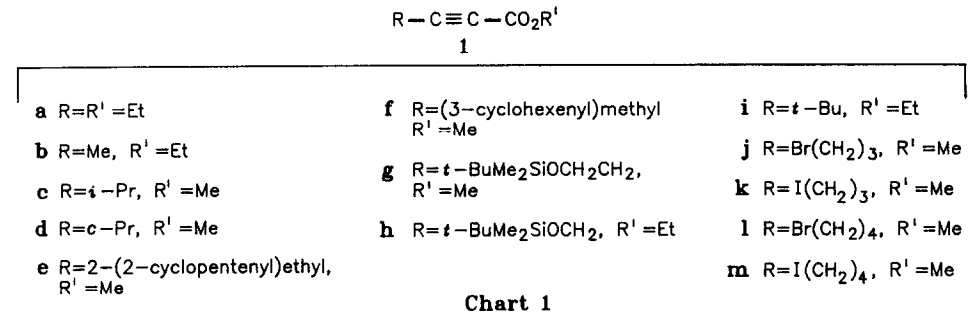
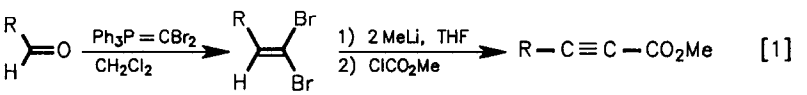


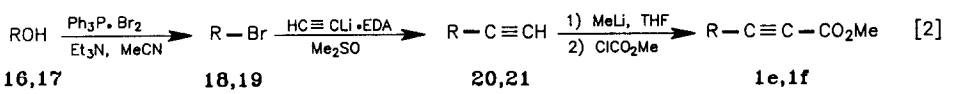
Chart 1

CH_2Cl_2[6] provided the 1,1-dibromo-1-alkenes 14[7] and 15, which, upon treatment with 2 equivalents of MeLi in tetrahydrofuran (THF), followed by methyl chloroformate, gave the required esters 1c (30 % from 12) and 1d (52 % from 13).



12 R=*i*-Pr **14** R=*i*-Pr **1c** R=*i*-Pr
13 R=*c*-Pr **15** R=*c*-Pr **1d** R=*c*-Pr

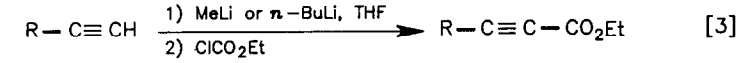
Reaction of the primary alcohols 16[8] and 17[9] with $Ph_3P{\cdot}Br_2$[10] in MeCN containing Et_3N provided the bromides 18 and 19,[11] which, upon reaction with lithium acetylide-ethylenediamine complex[12] in Me_2SO, were converted into the 1-alkynes 20 and 21. The latter substances were readily transferred into the α,β-acetylenic esters 1e (51 % from 16) and 1f (33 % from 17) (eq. [2]).



16,17 **18,19** **20,21** **1e,1f**

16,18,20,1e, R=2-(2-cyclopentenyl)ethyl
17,19,21,1f R=(3-cyclohexenyl)methyl

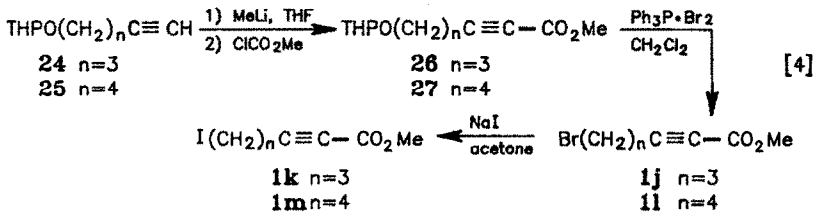
The 2-pentynoate 1g was prepared (92 %) by treatment of methyl 5-hydroxy-2-pentynoate[13] with t-$BuMe_2SiCl$ in Me_2NCHO containing imidazole. Substrates 1h and 1i[14] were obtained in excellent yields from the 1-alkynes 22[15] and 23, respectively, as summarized in eq. [3].



22 R= *t*-$BuMe_2SiOCH_2$ **1h** R= *t*-$BuMe_2SiOCH_2$
23 R= *t*-Bu **1i** R= *t*-Bu

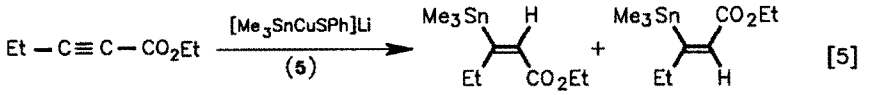
The ω-halo α,β-acetylenic esters 1j - 1m were produced by the reactions summarized in eq. [4]. The 1-alkynes 24 (prepared by treatment of 4-pentyn-1-ol with dihydropyran in the presence of pyridinium p-toluenesulfonate[16]) and 25[17] were converted into the corresponding esters

26 and 27, which, upon reaction with $Ph_3P{\cdot}Br_2$ in CH_2Cl_2,[18] were transformed directly into the bromides 1j (68 % from 24) and 1ℓ (79 % from 25). Treatment of the latter two substances with NaI in acetone provided the corresponding iodides 1k (91 %) and 1m (90 %).



[4]

(b) Reaction of α,β-acetylenic esters 1 with $[Me_3SnCuSPh]Li$ (5). Our initial experiments were carried out with ethyl 2-pentynoate (1a). Treatment of this substrate with 1.3 equivalents of 5 (THF, -78 °C, 3 h), followed by addition of MeOH, gave, in 69 % yield, a 68:32 mixture of the geometric isomers 10a and 11a, respectively (eq. [5]). On the other hand, when the reaction was carried out with 2.5 equivalents of 5 at -100 °C for 6 h, workup provided 10a and 11a in a ratio of 97:3, respectively. However, the addition process could be performed in a shorter time and with even higher stereoselectivity by adding a THF solution of 1a containing 1.7 equivalents of MeOH[19] to a solution of 2 equivalents of 5 (-100 °C, 15 min; -78 °C, 3 h). Under these conditions, the (E) isomer 10a was obtained in essentially pure form (< 1 % 11a) (eq. [5]).



[5]

1a → 10a + 11a

THF, −78°C, 3h; MeOH	68	:	32	(69%)
THF, −100°C, 6h; MeOH	97	:	3	(81%)
THF, MeOH, −78°C, 3h	>99	:	<1	(79%)
THF, −48°C, 4h; MeOH	2	:	98	(76%)

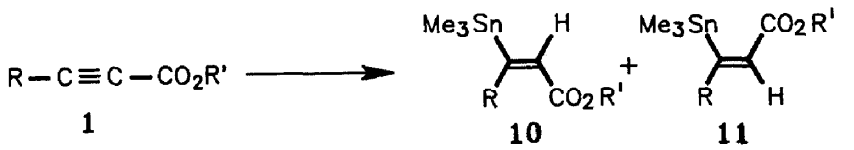
Importantly, it was found that the addition reaction could also be controlled experimentally to produce, highly stereoselectively, the (Z) isomer 11a. Thus, treatment of 1a with 1.2 equivalents of 5 at -48 °C for 4 h, followed by addition of MeOH, afforded a 2:98 mixture of 10a and 11a, respectively (eq. [5]).

The experiments summarized above showed that, in the reaction of ethyl 2-pentynoate (1a) with the phenylthiocuprate 5, the overall regioselective addition of the elements of trimethylstannane across the triple bond can be controlled experimentally to produce, highly stereoselectively, either of the two possible geometric isomers 10a and 11a. In order to demonstrate the generality of these transformations, the reactions of 5 with other α,β-acetylenic esters were investigated. The results of this study are summarized in Table 1.

A number of points should be made in connection with the data given in Table 1. The stereochemical control mentioned above was demonstrated with two additional substrates, 1b (entries 3 and 4) and 1g (entries 9 and 10). In each case, treatment of the actylenic ester with 5 in the presence of MeOH (-78 °C) (conditions A) afforded stereoselectively the product with (E) stereochemistry, while reaction with 5 at -48 °C, followed by protonation with MeOH (conditions B), gave primarily the (Z) α,β-unsaturated ester. Furthermore, by use of conditions B, the stereoselective conversions of a number of additional α,β-acetylenic esters (1c-f, 1j, 1ℓ; entries 5-8, 14, 15) into the corresponding alkyl (Z)-3-trimethylstannyl-2-alkenoates were effected smoothly and quite efficiently. Interestingly, this type of transformation is successful even on substrates (1j, 1ℓ) containing a primary bromide (entries 14 and 15).

Compared with the other substrates listed in Table 1, ethyl 4,4-dimethyl-2-pentynoate (1i) behaved anomalously. When this α,β-acetylenic ester was allowed to react with $[Me_3SnCuSPh]Li$

Table 1. Reaction of α,β-acetylenic esters 1 with [$Me_3SnCuSPh$]Li (5)



1 10 11

Entry	Starting material	R	R'	Conditions[a]	Products (ratio)[b]	Yield (%)[c]
1	1a	Et	Et	A	10a,11a(>99:<1)	79
2	1a	Et	Et	B	10a,11a(2:98)	76
3	1b	Me	Et	A	10b,11b(>99:<1)	78
4	1b	Me	Et	B	10b,11b(2:98)	76
5	1c	i-Pr	Me	B	10c,11c(6:94)	73
6	1d	c-Pr	Me	B	10d,11d(5:95)	72
7	1e	Y[d]	Me	B	10e,11e(2:98)	77
8	1f	Z[d]	Me	B	10f,11f(3:97)	71
9	1g	t-$BuMe_2SiO(CH_2)_2$	Me	A	10g,11g(96:4)	82
10	1g	t-$BuMe_2SiO(CH_2)_2$	Me	B	10g,11g(4:96)	81
11	1h	t-$BuMe_2SiOCH_2$	Et	B	10h,11h(9:91)	29[e]
12	1i	t-Bu	Et	C	10i,11i(8:92)	84
13	1i	t-Bu	Et	D	10i,11i(2:98)	86
14	1j	$Br(CH_2)_3$	Me	B	10j,11j(7:93)	72
15	1ℓ	$Br(CH_2)_4$	Me	B	10ℓ,11ℓ(5:95)	74

[a] All reactions were carried out in THF. A: 2.0 equiv. 5, 1.7 equiv. MeOH, -100 °C, 15 min, -78 °C, 3 h; B: 1.3 equiv. 5, -78 °C, 15 min, -48 °C, 4 h, then quench with MeOH; C: 3.0 equiv. 5, 1.7 equiv. EtOH, -100 °C, 15 min, -78 °C, 6 h; D: 1.4 equiv. 5, -78 °C, 15 min, -48 °C, 4 h, then quench with EtOH.

[b] Product ratios were determined by gas-liquid chromatographic analyses.

[c] Yields refer to distilled product mixtures (entries 4, 9, 10, 12, 13) or to isolated, distilled major product (entries 1-3, 5-8, 11, 14, 15).

[d] Y = 2-(2-cyclopentenyl)ethyl; Z = (3-cyclohexenyl)methyl.

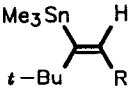
[e] Also isolated were 10 h (2 %) and ethyl (Z)-4-tert-butyldimethylsiloxy-3-phenylthio-2-butenoate (31) (35 %).

(5) at -78 °C in the presence of EtOH, it was found that 3 equivalents of reagent and a reaction time of 6 h were required for complete disappearance of starting material (conditions C, entry 12). Not surprisingly, the sterically bulky tert-butyl group retards the rate of addition. More important, however, was the finding that the major product of this reaction was not the expected (E) isomer 10i, but the (Z) isomer 11i (ratio of 10i:11i ≈ 8:92). Indeed, we were unable to find conditions under which the reaction of 1i with 5 would produce 10i stereoselectively. For example, even when the reaction was carried out in the presence of acetic acid,[2] the major product was 11i. Under these conditions, a large amount of starting material was also recovered.

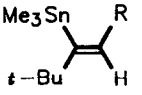
Treatment of 1i with 5 at -48 °C, followed by addition of EtOH (conditions D, entry 13), gave the expected result, providing the geometric isomers 10i and 11i in a ratio of about 2:98, respectively.

It seemed possible that, due to the steric bulk of the tert-butyl group, the addition of [$Me_3SnCuSPh$]Li (5) to the triple bond of 1i might have occurred, at least to some extent, with regiochemistry opposite to that initially expected. Consequently, it seemed desirable to show conclusively that, in each of the products of these reactions (Table 1, entries 12 and 13), the trimethylstannyl group was situated on the β carbon of the α,β-unsaturated ester moiety. To that end, the major product 11i was reduced with $LiAl(OEt)H_3$.[21] In the ^1H NMR spectrum of the resultant product 28, the vinyl proton gave rise to a triplet (J = 7 Hz, with satellite peaks, $^3J_{Sn-H}$ = 148 Hz) at δ 6.17. In similar fashion, reduction of the minor product 10i with i-Bu_2AlH in pentane provided the alcohol 29, the ^1H NMR spectrum of which exhibited a triplet

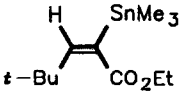
(J = 6 Hz, with satellite peaks, $^3J_{Sn-H}$ = 90 Hz) at δ 5.57 due to the olefinic proton. Thus, in both of the products derived from the reaction of **1i** with **5**, the vinyl proton is geminal to the ester group. Clearly, neither of the products was the regioisomeric substance **30**.



10i R=CO_2Et
28 R=CH_2OH

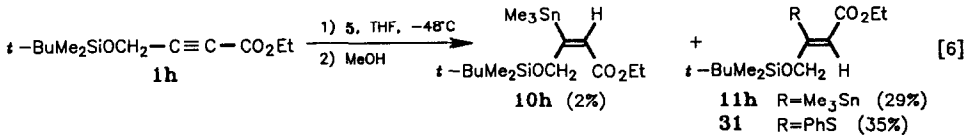


11i R=CO_2Et
29 R=CH_2OH



30

Treatment of ethyl 4-tert-butyldimethylsiloxy-2-butynoate (**1h**) with [$Me_3SnCuSPh$]Li (**5**) under conditions B (Table 1, entry 11) also led to an unexpected result. Although the products of Me_3Sn transfer, **10h** and **11h**, were produced in the expected ratio (≈ 9:91, respectively), the combined isolated yield of these substances was only 31 %. Also obtained, in 35 % yield, was a product that proved to be ethyl (Z)-4-tert-butyldimethylsiloxy-3-phenylthio-2-butenoate (**31**) (eq. [6]). Thus, in the case of substrate **1h**, PhS transfer is competitive with Me_3Sn transfer. It may be noted that the α,β-acetylenic ester **1g**, the next higher homolog of **1h**, behaves normally in its reactions with **5** (entries 9 and 10). Although the reasons underlying the anomalous behavior of **1h** remain obscure, it seems likely that the electron-withdrawing effect of the ether oxygen close to the triple bond is in some way involved.



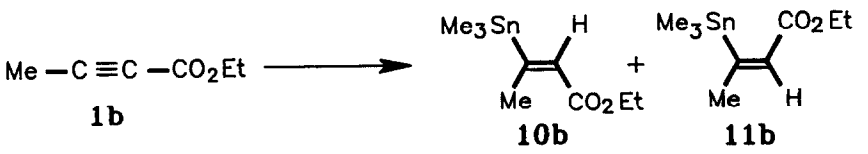
[6]

The results summarized in Table 1 show that, in general, the cuprate reagent **5** can be used effectively for the stereoselective conversion of α,β-acetylenic esters **1** into either of the geometrically isomeric products **10** or **11**. Subsequent work showed that other (trimethylstannyl)copper(I) species (e.g. **4**, **7**) also effect the efficient transformation of **1** into **10** (vide infra). However, of the various reagents **4**-**7** that we have studied, only the phenylthiocuprate **5** proved effective for the efficient, stereoselective conversion of **1** into alkyl (Z)-3-trimethylstannyl-2-alkenoates (**11**).

It should also be noted that, as a procedure for the controlled preparation of β-trimethylstannyl α,β-unsaturated esters, the method described above is notably superior to that involving direct hydrostannylation of α,β-acetylenic esters. For example, treatment (neat, 50 °C, 47 h) of ethyl 2-butynoate (**1b**) with Me_3SnH has been reported to afford, in 65 % yield, an inseparable mixture of all four possible regio- and stereoisomers.[22]

(c) Reaction of ethyl 2-butynoate (**1b**) with the (trimethylstannyl)copper(I) reagents **4**-**7**. Table 2 summarizes some of the results obtained from a brief study of the reactions of ethyl 2-butynoate (**1b**) with a number of (trimethylstannyl)copper(I) reagents. It had been shown previously (entry 1) that treatment of **1b** with [$Me_3SnCuSPh$]Li (**5**) in THF at -48 °C afforded, upon workup, a 2:98 mixture of the products **10b** and **11b**. Under identical conditions, the reaction of **1b** with the bis(trimethylstannyl)cuprate **6** proved to be much less stereoselective, providing the two products in a ratio of about 1:2 (entry 2). Interestingly, however, the reagents **7** and **4** gave exclusively ethyl (E)-3-trimethylstannyl-2-butenoate (**10b**), even under reaction conditions whereby the cuprate **5** produced very largely the geometric isomer **11b** (entries 3,4 vs. entry 1). Furthermore, it was shown that **1b** reacted efficiently with $Me_3SnCu{\cdot}Me_2S$ (**4**) at lower temperatures (e.g. -78 °C) to provide the expected product **10b** (entry 5).

Table 2. Reaction of ethyl 2-butynoate (1b) with the (trimethylstannyl)copper(I) reagents 4-7



Entry	Reagent, Conditions[a]	Ratio, 10b:11b[b]	Yield (%)[c]
1[d]	$[Me_3SnCuSPh]Li$ (5) -48 °C, 4 h	2:98	76
2	$[Me_3SnCuSnMe_3]Li$ (6) -48 °C, 4 h	32:68	74
3	$Me_3SnCuC{\equiv}C(OMe)Me_2$ (7) -48 °C, 4 h	>99:<1	82
4	$Me_3SnCu{\cdot}Me_2S$ (4) -48 °C, 3 h	>99:<1	68
5	$Me_3SnCu{\cdot}Me_2S$ (4) -78 °C, 3 h	>99:<1	76

[a] All reactions were carried out in THF with 1.3 equiv. of reagent.
[b] Product ratios were determined by gas-liquid chromatographic analyses.
[c] Yields refer to isolated, distilled product(s).
[d] Same as entry 4 in Table 1.

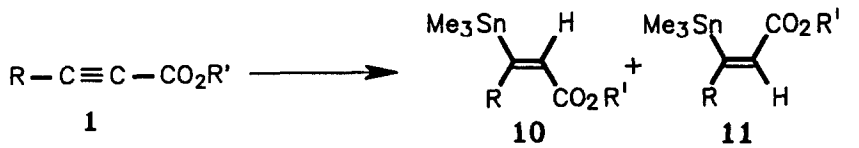
From the viewpoint of synthesis, the results given in Table 2 indicate that the efficient preparation of alkyl (Z)-3-trimethylstannyl-2-alkenoates (e.g. 11b) from α,β-acetylenic esters must involve use of the phenylthiocuprate 5. On the other hand, stereoselective conversion of the acetylenic esters into the geometrically isomeric products (e.g. 10b) can be accomplished by use of any of the reagents 4, 5, or 7 (Tables 1 and 2). However, the reagent of choice is probably $Me_3SnCu{\cdot}Me_2S$ (4), since this species is very easily prepared[2] and its reactions with α,β-acetylenic esters are generally clean and efficient. The use of reagent 4 for the conversion of α,β-acetylenic esters into (E)-3-trimethylstannyl-2-alkenoates is described below.

(d) Reaction of α,β-acetylenic esters 1 with $Me_3SnCu{\cdot}Me_2S$ (4). The results derived from an investigation of the reactions of a number of α,β-acetylenic esters 1 with reagent 4 are summarized in Table 3. It is evident that, in nearly all of the cases studied, the reactions are highly stereoselective and provide cleanly the corresponding alkyl (E)-3-trimethylstannyl-2-alkenoates (10). In the experiments summarized in entries 1-6, 9, and 10, essentially none of the geometric isomers 11 could be detected (GLC) in the crude products. In the case of substrate 1h, however, a small amount of 11h was produced in addition to the expected product 10h (entry 7). It may also be noted that the presence of a primary bromide function does not interfere with this type of conversion (entries 9 and 10).

As was the case in its reactions with the phenylthiocuprate 5, substrate 1i gave an anomalous result (entry 8). Although, not unexpectedly, the reaction of 1i with 4 is sluggish at -78 °C, at a higher temperature (-20 °C), with 3 equivalents of reagent and in the presence of hexamethylphosphoramide (HMPA), the reaction proceeded to completion. However, the product mixture obtained consisted mainly of the (Z) isomer 11i (ratio of 10i:11i ≈ 12:80). Thus, it appears that the steric bulk of the tert-butyl group precludes the stereoselective acquisition of the (E) isomer 10i.

The reaction of 1i with 4 produced a small amount of a third product (Table 3, footnote f). This substance was not obtained pure. However, the ^1H NMR spectrum of a small enriched sample of this material showed the presence of Me_3Sn and tert-butyl groups, an ethyl ester function, and an olefinic proton (δ 5.58, singlet with satellite peaks, $^3J_{Sn-H}$ = 78 Hz). The

Table 3. Reaction of α,β-acetylenic esters 1 with $Me_3SnCu \cdot Me_2S$ (4)



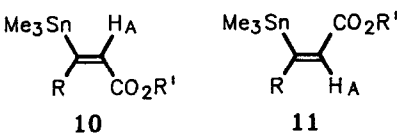
Entry	Starting Material	R	R'	Conditions[a]	Product(s) (ratio)[b]	Yield (%)[c]
1	1a	Et	Et	A	10a	80
2[d]	1b	Me	Et	A	10b	76
3	1c	i-Pr	Me	A	10c	77
4	1d	c-Pr	Me	A	10d	81
5	1e	Y[e]	Me	A	10e	84
6	1f	Z[e]	Me	A	10f	72
7	1h	t-$BuMe_2SiOCH_2$	Et	A	10h,11h(95:5)	80
8	1i	t-Bu	Et	B	10i,11i(12:80)[f]	79
9	1j	$Br(CH_2)_3$	Me	A	10j	81
10	1ℓ	$Br(CH_2)_4$	Me	A	10ℓ	84

[a] A: THF, 1.3 equiv. 4, -78 °C, 3 h, then quench with saturated aqueous NH_4Cl that had been adjusted to pH 8 by addition of aqueous NH_4OH; B: THF containing 10% HMPA, 3.0 equiv. 4, -20 °C, 6 h, then quench as in A.
[b] Product ratios were determined by gas-liquid chromatographic analyses. In the experiments summarized by entries 1-6, 9, and 10, only product 10 was detected.
[c] Yields refer to isolated, distilled product(s).
[d] Same as entry 5 in Table 2.
[e] Y = 2-(2-cyclopentenyl)ethyl; Z = (3-cyclohexenyl)methyl.
[f] Also present was a third component, thought to be ethyl (E)-4,4-dimethyl-2-trimethylstannyl-2-pentenoate (30).

magnitude of the Sn-H coupling constant indicates a cis relationship between the Me_3Sn group and the vinyl proton (vide infra). Since this compound was clearly different from 10i, it seems highly likely that it possesses structure 30. Apparently, due to the presence of the bulky tert-butyl group, addition of reagent 4 to the triple bond of 1i takes place, to a small extent, with regiochemistry opposite to that expected.

(e) Regarding the stereochemistry of the products 10 and 11. The stereochemical assignments with respect to the products 10 and 11 listed in Tables 1 - 3 were readily made on the basis of ^1H NMR spectroscopy. All of these substances are, of course, α,β-unsaturated esters and, with the exception of 10i and 11i in which R = tert-butyl, all contain at least one γ proton. For any given pair of geometric isomers, the γ proton(s) of the (Z) isomer 10, being situated on a carbon cis to the CO_2R' group, would be expected to resonate at lower field than the corresponding proton(s) of the (E) isomer 11. This expectation was realized for each pair of isomers 10 and 11.

Even more compelling evidence for the stereochemistry of 10 and 11 was provided, in each case, by the magnitude of the coupling constant between the α olefinic proton and the tin atom (^{117}Sn, ^{119}Sn) of the Me_3Sn group. It is well known[23] that when a trialkylstannyl group and a proton are vicinal on a carbon-carbon double bond, the $^3J_{Sn-H}$ value is much larger when these moieties are trans than when they are cis. Indeed, for compounds 10 and 11, the $^3J_{Sn-H_A}$ values are in the ranges 71-87 Hz and 118-126 Hz, respectively.

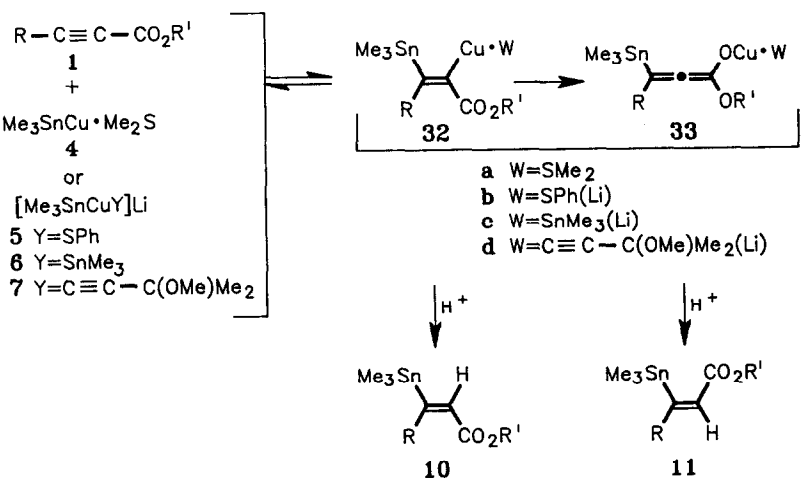


(f) Mechanistic considerations. A possible pathway for the addition of (trimethylstan-

nyl)copper(I) reagents to α,β-acetylenic esters 1, to afford products 10 and (or) 11, is shown in Scheme 1. It has been well established[1,3,24,25] that organocopper(I) species add kinetically to carbon-carbon triple bonds in a cis fashion. Therefore, it is not unreasonable to postulate that addition of reagents 4-7 to 1 provides initially the vinylcopper(I) intermediates 32.[26,27] We propose further that, depending on a number of factors, the latter species may rearrange to the corresponding allenoates 33.[26] Protonation of 32, the "kinetic" intermediates, provides the (E) α,β-unsaturated esters 10, while protonation of the allenoates 33 proceeds in stereoselective fashion to produce the geometric isomers 11.[29]

Interestingly, the nature of W in 32 appears to have a profound effect on the facility with which this type of intermediate rearranges to 33. For example, the vinylcuprates 32b, derived from the reactions of 1 with the phenylthiocuprate 5, are quite unstable even at low temperatures. Indeed, at -78 °C, the highly stereoselective conversions of 1 into 10, using reagent 5, can be achieved only if the reactions are carried out in the presence of a proton source. On the other hand, at -48 °C, intermediates 32b readily rearrange to 33b, which, upon protonation, afford products 11 stereoselectivity (Table 1).

In contrast to 32b, the intermediates 32a and 32d are, in general, stable at -48 °C and, upon protonation, provide products 10 with complete stereoselectivity (Tables 2 and 3). On the other hand, under identical conditions, the cuprate intermediate 32c (R = Me, R' = Et) rearranges partially to 33c (R = Me, R' = Et) and protonation leads to a mixture of 10b and 11b (Table 2, entry 2). Thus, of the three types of cuprate intermediates 32b-d, 32b and 32d appear to be the least and the most stable, respectively, while 32c is of intermediate stability.

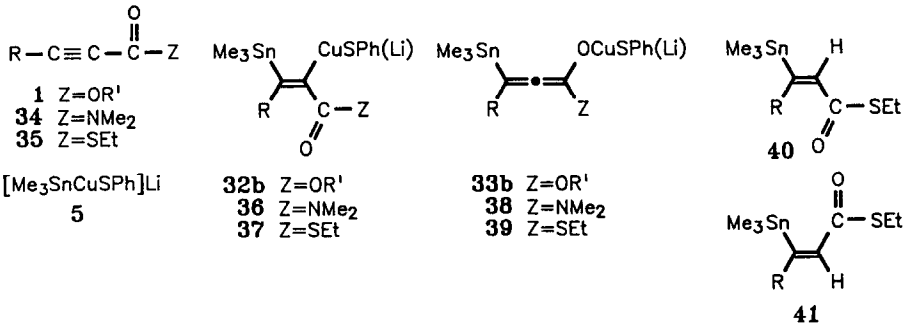


Scheme 1

To a limited extent, the nature of R also affects the stability of 32. The generalizations discussed above hold for all the substrates 1 studied, except ethyl 4,4-dimethyl-2-pentynoate (1i). Even when the reaction of 1i with 5 was carried out at -78 °C in the presence of EtOH, the predominant product was 11i (Table 1, entry 12). Similarly, the major product derived from the reaction of 1i with $Me_3SnCu{\cdot}Me_2S$ (4) was also 11i (Table 3, entry 8). The latter result is in marked contrast to those obtained from the reaction of 4 with other α,β-acetylenic esters 1 (Table 3). The results obtained with substrate 1i can be rationalized by postulating that the steric bulk of the tert-butyl group destabilizes intermediates 32a and b (R = t-Bu) and facilitates the conversion of these species into the corresponding allenoates 33a and b (R = t-Bu), respectively. Protonation of the latter intermediates provides the observed major product 11i.[29]

We have not yet been able to obtain direct evidence for the intermediacy of the allenoates

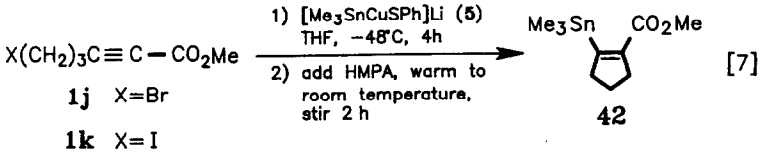
33, since all attempts to trap these species with electrophilic reagents such as trialkylsilyl or acyl chlorides failed to provide identifiable, functionalized allenes. However, evidence for the reasonableness of the proposed conversion of 32b into 33b was derived from related work done in our laboratories. It has been shown[31] that intermediates 36, derived from the reaction of N,N-dimethyl-2-alkynamides 34 with the phenylthiocuprate 5, are notably more stable than the intermediates 32b obtained from α,β-acetylenic esters 1. Thus, in THF solution, the vinylcuprates 36 show little or no inclination to rearrange to the corresponding allenoate-type species 38, even when R = t-Bu.[31] In sharp contrast, reaction of α,β-acetylenic thiolesters 35 with 5 in THF under a variety of conditions, even at -78 °C in the presence of HOAc, gave very largely the (Z) products 41.[32] Apparently, the putative intermediates 37, protonation of which would have provided products 40, are very unstable and readily rearrange to the allenoates 39. Thus, of the three types of vinylcuprate intermediates, 36 are the most stable, 32b are of intermediate stability, and 37, if formed at all, are least stable. This order of stability is



not unexpected, since one would anticipate that the conversion of these species into the corresponding allenoate intermediates would be most facile with thiolesters (ketonic-like properties) and least likely with dimethylamide substrates.

(g) Reaction of the ω-halo α,β-acetylenic esters 1j-m with [Me$_3$SnCuSPh]Li (5). Intramolecular alkylation. In work related to that reported herein, we[33] and others[20] have found that intermediates such as 32 and (or) 33 cannot be trapped intermolecularly with electrophiles other than proton. Since one would expect intramolecular trapping to be a more facile process, we decided to study the reaction of substrates 1j-m with reagent 5 at higher temperatures. It may be recalled (vide supra) that the bromides 1j and 1ℓ react with reagents 4 and 5 at low temperatures (-78 °C to -48 °C) to afford "normal" products (β-trimethylstannyl α,β-unsaturated esters) in which the bromine atom had been retained.

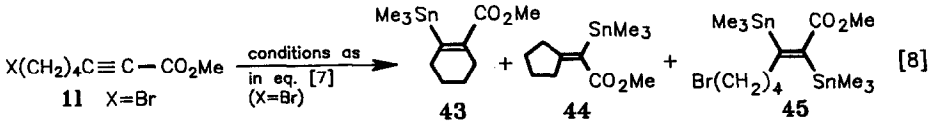
Reaction of the ester 1j with 5, under conditions shown in eq. [7], gave an oil that consisted largely of one product, accompanied by very minor amounts of a number of unidentified substances. Chromatography of the mixture provided the cyclic ester 42[34] in 77 % yield. A very similar reaction involving the iodide 1k produced the same product (78 %). Thus, intramolecular alkylation of the intermediates derived from interaction of 1j and 1k with 5 are facile processes.



[7]

Reaction of the cuprate 5 with the ω-halo α,β-acetylenic esters 1ℓ and 1m, the next higher homologs of 1j and 1k, respectively, gave very different results (eq. [8]). The crude product derived from 1ℓ contained only a very small amount (< 3 %) of a product with GLC retention time identical with that of methyl 2-trimethylstannyl-1-cyclohexenecarboxylate (43).[34] The major

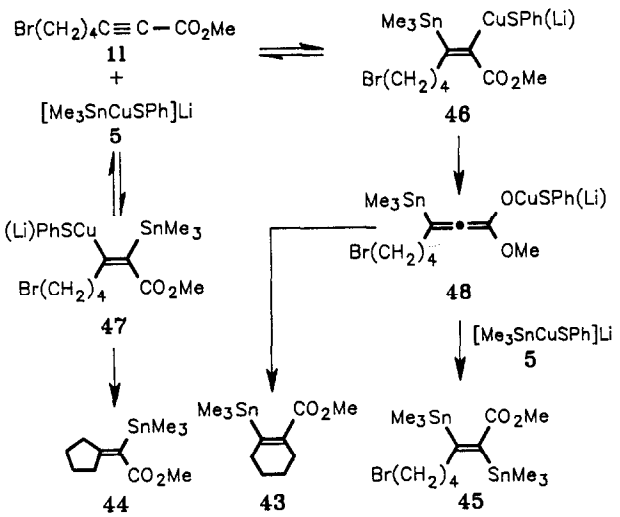
products, isolated by column chromatography of the mixture on silica gel, proved to be the α-trimethylstannyl α,β-unsaturated ester 44 (43 %) and methyl (E)-7-bromo-2,3-bis(trimethylstannyl)-2-heptenoate (45).



The structure of 44, the chromatographic properties of which were clearly different from those of 43,[34] was readily established by examination of its spectra. Of particular note was the ^{1}H NMR spectrum, which exhibited, in addition to the signals due to the Me_3Sn and CO_2Me moieties, a 4-proton multiplet at δ 1.5-1.8 and a pair of 2-proton signals (broad triplets, J = 7 Hz) at δ 2.38 and 2.70 due to the allylic methylene groups situated trans and cis to the CO_2Me group, respectively.

Since we had shown[33] that, under appropriate conditions, reaction of α,β-acetylenic esters with (trimethylstannyl)copper(I) reagents affords good yields of the corresponding alkyl (E)-2,3-bis(trimethylstannyl)-2-alkenoates, the production of 45 (eq. [8]) was not particularly surprising. The spectra of 45, particularly when compared with those of structurally similar substances,[33] readily corroborated the structural assignment.

The formation of products 43-45 may be rationalized as shown in Scheme 2. As mentioned previously,[27] the addition of (trimethylstannyl)copper(I) reagents to the triple bond of α,β-acetylenic esters is reversible. Furthermore, we had obtained some evidence that these additions can take place in both possible regiochemical orientations (Table 3, entry 8). Indeed, the production of compound 44 (eq. [8]) provides excellent evidence for both of these reaction characteristics. Thus, it may be proposed that (reversible) addition of 5 to 11 gives primarily intermediate 46, but that the regioisomeric species 47 can also be formed. Appar-



Scheme 2

ently, the cyclization of 47 to the five-membered ring product 44 is faster than the isomerization of 46 to 48 and, therefore, 44 is the major product. Furthermore, ring closure of the allenoate 48 to the cyclohexenecarboxylate 43 is, apparently, quite slow and, consequently, 48 reacts preferentially with a second equivalent of reagent 5 to produce the bis(trimethylstannyl) ester 45. The mechanism for this latter coupling remains obscure,

although this type of transformation has some precedent in alkylcopper(I) chemistry.[1a]

Reaction of substrate **1m** with **5** gave a product mixture very similar to that derived from **1ℓ**. Thus, it is evident that, although the reactions of **5** with **1j** and **1k** (eq. [7]) provide acceptable methods for the preparation of methyl 2-trimethylstannyl-1-cyclopentenecarboxylate (**42**), treatment of **1ℓ** and **1m** with **5** under similar conditions (eq. [8]) does not lead to useful yields of the corresponding cyclohexenecarboxylate **43**.

CONCLUSION

The investigations described herein showed that (trimethylstannyl)copper(I) reagents can be employed effectively for the conversion of α,β-acetylenic esters into β-trimethylstannyl α,β-unsaturated esters. Furthermore, it was shown that, in nearly all cases studied, the stereochemical outcome of these reactions can be controlled by a judicious choice of reagent and (or) reaction conditions. Thus, both alkyl (E)- and (Z)-3-trimethylstannyl-2-alkenoates can be produced highly stereoselectively. The chemistry of these substances, which have proven to be very useful intermediates for organic synthesis,[4,35] will be the subject of future publications.

EXPERIMENTAL

General. Distillation temperatures, which refer to short path (Kugelrohr) distillations, and melting points are uncorrected. IR spectra were recorded on Perkin Elmer models 710 or 710B spectrophotometers and were calibrated using the 1601 cm^{-1} band of polystyrene film. ^1H NMR spectra were recorded on $CDCl_3$ solutions. Signal positions are given in ppm (δ) relative to Me_4Si. In cases of compounds containing Me_3Sn and (or) trialkylsilyl groups, the resonance positions were determined relative to the $CHCl_3$ signal (δ 7.25). The tin-proton coupling constants(J_{Sn-H}) are given as the average of the ^{117}Sn and ^{119}Sn values. High resolution mass spectra were recorded with Kratos/AEI MS 50 or MS 902 mass spectrometers. In cases of compounds containing Me_3Sn groups, the molecular mass determinations were based on ^{120}Sn and were often made on the M^+-Me peak.[36] Gas-liquid chromatography was accomplished with Hewlett-Packard models 5832A (thermal conductivity detectors, 6 ft x 0.125 in stainless steel columns packed with 3-5 % OV-17 or 5 % OV-210 on Chromosorb W(HP)) and 5880 (flame ionization detector, 25 m x 0.21 mm fused silica column coated with cross-linked SE-54) gas chromatographs. Analytical TLC was carried out on 20 x 5 cm glass plates coated with 0.5 mm of E. Merck silica gel 60 or on commercial silica gel plates (Eastman Chromatogram Sheet Type 13181 or E. Merck, Type 5554). Preparative TLC was carried out on 20 x 20 cm glass plates coated with 0.7 mm of E. Merck silica gel 60. Conventional and flash[37] column chromatography were done on 70-230 and 230-400 mesh silica gel (E. Merck), respectively. Reagents and solvents were purified and dried using standard methods.

Note. All compounds for which high resolution mass measurements are given exhibited essentially one spot on TLC analysis and (or) one peak on GLC analyses.

Note. All reactions were carried out under an atmosphere of dry argon using oven- or flame-dried glassware.

1,1-Dibromo-3-methyl-1-butene (14). To a reagent prepared by stirring a mixture of zinc dust (10.5 g, 160 mmol), Ph_3P (42 g, 160 mmol), and CBr_4 (53.1 g, 160 mmol)in 200 mL of dry CH_2Cl_2 at room temperature for 24 h[6] was added 5.76 g (80 mmol) of 2-methylpropanal (**12**). The tan suspension was stirred at room temperature for 2 h. Petroleum ether (1L) was added and the supernatant solution was decanted from the oil. The oil was taken up in 200 mL of CH_2Cl_2, petroleum ether (1L) was added to the solution, and the supernatant solution was again decanted from the red oil. Concentration of the combined petroleum ether solutions, followed by flash distillation (0.1 Torr, receiving bulb cooled to -78 °C) of the residual oil, afforded 10.6 g (58 %) of the dibromo alkene **14**[7] as a clear, colorless oil that exhibited IR (neat) 1600, 1460, 1160, 870, 790 cm^{-1}; ^1H NMR (80 MHz) δ 0.99 (d, 6H, J = 7 Hz), 2.55 (d septets, 1H, J = 9, 7 Hz), 6.21 (d, 1H, J = 9 Hz).

1,1-Dibromo-2-cyclopropylethylene (15). This substance (7.51 g, 67 %) was prepared from 3.50 g (50 mmol) of cyclopropanecarboxaldehyde (**13**)[5] via a procedure very similar to that described above. Flash distillation (0.05 Torr, receiving bulb cooled to -78 °C) of the crude product provided **15** as a colorless oil that exhibited IR (neat) 3060, 2990, 960, 785, 770 cm^{-1}; ^1H NMR (100 MHz) δ 0.4-0.6 and 0.7-0.9 (m, m, 2H each), 1.4-1.8 (m, 1H), 5.81 (d, 1H, J = 9 Hz). Exact Mass calcd. for $C_5H_6{}^{81}Br_2$: 227.8796; found: 227.8804.

Methyl 4-methyl-2-pentynoate (1c). To a cold (-78 °C), stirred solution of the dibromo alkene **14** (9.12 g, 40 mmol) in 200 mL of dry THF was added a solution of MeLi in Et_2O (68 mL, 84 mmol). After the yellow solution had been stirred at -78 °C for 1 h and at room temperature for 1 h, it was cooled to -20 °C. Methyl chloroformate (3.71 g, 48 mmol) was added slowly and the reaction mixture was stirred at -20 °C for 1 h and at room temperature for 1 h. Saturated aqueous $NaHCO_3$ and Et_2O were added and the layers were separated. The organic solution was washed with saturated aqueous $NaHCO_3$, dried ($MgSO_4$), and concentrated. Distillation (55-60

°C/13 Torr) of the residual oil gave 2.64 g (52 %) of the ester **1c** as a colorless oil that exhibited IR (neat) 2210, 1710, 1385, 1370, 1260 cm^{-1}; ^1H NMR (80 MHz) δ 1.18 (d, 6H, J = 7 Hz), 2.64 (septet, 1H, J = 7 Hz), 3.72 (s, 3H). Exact Mass calcd. for $C_7H_{10}O_2$: 126.0681; found: 126.0685.

Methyl 3-cyclopropylpropynoate (1d). This ester (1.92 g, 78 %, distilled at 80-85 °C/20 Torr), prepared from the dibromo alkene **15** (4.52 g, 20 mmol) via a procedure identical with that described above, was obtained as a colorless oil that showed IR (neat) 2990,2940, 2210, 1700, 1270 cm^{-1}; ^1H NMR (80 MHz) δ 0.85-0.95 (m, 4H), 1.2-1.5 (m, 1H), 3.72 (s, 3H). Exact Mass calcd. for $C_7H_8O_2$: 124.0525; found: 124.0525.

1-Bromo-2-(2-cyclopentenyl)ethane (18). To a cold (0 °C), stirred slurry of triphenylphosphine dibromide[10] (33 mmol) in 75 mL of dry MeCN was added Et_3N (8.36 mL, 60 mmol) and a solution of 2-(2-cyclopentenyl)ethanol (**16**)[8] (3.36 g, 30 mmol) in 5 mL of dry MeCN and the mixture was stirred at room temperature for 30 min. The mixture was diluted with 300 mL of petroleum ether and then was filtered through a short column of silica gel (elution with 200 mL of petroleum ether). Concentration (distillation at atmospheric pressure) of the combined eluates, followed by distillation (65-70 °C/12 Torr) of the residual oil gave 4.61 g (88 %) of the bromide **18** as a colorless oil that exhibited IR (neat) 3030, 720 cm^{-1}; ^1H NMR (60 MHz) δ 1.06-1.66 (m, 1H), 1.66-2.50 (m, 5H), 2.50-3.00 (m, 1H), 3.29 (t, 2H, J = 7 Hz), 5.47-5.83 (m, 2H). Exact Mass calcd. for $C_7H_{11}{}^{79}Br$: 174.0044; found: 174.0037.

4-(Bromomethyl)cyclohexene (19). This bromide was prepared from (3-cyclohexenyl)methanol (**17**)[9] via a procedure identical with that described above, except that the reaction time was 1 h rather than 30 min. From 560 mg (5 mmol) of the alcohol there was obtained, after distillation (72-78 °C/12 Torr) of the crude product, 687 mg (79 %) of the bromide **19**[11] as a colorless oil that exhibited IR (neat) 3020, 1640, 1420 cm^{-1}; ^1H NMR (80 MHz) δ 1.0-1.6 (m, 2H), 1.6-2.4 (m, 5H), 3.37 (d, 2H, J = 6 Hz), 5.52-5.85 (m, 2H). Exact Mass calcd. for $C_7H_{11}{}^{79}Br$: 174.0044; found: 174.0044.

4-(2-Cyclopentenyl)-1-butyne (20). To a cool (10 °C), stirred slurry of lithium acetylide-ethylenediamine complex[12] (2.18 g, 23.6 mmol) in 10 mL of dry Me_2SO was added dropwise the bromide **18** (3.44 g, 19.7 mmol). The mixture was stirred at room temperature for 2 h. Hydrochloric acid (6 M, 10 mL) was added slowly and the mixture was extracted with Et_2O (4 x 25 mL). The combined extracts were washed twice with water, dried ($MgSO_4$), and concentrated. Distillation (58-61 °C/12 Torr) of the remaining oil gave 1.69 g (71 %) of the 1-alkyne **20**, a clear oil that exhibited IR (neat) 3295, 3035, 2100, 730, 640 cm^{-1}; ^1H NMR (80 MHz) δ 1.12-1.75 (m, 3H), 1.94 (t, 1H, J = 1.5 Hz), 2.05-2.50 (m, 5H), 2.55-3.00 (m, 1H), 5.55-5.83 (m, 2H). Exact Mass calcd. for C_9H_{12}: 120.0939; found: 120.0934.

3-(3-Cyclohexenyl)propyne (21). This material (978 mg, 54 %, distilled at 62-68 °C/12 Torr), obtained as a colorless oil from 2.62 g (15 mmol) of the bromide **19** via a procedure very similar to that described above, exhibited IR (neat) 3280, 3000, 2100 cm^{-1}; ^1H NMR (100 MHz) δ 1.1-1.6 (m, 3 H), 1.6-2.3 (m, 6H), 1.97 (t, 1H, J = 1.5 Hz), 5.6-5.7 (m, 2H). Exact Mass calcd. for C_9H_{12}: 120.0939; found: 120.0942.

5-Tetrahydropyranyloxy-1-pentyne (24). A solution of 4-pentyn-1-ol (8.4 g, 100 mmol), dihydropyran (12.6 g, 150 mmol), and pyridinium p-toluenesulfonate[16] (2.5 g, 10 mmol) in 300 mL of dry CH_2Cl_2 was stirred at room temperature for 12 h. The mixture was diluted with 1L of Et_2O, washed with brine (2 x 15 mL), dried ($MgSO_4$), and concentrated. Distillation (95-100 °C/12 Torr) of the residual oil gave 16.0 g (95 %) of the 1-alkyne **24** as a colorless oil that exhibited IR (neat) 3280, 2090, 1140, 1120 cm^{-1}; ^1H NMR (80 MHz) δ 1.3-2.1 (m, 8H), 1.88 (t, 1H, J = 1.5 Hz), 2.30 (dt, 2H, J = 1.5, 6.5 Hz), 3.3-4.1 (m, 4H), 4.58 (br s, 1H). Exact Mass calcd. for $C_{10}H_{16}O_2$: 168.1151; found: 168.1140.

Methyl 5-(2-cyclopentenyl)-2-pentynoate (1e). To a cold (-78 °C), stirred solution of 4-(2-cyclopentenyl)-1-butyne (**20**) (1.68 g, 14 mmol) in 50 mL of dry THF was added a solution of MeLi in Et_2O (12.4 mL, 15.4 mmol) and the resulting solution was stirred at -78 °C for 1 h and at -20 °C for 1 h. Methyl chloroformate (1.30 mL, 16.8 mmol) was added and the reaction mixture was stirred at -20 °C for 1 h and at room temperature for 1 h. Saturated aqueous $NaHCO_3$ and Et_2O were added and the layers were separated. The organic layer was washed with saturated aqueous $NaHCO_3$, dried ($MgSO_4$), and concentrated. Distillation (82-85 °C/0.2 Torr) of the residual material provided 2.04 g (82 %) of the 2-pentynoate **1e**, a colorless oil that exhibited IR (neat) 3030, 2210, 1710, 1260 cm^{-1}; ^1H NMR (100 MHz) δ 1.18-1.76 (m, 3H), 1.88-2.46 (m, 5H), 2.56-2.94 (m, 1H), 3.74 (s, 3H), 5.54-5.83 (m, 2H). Exact Mass calcd. for $C_{11}H_{14}O_2$: 178.0994; found: 178.0981.

The following α,β-acetylenic esters were prepared via procedures very similar to that employed for the synthesis of **1e** (see above).

Methyl 4-(3-cyclohexenyl)-2-butynoate (1f) (1.12 g, 77 %; distillation temperature 85-92 °C/0.4 Torr) was obtained as a colorless oil from 978 mg (8.15 mmol) of the propyne **21** and 0.82 mL (10.6 mmol) of MeO_2C-Cl. Compound **1f** exhibited IR (neat) 3000, 2220, 1710, 1260 cm^{-1}; ^1H NMR (80 MHz) δ 1.2-2.3 (m, 7H), 2.37 (br d, 2H, J = 6 Hz), 3.78 (s, 3H), 5.6-5.7 (m, 2H). Exact Mass calcd. for $C_{11}H_{14}O_2$: 178.0994; found: 178.0988.

Ethyl 4-(tert-butyldimethylsiloxy)-2-butynoate (1h) (2.03 g, 83 %; distillation temperature 78-85 °C/0.1 Torr), a colorless oil obtained from 1.7 g (10 mmol) of 3-(tert-butyldimethylsiloxy)propyne (22)[15] and 1.15 mL (12 mmol) of EtO_2C-Cl, exhibited IR (neat) 2220, 1710, 1250, 1110, 1060, 840 cm^{-1}; ^1H NMR (80 MHz) δ 0.14 (s, 6H), 0.92 (s, 9H), 1.30 (t, 3H, J = 7 Hz), 4.24 (q, 2H, J = 7 Hz), 4.43 (s, 2H). Exact Mass calcd. for $C_{12}H_{22}O_3Si$: 242.1338; found: 242.1331.

Methyl 6-tetrahydropyranyloxy-2-hexynoate (26) (8.31 g, 92 %; distillation temperature 120-125 °C/0.5 Torr) was obtained as a colorless oil from 6.72 g (40 mmol) of the 1-pentyne 24 and 3.71 mL (48 mmol) of MeO_2C-Cl. The ester 26 exhibited IR (neat) 2210, 1710, 1430, 1260 cm^{-1}; ^1H NMR (80 MHz) δ 1.3-2.0 (m, 8H), 2.42 (t, 2H, J = 7 Hz), 3.3-4.0 (m, 4H), 3.70 (s, 3H), 4.53 (br s, 1H). Exact Mass calcd. for $C_{12}H_{18}O_4$: 226.1205; found: 226.1195.

Methyl 7-tetrahydropyranyloxy-2-heptynoate (27) (4.58 g, 89 %; distillation temperature 125-130 °C/0.3 Torr) was obtained as a colorless oil from 3.9 g (21.4 mmol) of 6-tetrahydropyranyloxy-1-hexyne (25)[17] and 2.5 mL (32 mmol) of MeO_2C-Cl. The ester 27 exhibited IR (neat) 2220, 1710, 1260 cm^{-1}; ^1H NMR (60 MHz) δ 1.3-2.1 (m, 10H), 2.36 (br t, 2H, J = 7 Hz), 3.2-4.1 (m, 4H), 3.74 (s, 3H), 4.4-4.7 (m, 1H).

Methyl 5-(tert-butyldimethylsiloxy)-2-pentynoate (1g). To a stirred solution of methyl 5-hydroxy-2-pentynoate[13] (2.80 g, 22 mmol) in 25 mL of dry Me_2NCHO was added imidazole (3.71 g, 55 mmol) and t-$BuMe_2SiCl$ (3.96 g, 26 mmol) and the mixture was stirred at room temperature for 20 h. Aqueous $NaHCO_3$ (5 %) was added and the mixture was extracted thoroughly with Et_2O. The combined extracts were washed (5 % aqueous $NaHCO_3$), dried ($MgSO_4$), and concentrated. Distillation (72-79 °C/0.08 Torr) of the remaining oil gave 4.91 g (92 %) of the ester 1g, a colorless oil that exhibited IR (neat) 2240, 1717, 1258 cm^{-1}; ^1H NMR (80 MHz) δ 0.08 (s, 6H), 0.90 (s, 9H), 2.56 (t, 2H, J = 7 Hz), 3.77 (s, 3H), 3.81 (t, 2H, J = 7 Hz). Exact Mass calcd. for $C_8H_{13}O_3Si$ (M^+-t-Bu): 173.0633; found: 173.0632.

Ethyl 4,4-dimethyl-2-pentynoate (1i). To a cold (-78 °C), stirred solution of 3,3-dimethyl-1-butyne (23) (0.82 g, 10 mmol) in 30 mL of dry THF was added dropwise a solution of n-BuLi in hexane (6.56 mL, 10.5 mmol). The solution was warmed to -20 °C and stirred for 1 h. A solution of EtO_2C-Cl (1.41 g, 13 mmol) in 10 mL of dry THF was added, the solution was warmed to room temperature and stirred for 1 h. Saturated aqueous NH_4Cl and Et_2O were added and the organic layer was separated, washed with brine, dried ($MgSO_4$), and concentrated by distillation at atmospheric pressure. Fractional distillation (15 cm Vigreaux column) of the residual oil provided 1.33 g (86 %) of the acetylenic ester 1i as a colorless oil, b.p. 81-84 °C/25 Torr (lit.[14] b.p. 73-74.5 °C/14 Torr); IR (neat) 2215, 1708, 1280 cm^{-1}; ^1H NMR (80 MHz) δ 1.29 (s, 9H), 1.32 (t, 3H, J = 7 Hz), 4.26 (q, 2H, J = 7 Hz).

Methyl 6-bromo-2-hexynoate (1j). To a stirred suspension of $Ph_3P{\cdot}Br_2$ (16.5 mmol) in 80 mL of dry CH_2Cl_2[18] was added a solution of the tetrahydropyranyl ether 26 (3.39 g, 15 mmol) in 10 mL of dry CH_2Cl_2. After the yellow solution had been stirred at room temperature for 30 min, it was washed with water (2 x 40 mL) and dried ($MgSO_4$). Removal of the solvent, followed by flash chromatography of the residual oil on silica gel (3 x 15 cm column; 1:9 Et_2O - petroleum ether) provided an oil that, upon distillation (112-114 °C/12 Torr), gave 2.34 g (74 %) of the bromo ester 1j. This material, a colorless liquid, exhibited IR (neat) 2220, 1710, 1430, 1260, 1080, 760 cm^{-1}; ^1H NMR (80 MHz) δ 2.09 (quintet, 2H, J = 6 Hz), 2.53 (t, 2H, J = 6 Hz), 3.49 (t, 2H, J = 6 Hz), 3.74 (s, 3H). Exact Mass calcd. for $C_7H_9{}^{81}BrO_2$: 205.9765; found: 205.9790.

Methyl 7-bromo-2-heptynoate (1k). This substance (1.76 g, 89 %; distillation temperature 135-140 °C/12 Torr) was prepared from the tetrahydropyranyl ether 27 (2.16 g, 9.0 mmol) via a procedure very similar to that described above. Compound 1k was obtained as a colorless oil that exhibited IR (neat) 2220, 1710, 1435, 1260, 1080, 760 cm^{-1}; ^1H NMR (80 MHz) δ 1.0-2.2 (m, 4H), 2.41 (t, 2H, J = 6.5 Hz), 3.44 (t, 2H, J = 6 Hz), 3.77 (s, 3H). Exact Mass calcd. for $C_8H_{11}{}^{79}BrO_2$: 217.9942; found: 217.9940.

Methyl 6-iodo-2-hexynoate (1l). A solution of the bromo ester 1j (570 mg, 2.8 mmol) in 10 mL of dry acetone containing 650 mg (4.3 mmol) of anhydrous NaI was stirred at room temperature for 10 h. Most of the solvent was removed (reduced pressure) and the residue was treated with 30 mL of Et_2O. The organic solution was washed successively with brine (5 mL), saturated aqueous sodium thiosulfate (2 x 5 mL), and brine (5 mL) and then was dried ($MgSO_4$) and concentrated. Distillation (90-95 °C/0.4 Torr) of the residual oil afforded 640 mg (91 %) of the iodo ester 1l as a colorless oil that exhibited IR (neat) 2210, 1710, 1430, 1260, 1080, 755 cm^{-1}; ^1H NMR (80 MHz) δ 2.07 (tt, 2H, J = 7, 6.5 Hz), 2.51 (t, 2H, J = 7 Hz), 3.29 (t, 2H, J = 6.5 Hz), 3.77 (s, 3H). Exact Mass calcd. for $C_7H_9IO_2$: 251.9647; found: 251.9653.

Methyl 7-iodo-2-heptynoate (1m). This material (425 mg, 90 %; distillation temperature 113-120 °C/0.7 Torr) was prepared from the bromo ester 1k (387 mg, 1.77 mmol) via a procedure very similar to that described above. Compound 1m, a colorless oil, exhibited IR (neat) 2210, 1705, 1430, 1260, 1080, 755 cm^{-1}; ^1H NMR (80 MHz) δ 1.5-2.2 (m, 4H), 2.38 (t, 2H, J = 6.5 Hz), 3.21 (t, 2H, J = 6.5 Hz), 3.76 (s, 3H). Exact Mass calcd. for $C_8H_{11}IO_2$: 265.9803; found: 265.9807.

Reaction (THF, -78 °C) of α,β-acetylenic esters 1a, b, g with [$Me_3SnCuSPhLi_2$ (5) in the presence of MeOH (Table 1, entries 1,3,9). General procedure I. To a cold (-100 °C), stirred solution of the cuprate reagent 5 (1.0 mmol) in 10 mL of dry THF was added, dropwise, a solution of the α,β-acetylenic ester (0.5 mmol) in 0.5 mL of dry THF containing 0.85 mmol of dry

MeOH. The reaction mixture was stirred at -100 °C for 15 min and at -78 °C for 3 h. MeOH (0.2 mL) and Et_2O (30 mL) were added and the mixture was allowed to warm to room temperature. The resulting yellow slurry was filtered through a short column of silica gel (10 g, elution with 30 mL of Et_2O). The oil obtained by concentration of the combined eluate was chromatographed on silica gel (~ 3 g). Elution with petroleum ether (~ 10 mL) gave $Me_3SnSnMe_3$. Further elution with Et_2O (~ 8 mL), followed by distillation of the material thus obtained, provided the product(s).

The following substances were prepared via general procedure I.

Ethyl (E)-3-trimethylstannyl-2-pentynoate (10a) (79 %). Distillation temperature 110-125 °C/20 Torr; IR (neat) 1715, 1598, 1175, 775 cm^{-1}; ^1H NMR (100 MHz) δ 0.12 (s, 9H, $^2J_{Sn-H}$ = 54 Hz), 0.99 (t, 3H, J = 8 Hz), 1.22 (t, 3H, J = 7 Hz), 2.85 (br q, 2H, J = 8 Hz), 4.11 (q, 2H, J = 7 Hz), 5.89 (t, 1H, J = 1.5 Hz, $^3J_{Sn-H}$ = 73 Hz). Exact Mass calcd. for $C_9H_{17}O_2Sn$ (M^+-Me): 277.0250; found: 277.0250. Anal. calcd. for $C_{10}H_{20}O_2Sn$: C 41.28, H 6.93; found: C 41.36, H 7.02.

Ethyl (E)-3-trimethylstannyl-2-butenoate (10b) (78 %). Distillation temperature 105-113 °C/20 Torr; IR (neat) 1712, 1603, 1180, 773 cm^{-1}; ^1H NMR (100 MHz) δ 0.10 (s, 9H, $^2J_{Sn-H}$ = 54 Hz), 1.22 (t, 3H, J = 7 Hz), 2.34 (d, 3H, J = 2 Hz, $^3J_{Sn-H}$ = 50 Hz), 4.12 (q, 2H, J = 7 Hz), 5.95 (q, 1H, J = 2 Hz, $^3J_{Sn-H}$ = 73 Hz). Exact Mass calcd. for $C_8H_{15}O_2Sn$ (M^+-Me): 263.0094; found: 263.0074. Anal. calcd. for $C_9H_{18}O_2Sn$: C 39.03, H 6.55; found: C 39.06, H 6.50.

Methyl (E)-5-tert-butyldimethylsiloxy-3-trimethylstannyl-2-pentenoate (10g). The substrate 1g was converted, via general procedure I, into a 96:4 mixture (82 %) of 10g and 11g (distillation temperature 120-135 °C/0.2 Torr). A pure sample of 10g, obtained by preparative TLC (99:1 petroleum ether - Et_2O), exhibited IR (neat) 1715, 1595, 1265, 780 cm^{-1}; ^1H NMR (100 MHz) δ 0.02 (s, 6H), 0.17 (s, 9H, $^2J_{Sn-H}$ = 60 Hz), 0.86 (s, 9H), 3.12 (t, 2H, J = 7 Hz), 3.68 (overlapping s and t, 5H, J = 7 Hz), 6.05 (br s, 1H, $^3J_{Sn-H}$ = 72 Hz). Exact Mass calcd. for $C_{14}H_{29}O_3SiSn$ (M^+-Me): 393.0908; found: 393.0906. Anal. calcd. for $C_{15}H_{32}O_3SiSn$: C 44.25, H 7.92; found: C 44.23, H 8.04.

Preparation of Ethyl (E)- (10i) and (Z)-4,4-dimethyl-3-trimethylstannyl-2-pentenoate (11i) (Table 1, entry 12). Reaction of the acetylenic ester 1i with $[Me_3SnCuSPh]Li$ (5) was carried out under conditions similar to those summarized in general procedure I (see Table 1, footnote a, conditions C). The product (84 %) (distillation temperature 143-156 °C/20 Torr) was an 8:92 mixture of 10i and 11i, respectively. Preparative TLC provided a pure sample of each isomer. Compound 10i exhibited IR (neat) 1720, 1585, 780 cm^{-1}; ^1H NMR (100 MHz) δ 0.18 (s, 9H, $^2J_{Sn-H}$ = 52 Hz), 1.18 (s, 9H), 1.28 (t, 3H, J = 7 Hz), 4.16 (q, 2H, J = 7 Hz), 5.84 (s, 1H, $^3J_{Sn-H}$ = 87 Hz). Exact Mass calcd. for $C_{11}H_{21}O_2Sn$ (M^+-Me): 305.0564; found: 305.0560; Anal. calcd. for $C_{12}H_{24}O_2Sn$: C 45.18, H 7.58; found: C 44.98, H 7.43. Compound 11i exhibited IR (neat) 1705, 1590, 1205, 780 cm^{-1}; ^1H NMR (100 MHz) δ 0.20 (s, 9H, $^2J_{Sn-H}$ = 54 Hz), 1.12 (s, 9H), 1.26 (t, 3H, J = 7 Hz), 4.18 (q, 2H, J = 7 Hz), 6.35 (s, 1H, $^3J_{Sn-H}$ = 126 Hz). Exact Mass calcd. for $C_{11}H_{21}O_2Sn$ (M^+-Me): 305.0564; found: 305.0555.

(Z)-4,4-Dimethyl-3-trimethylstannyl-2-penten-1-ol (29). To a cold (0 °C) stirred solution of $LiAlH_4$ (0.13 mmol) in 2 mL of dry Et_2O was added 7.6 μL (0.13 mmol) of dry EtOH. A solution of the unsaturated ester 11i (32 mg, 0.10 mmol) in 0.5 mL of dry Et_2O was added dropwise and the mixture was stirred at 0 °C for 30 min and at room temperature for 1 h. $Na_2SO_4 \cdot 10H_2O$ was added and the mixture was stirred until a white granular precipitate had formed. The mixture was filtered and the collected material was washed several times with warm Et_2O. Concentration of the combined filtrate, followed by distillation (65-75 °C/0.07 Torr) of the residual oil, gave 24 mg (87 %) of the alcohol 29, a colorless oil that exhibited IR (neat) 3330, 780 cm^{-1}; ^1H NMR (80 MHz) δ 0.23 (s, 9H, $^2J_{Sn-H}$ = 52 Hz), 1.06 (s, 9H), 1.26 (br s, 1H), 4.14 (unresolved m, 2H), 6.17 (t, 1H, J = 7 Hz, $^3J_{Sn-H}$ = 148 Hz). Exact Mass calcd. for $C_9H_{19}OSn$ (M^+-Me): 263.0458; found: 263.0455.

(E)-4,4-Dimethyl-3-trimethylstannyl-2-penten-1-ol (28). To a cold (-78 °C) stirred solution of the ester 10i (28 mg, 0.09 mmol) in 2 mL of dry pentane was added 0.25 mL of a 1 M solution of i-Bu_2AlH in hexane and the mixture was stirred at -78 °C for 1 h and at 0 °C for 1 h. Saturated aqueous NH_4Cl (0.2 mL) was added and the mixture was allowed to warm to room temperature. The white slurry was treated with $MgSO_4$ and then was filtered through a short column of Florisil. The column was eluted with Et_2O. Removal of the solvent from the combined eluate, followed by distillation (85-90 °C/20 Torr) of the remaining oil, gave 22 mg (91 %) of the alcohol 28, a colorless oil that exhibited IR (neat) 3280, 1365, 1050, 775 cm^{-1}; ^1H NMR (80 MHz) δ 0.17 (s, 9H, $^2J_{Sn-H}$ = 51 Hz), 1.15 (s, 9H), 1.37 (t, 1H, J = 6 Hz, exchanges with D_2O), 4.42 (dd, 2H, J = 6, 6 Hz), 5.57 (t, 1H, J = 6 Hz, $^3J_{Sn-H}$ = 90 Hz). Exact Mass calcd. for $C_9H_{19}OSn$ (M^+-Me): 263.0458; found: 263.0458.

Reaction (THF, -48 °C) of α,β-acetylenic esters 1a-j, 1ℓ with $[Me_3SnCuSPh]Li$ (5) in the absence of MeOH (Table 1, entries 2, 4-8, 10, 11, 13-15). General procedure II. To a cold (-78 °C), stirred solution of the cuprate reagent 5 (0.39 mmol) in 5 mL of dry THF was added a solution of the α,β-acetylenic ester (0.3 mmol) in 0.5 mL of dry THF. The reaction mixture was stirred at -78 °C for 15 min and at -48 °C for 4 h. MeOH or EtOH (0.2 mL) and Et_2O (30 mL) were added and the mixture was allowed to warm to room temperature. The yellow slurry was treated with anhydrous $MgSO_4$ and then was filtered through a short column of Florisil (elution with 30 mL of

Et_2O). Concentration of the combined eluate gave an oil, which was either distilled directly to give the products(s), or was chromatographed on silica gel (8-15 g, elution with an appropriate mixture of petroleum ether and Et_2O). Distillation of the product thus obtained gave pure alkyl (Z)-3-trimethylstannyl-2-alkenoate.

The following substances were prepared via general procedure II.

Ethyl (Z)-3-trimethylstannyl-2-pentenoate (11a) (76 %). Distillation temperature 120-125 °C/20 Torr; IR (neat) 1701, 1601, 1195, 773 cm^{-1}; ^1H NMR (100 MHz) δ 0.12 (s, 9H, $^2J_{Sn-H}$ = 54 Hz), 0.98 (t, 3H, J = 7.5 Hz), 1.24 (t, 3H, J = 7 Hz), 2.41 (br q, 2H, J = 7.5 Hz), 4.15 (q, 2H, J = 7 Hz), 6.34 (t, 1H, J = 2 Hz, $^3J_{Sn-H}$ = 121 Hz). Exact Mass calcd. for $C_9H_{17}O_2Sn$ (M^+-Me): 277.0250; found: 277.0252. Anal. calcd. for $C_{10}H_{20}O_2Sn$: C 41.28, H 6.93; found: C 41.58, H 7.10.

Ethyl (Z)-3-trimethylstannyl-2-butenoate (11b). The α,β-acetylenic ester 1b was converted, via general procedure II, into a 2:98 mixture (76 %) of 10b and 11b (distillation temperature 103-115 °C/20 Torr). A pure sample of 11b, obtained by preparative TLC (99:1 petroleum ether - Et_2O), exhibited IR (neat) 1700, 1601, 1200, 772 cm^{-1}; ^1H NMR (100 MHz) δ 0.16 (s, 9H, $^2J_{Sn-H}$ = 55 Hz), 1.25 (t, 3H, J = 7 Hz), 2.12 (d, 3H, J = 2 Hz, $^3J_{Sn-H}$ = 45 Hz), 4.16 (q, 2H, J = 7 Hz), 6.29 (q, 1H, J = 2 Hz, $^3J_{Sn-H}$ = 118 Hz). Exact Mass calcd. for $C_8H_{15}O_2Sn$ (M^+-Me): 263.0094; found: 263.0074. Anal. calcd. for $C_9H_{18}O_2Sn$: C 39.03, H 6.55; found: C 39.37, H 6.50.

Methyl (Z)-4-methyl-3-trimethylstannyl-2-pentenoate (11c) (73 %). Distillation temperature 105-115 °C/12 Torr; IR (neat) 1700, 1590, 1310, 1210, 780 cm^{-1}; ^1H NMR (80 MHz) δ 0.14 (s, 9H, $^2J_{Sn-H}$ = 53.5 Hz), 1.03 (d, 6H, J = 7 Hz), 2.72 (d septets, 1H, J = 1, 7 Hz), 3.71 (s, 3H), 6.36 (d, 1H, J = 1 Hz, $^3J_{Sn-H}$ = 126 Hz). Exact Mass calcd. for $C_9H_{17}O_2Sn$ (M^+-Me): 277.0251; found: 277.0254.

Methyl (Z)-3-cyclopropyl-3-trimethylstannylpropenoate (11d) (72 %). Distillation temperature 92-100 °C/12 Torr; IR (neat) 3070, 1700, 1320, 780 cm^{-1}; ^1H NMR (80 MHz) δ 0.19 (s, 9H, $^2J_{Sn-H}$ = 55 Hz), 0.5-1.0 (m, 4H), 1.6-1.9 (m, 1H), 3.68 (s, 3H), 6.08 (d, 1H, J = 1 Hz, $^3J_{Sn-H}$ = 118 Hz). Exact Mass calcd. for $C_9H_{15}O_2Sn$ (M^+-Me): 275.0094; found: 275.0083.

Methyl (Z)-5-(2-cyclopentenyl)-3-trimethylstannyl-2-pentenoate (11e) (77 %). Distillation temperature 90-100 °C/0.2 Torr; IR (neat) 1700, 1595, 1210, 780 cm^{-1}; ^1H NMR (80 MHz) δ 0.19 (s, 9H, $^2J_{Sn-H}$ = 54.5 Hz), 1.1-1.7 (m, 4H), 1.9-2.8 (m, 3H), 2.45 (overlapping dt, 2H, J = 1, 7.5 Hz), 3.73 (s, 3H), 5.6-5.8 (m, 2H), 6.38 (t, 1H, J = 1 Hz, $^3J_{Sn-H}$ = 118 Hz). Exact Mass calcd. for $C_{13}H_{21}O_2Sn$ (M^+-Me): 329.0564; found: 329.0562.

Methyl (Z)-4-(3-cyclohexenyl)-3-trimethylstannyl-2-butenoate (11f) (71 %). Distillation temperature 84-88 °C/0.6 Torr; IR (neat) 1705, 1595, 1210, 780 cm^{-1}; ^1H NMR (80 MHz) δ 0.18 (s, 9H, $^2J_{Sn-H}$ = 54.5 Hz), 1.0-2.2 (m, 7H), 2.3-2.5 (m, 2H), 3.73 (s, 3H), 5.5-5.7 (m, 2H), 6.33 (br s, 1H, $^3J_{Sn-H}$ = 118 Hz). Exact Mass calcd. for $C_{13}H_{21}O_2Sn$ (M^+-Me): 329.0564; found: 329.0565.

Methyl (Z)-5-tert-butyldimethylsiloxy-3-trimethylstannyl-2-pentenoate (11g). The substrate 1g was converted, via general procedure II, into a 4:96 mixture (81 %) of 10g and 11g (distillation temperature 110-122 °C/0.2 Torr). A pure sample of 11g, obtained by preparative TLC (99:1 petroleum ether - Et_2O), exhibited IR (neat) 1703, 1601, 780 cm^{-1}; ^1H NMR (100 MHz) δ 0.02 (s, 6H), 0.16 (s, 9H, $^2J_{Sn-H}$ = 55 Hz), 0.87 (s, 9H), 2.63 (m, 2H, $^3J_{Sn-H}$ = 47 Hz), 3.64 (t, 2H, J = 7 Hz), 3.72 (s, 3H), 6.41 (t, 1H, J = 2 Hz, $^3J_{Sn-H}$ = 118 Hz). Exact Mass calcd. for $C_{14}H_{29}O_3SiSn$ (M^+-Me): 393.0908; found: 393.0891.

Ethyl (Z)-4-tert-butyldimethylsiloxy-3-trimethylstannyl-2-butenoate (11h). Reaction of the α,β-acetylenic ester 1h with $[Me_3SnCuSPh]Li$ (5) as described in general procedure II provided a crude product that contained (GLC analysis) a 9:91 mixture of the isomeric esters 10h and 11h, along with a product having a longer retention time. Column chromatography of the mixture on silica gel (8 g, 40:1 petroleum ether - Et_2O) provided 29 % of the (Z) ester 11h, 2 % of the (E) ester 10h (vide infra), and 35 % of ethyl (Z)-4-tert-butyldimethylsiloxy-3-phenylthio-2-butenoate (31). Compound 11h (distillation temperature 95-100 °C/0.15 Torr) exhibited IR (neat) 1700, 1305, 1195, 1120 845, 780 cm^{-1}; ^1H NMR (80 MHz) δ 0.15 (s, 6H), 0.25 (s, 9H, $^2J_{Sn-H}$ = 55 Hz), 1.00 (s, 9H), 1.35 (t, 3H, J = 7 Hz), 4.25 (q, 2H, J = 7 Hz), 4.49 (d, 2H, J = 2 Hz, $^3J_{Sn-H}$ = 15 Hz), 6.70 (t, 1H, J = 2 Hz, $^3J_{Sn-H}$ = 114 Hz). Exact Mass calcd. for $C_{14}H_{29}O_3SiSn$ (M^+-Me): 393.0908; found: 393.0906. Compound 31 (distillation temperature 125-135 °C/0.15 Torr) exhibited IR (neat) 1695, 1580, 1200, 1110, 850 cm^{-1}; ^1H NMR (80 MHz) δ -0.05 (s, 6H), 0.83 (s, 9H), 1.32 (t, 3H, J = 7 Hz), 3.91 (d, 2H, J = 2 Hz), 4.24 (q, 2H, J = 7 Hz), 6.32 (t, 1H, J = 2 Hz), 7.25-7.65 (m, 5H). Exact Mass calcd. for $C_{18}H_{28}O_3SSi$: 352.1528; found: 352.1529.

Ethyl (Z)-4,4-dimethyl-3-trimethylstannyl-2-pentenoate (11i). Reaction of the substrate 1i with $[Me_3SnCuSPh]Li$ (5) via conditions very similar to those described in general procedure II (see Table 1, footnote a, conditions D), gave a product (86 %, distillation temperature 145-157 °C/20 Torr) consisting of a 2:98 mixture of 10i and 11i. The major product 11i exhibited spectra identical with those summarized previously (vide supra).

Methyl (Z)-6-bromo-3-trimethylstannyl-2-hexenoate (11j) (72 %). Distillation temperature

93-100 °C/0.2 Torr; IR (neat) 1700, 1595, 1210, 775 cm^{-1}; ^1H NMR (80 MHz) δ 0.19 (s, 9H, $^2J_{Sn-H}$ = 55 Hz), 1.7-2.2 (m, 2H), 2.59 (br t, 2H, J = 7 Hz), 3.39 (t, 2H, J = 6.5 Hz), 3.74 (s, 3H), 6.42 (t, 1H, J = 1 Hz, $^3J_{Sn-H}$ = 116 Hz). Exact Mass calcd. for $C_9H_{16}{}^{81}BrO_2Sn$ (M^+-Me): 356.9335; found: 356.9342.

Methyl (Z)-7-bromo-3-trimethylstannyl-2-heptenoate (11*l*) (74 %). Distillation temperature 90-95 °C/0.1 Torr; IR (neat) 1700, 1595, 1335, 1210, 775 cm^{-1}; ^1H NMR (80 MHz) δ 0.20 (s, 9H, $^2J_{Sn-H}$ = 55 Hz), 1.4-2.1 (m, 4H), 2.45 (br t, 2H, J = 7 Hz), 3.42 (t, 2H, J = 6 Hz), 3.73 (s, 3H), 6.37 (t, 1H, J = 1 Hz, $^3J_{Sn-H}$ = 118 Hz). Exact Mass calcd. for $C_{10}H_{18}{}^{81}BrO_2Sn$ (M^+-Me): 370.9492; found: 370.9502.

Reaction of ethyl 2-butynoate (1b) with the (trimethylstannyl)copper(I) reagents 4, 6, and 7 (Table 2, entries 2-5). General procedure III. To a cold (-78 °C), stirred solution of $(Me_3Sn)_2CuLi$ (6), $[Me_3SnCu{\equiv}C\text{-}C(OMe)Me_2]Li$ (7), or $Me_3SnCu{\cdot}Me_2S$ (4) (0.39 mmol) in 5 mL of dry THF was added a solution of ethyl 2-butynoate (1b) (34 mg, 0.3 mmol) in 0.5 mL of dry THF. The mixture was stirred at -78 °C for 3 h or at -48 °C for 3 or 4 h (see Table 2). Saturated aqueous NH_4Cl-NH_4OH (pH 8) (5 mL) and Et_2O (30 mL) were added and the mixture was stirred vigorously at room temperature until the aqueous phase became deep blue. The organic layer was separated, washed with saturated aqueous NH_4Cl-NH_4OH (pH 8), dried ($MgSO_4$), and concentrated. The residual oil was distilled under reduced pressure to provide the product(s) 10b and (or) 11b, which were spectrally identified (vide supra). The results of these experiments are summarized in Table 2.

Reaction of α,β-acetylenic esters 1a-f, h-j, *l* with $Me_3SnCu{\cdot}Me_2S$ (4) (Table 3, entries 1-7, 9, 10). General procedure IV. To a cold (-78 °C), stirred solution of reagent 4 (0.39 mmol) in 5 mL of dry THF was added a solution of the α,β-acetylenic ester 1 (0.3 mmol) in 0.5 mL of dry THF. The dark red solution was stirred at -78 °C for 3 h. Saturated aqueous NH_4Cl-NH_4OH (pH 8) (0.5 mL) and Et_2O (30 mL) were added, the mixture was allowed to warm to room temperature, and stirring was continued until the aqueous phase became deep blue. The organic layer was separated, washed twice with 5 mL of saturated aqueous NH_4Cl-NH_4OH (pH 8), dried ($MgSO_4$), and concentrated. The residual oil was chromatographed on 3 g of silica gel. Elution with petroleum ether (10 mL) gave $Me_3SnSnMe_3$. Elution with Et_2O, followed by concentration of the resultant eluate and distillation of the crude oil, gave the product(s).

In addition to compounds 10a (80 %) and 10b (76 %), the spectra of which were recorded earlier (vide supra), the following substances were prepared by general procedure IV.

Methyl (E)-4-methyl-3-trimethylstannyl-2-pentenoate (10c) (77 %). Distillation temperature 108-115 °C/12 Torr; IR (neat) 1710, 1580, 1180, 780 cm^{-1}; ^1H NMR (80 MHz) δ 0.20 (s, 9H, $^2J_{Sn-H}$ = 53 Hz), 1.02 (d, 6H, J = 7 Hz), 3.68 (s, 3H), 4.02 (d septets, 1H, J = 1, 7 Hz), 5.87 (d, 1H, J = 1 Hz, $^3J_{Sn-H}$ = 76 Hz). Exact Mass calcd. for $C_9H_{17}O_2Sn$ (M^+-Me): 277.0251; found: 277.0253.

Methyl (E)-3-cyclopropyl-3-trimethylstannylpropenoate (10d) (81 %). Distillation temperature 85-92 °C/12 Torr; IR (neat) 3060, 1710, 1570, 1200, 1180, 1150, 780 cm^{-1}; ^1H NMR (80 MHz) δ 0.18 (s, 9H, $^2J_{Sn-H}$ = 54 Hz), 0.4-0.7, 0.8-1.1 (m, m, 2H each), 3.1-3.4 (m, 1H), 3.72 (s, 3H), 5.95 (d, 1H, J = 1 Hz, $^3J_{Sn-H}$ = 71 Hz). Exact Mass calcd. for $C_9H_{15}O_2Sn$ (M^+-Me): 275.0094; found: 275.0083.

Methyl (E)-5-(2-cyclopentenyl)-3-trimethylstannyl-2-pentenoate (10e) (84 %). Distillation temperature 85-92 °C/ 0.2 Torr; IR (neat) 3030, 1710, 1590, 1170, 775 cm^{-1}; ^1H NMR (80 MHz) δ 0.20 (s, 9H, $^2J_{Sn-H}$ = 53 Hz), 1.2-1.7 (m, 4H), 1.8-2.5 (m, 2H), 2.5-2.8 (m, 1H), 2.95 (td, 2H, J = 8, 1 Hz), 3.72 (s, 3H), 5.6-5.8 (m, 2H), 5.97 (t, 1H, J = 1 Hz, $^3J_{Sn-H}$ = 73 Hz). Exact Mass calcd. for $C_{13}H_{21}O_2Sn$ (M^+-Me): 329.0564; found: 329.0562.

Methyl (E)-4-(3-cyclohexenyl)-3-trimethylstannyl-2-butenoate (10f) (72 %). Distillation temperature 85-90 °C/0.8 Torr; IR (neat) 1720, 1590, 1205, 1160, 780, 660 cm^{-1}; ^1H NMR (80 MHz) δ 0.19 (s, 9H, $^2J_{Sn-H}$ = 54 Hz), 1.0-2.3 (m, 7H), 2.8-3.0 (m, 2H), 3.69 (s, 3H), 5.6-5.8 (m. 2H), 6.05 (t, 1H, J = 1 Hz, $^3J_{Sn-H}$ = 73 Hz). Exact Mass calcd. for $C_{13}H_{21}O_2Sn$ (M^+-Me): 329.0564; found: 329.0560.

Ethyl (E)-4-tert-butyldimethylsiloxy-3-trimethylstannyl-2-butenoate (10h). Reaction of the α,β-acetylenic ester 1h with $Me_3SnCu{\cdot}Me_2S$ (4) as described in general procedure IV gave an oil (distillation temperature 92-100 °C/0.15 Torr, 80 % yield) that contained (GLC analysis) a 95:5 mixture of 10h and 11h. The two products were separated by preparative TLC (40:1 petroleum ether - Et_2O). The minor product gave spectra identical with those of 11h (vide supra), while the major product, 10h, exhibited IR (neat) 1705, 1595, 1185, 1080, 780 cm^{-1}; ^1H NMR (80 MHz) δ 0.15 (s, 6H), 0.26 (s, 9H, $^2J_{Sn-H}$ = 55 Hz), 0.98 (s, 9H), 1.35 (t, 3H, J = 7 Hz), 4.19 (q, 2H, J = 7 Hz), 4.94 (d, 2H, J = 3 Hz, $^3J_{Sn-H}$ = 30 Hz), 5.94 (t, 1H, J = 3 Hz, $^3J_{Sn-H}$ = 72 Hz). Exact Mass calcd. for $C_{14}H_{29}O_3SiSn$ (M^+-Me): 393.0908; found: 393.0918.

Methyl (E)-6-bromo-3-trimethylstannyl-2-hexenoate (10j) (81 %). Distillation temperature 105-112 °C/0.4 Torr; IR (neat) 1710, 1200, 1180, 775 cm^{-1}; ^1H NMR (80 MHz) δ 0.22 (s, 9H, $^2J_{Sn-H}$ = 54 Hz), 1.7-2.2 (m, 2H), 3.02 (br t, 2H, J = 7.5 Hz), 3.43 (t, 2H, J = 7 Hz), 3.69 (s, 3H), 6.03 (t, 1H, J = 1 Hz, $^3J_{Sn-H}$ = 71 Hz). Exact Mass calcd. for $C_9H_{16}{}^{81}BrO_2Sn$ (M^+-Me): 356.9335; found: 356.9333.

Methyl (E)-7-bromo-3-trimethylstannyl-2-heptenoate (10ℓ) (84 %). Distillation temperature 90-95 °C/0.3 Torr; IR (neat) 1710, 1590, 1200, 1180, 775 cm^{-1}; ^1H NMR (80 MHz) δ 0.22 (s, 9H, $^2J_{Sn-H}$ = 54 Hz), 1.4-2.1 (m, 4H), 2.93 (br t, 2H, J = 7.5 Hz), 3.45 (t, 2H, J = 6.5 Hz), 3.70 (s, 3H), 6.00 (br s, 1H, $^3J_{Sn-H}$ = 72 Hz). Exact Mass calcd. for $C_{10}H_{18}{}^{81}BrO_2Sn$ (M^+-Me): 370.9492; found: 370.9501.

Reaction of ethyl 4,4-dimethyl-2-pentynoate (1i) with $Me_3SnCu{\cdot}Me_2S$ (4) (Table 3, entry 8). To a cold (-78 °C), stirred solution of 4 (0.9 mmol) in 5 mL of dry THF was added successively 0.5 mL of dry HMPA and a solution of 1i (0.3 mmol) in 0.5 mL of dry THF. The solution was stirred at -78 °C for 15 min and at -20 °C for 6 h. Workup as described in general procedure IV (vide supra), followed by distillation of the crude product, gave an oil that consisted (GLC analysis) of a 12:80 mixture of 10i and 11i, along with a third component that was not fully identified but was thought to be ethyl (E)-4,4-dimethyl-2-trimethylstannyl-2-pentenoate (30). Pure samples of 10i and 11i, obtained from the mixture by preparative TLC, exhibited spectra identical with those summarized previously (vide supra).

Methyl 2-trimethylstannyl-1-cyclopentenecarboxylate (42). To a cold (-78 °C), stirred solution of $[Me_3SnCuSPh]Li$ (5) (0.39 mmol) in 5 mL of dry THF was added a solution of methyl 6-bromo-2-hexynoate (1j) (61 mg, 0.3 mmol) in 0.5 mL of dry THF. After the dark red reaction mixture had been stirred at -78 °C for 15 min and at -48 °C for 4 h, HMPA (0.5 mL) was added, the mixture was allowed to warm slowly to room temperature, and then was stirred for 2 h. Saturated aqueous NH_4Cl-NH_4OH (pH 8) (0.2 mL) and Et_2O (40 mL) were added and the mixture was stirred vigorously for 10 min. The brown slurry was treated with anhydrous $MgSO_4$ and then was filtered through a short column of Florisil. The column was eluted with Et_2O. After the combined eluate had been washed with saturated aqueous $CuSO_4$ (2 x 5 mL) and saturated aqueous NH_4Cl-NH_4OH (pH 8) (5 mL), it was dried ($MgSO_4$) and concentrated. GLC analysis indicated that the remaining oil contained $Me_3SnSnMe_3$, a major product, and several very minor components (< 5 % total). Flash chromatography of this material on silica gel (3 x 15 cm column, 1:100 Et_2O - petroleum ether), followed by distillation (85-90 °C/0.3 Torr) of the oil thus obtained, gave 66 mg (77 %) of the ester 42,[34] a colorless oil that exhibited IR (neat) 1700, 1260, 770 cm^{-1}; ^1H NMR (80 MHz) δ 0.16 (s, 9H, $^2J_{Sn-H}$ = 54 Hz), 1.94 (m, 2H), 2.63 (m, 4H), 3.71 (s, 3H). Exact Mass calcd. for $C_9H_{15}O_2Sn$ (M^+-Me): 275.0094; found: 275.0092.

Reaction of methyl 6-iodo-2-hexynoate (1k) (74.8 mg, 0.3 mmol) with reagent 5, via a procedure identical with that described above, gave 60 mg (73 %) of the ester 42, which exhibited spectra identical with those summarized above.

Reaction of methyl 7-bromo- and 7-iodo-2-heptynoate (1ℓ, 1m, respectively) with $[Me_3SnCuSPh]Li$ (5) in the presence of HMPA. Reaction of 1ℓ (66 mg, 0.3 mmol) with reagent 5 (0.39 mmol) was carried out via a procedure identical with that described above. Although GLC analysis of the crude product indicated the presence of $Me_3SnSnMe_3$, one major product (> 90 % of the mixture) and a small amount (3 %) of a substance having retention time identical with that of methyl 2-trimethylstannyl-1-cyclohexenecarboxylate (43),[34] TLC analysis showed the presence of a second major product. Flash chromatography of the mixture provided 39 mg (43 %) of the α-trimethylstannyl α,β-unsaturated ester 44 (distillation temperature 60-65 °C/0.9 Torr) and 31 mg (19 %) of methyl (E)-7-bromo-2,3-bis(trimethylstannyl)-2-heptenoate (45) (distillation temperature 125-130 °C/0.05 Torr). The latter substance did not evoke a response on the gas-liquid chromatography under usual conditions.

Compound 44 exhibited IR (neat) 1700, 1600, 1205, 1190, 775 cm^{-1}; ^1H NMR (80 MHz) δ 0.24 (s, 9H, $^2J_{Sn-H}$ = 54 Hz), 1.5-1.8 (m, 4H), 2.38 (br t, 2H, J = 7 Hz), 2.70 (br t, 2H, J = 7 Hz), 3.70 (s, 3H). Exact Mass calcd. for $C_{10}H_{17}O_2Sn$ (M^+-Me): 289.0251; found: 289.0251.

Compound 45 exhibited IR (neat) 1680, 1430, 1210, 770 cm^{-1}; ^1H NMR (80 MHz) δ 0.17 (s, 9H, $^2J_{Sn-H}$ = 53 Hz), 0.26 (s, 9H, $^2J_{Sn-H}$ = 54 Hz), 1.3-2.1 (m, 4H), 2.51 (br t, 2H, J = 7.5 Hz), 3.42 (t, 2H, J = 6.5 Hz), 3.72 (s, 3H). Exact Mass calcd. for $C_{13}H_{26}{}^{81}BrO_2Sn_2$ (M^+-Me): 534.9140; found: 534.9132

Reaction of the iodide 1m with 5 under conditions identical with those described above gave a very similar result. The crude product consisted of a 5:95 mixture of 43 and 44, respectively, along with methyl (E)-7-iodo-2,3-bis(trimethylstannyl)-2-heptenoate.

ACKNOWLEDGEMENTS

Financial support from the Natural Sciences and Engineering Research Council of Canada (NSERCC) and NSERCC postgraduate scholarships (to H.E.M. and J.M.C.) are gratefully acknowledged.

REFERENCES AND FOOTNOTES

1. (a) Corey, E.J.; Katzenellenbogen, J.A. J. Am. Chem. Soc., 1969, 91, 1851. (b) Siddall, J.B.; Biskup, M.; Fried, J.H. J. Am. Chem. Soc., 1969, 91, 1853. (c) Klein, J.; Turkel, R.M. J. Am. Chem. Soc., 1969, 91, 6168. (d) Klein, J.; Aminadav, N. J. Chem. Soc. (C), 1970, 1380. (e) Naf, F.; Degen, P. Helv. Chim. Acta, 1971, 54, 1939. (f) Corey, E.J.; Kim,

C.U.; Chen, R.H.K.; Takeda, M. J. Am. Chem. Soc., 1972, 94, 4395. (g) Bowlus, S.B.; Katzenellenbogen, J.A. Tetrahedron Lett., 1973, 1277. (h) Corey, E.J.; Chen, R.H.K. Tetrahedron Lett., 1973, 1611. (i) Klein, J.; Levene, R. J. Chem. Soc., Perkin Trans. II, 1973, 1971. (j) Anderson, R.J.; Corbin, V.L.; Cotterrell, G.; Cox, G.R.; Henrick, C.A.; Schaub, F.; Siddall, J.B. J. Am. Chem. Soc., 1975, 97, 1197. (k) Marino, J.P.; Browne, L.J. J. Org. Chem., 1976, 41, 3629. (ℓ) Roush, W.R.; Peseckis, S.M. J. Am. Chem. Soc., 1981, 103, 6696. (m) Marino, J.P.; Linderman, R.J. J. Org. Chem., 1981, 46, 3696. (n) Nishiyama, H.; Sasaki, M.; Itoh, K. Chemistry Lett., 1981, 905, 1363. (o) Poulter, C.D.; Wiggins, P.L.; Plummer, T.L. J. Org. Chem., 1981, 46, 1532. (p) Marino, J.P.; Linderman, R.J. J. Org. Chem., 1983, 48, 4621. (q) Walba, D.M.; Stoudt, G.S. J. Org. Chem., 1983, 48, 5404. (r) Oppolzer, W.; Mirza, S. Helv. Chim. Acta, 1984, 67, 730. (s) Crimmins, M.T.; Mascarella, S.W.; DeLoach, J.E. J. Org. Chem., 1984, 49, 3033. (t) Lewis, D.E.; Rigby, H.L. Tetrahedron Lett., 1985, 26, 3437. (u) Cooper, J.; Knight, D.W.; Gallagher, P.T. J. Chem. Soc., Chem. Commun., 1987, 1220.

2. Piers, E.; Morton, H.E.; Chong, J.M. Can. J. Chem. 1987, 65, 78.
3. Piers, E.; Chong, J.M. Can. J. Chem., 1988, in press.
4. For preliminary reports regarding some of the work reported herein, see Piers, E.; Morton, H.E. J. Org. Chem., 1980, 45, 4263; Piers, E.; Chong, J.M.; Morton, H.E. Tetrahedron Lett., 1981, 22, 4905.
5. Young, L.B.; Trahosk, W.S. J. Org. Chem., 1967, 32, 2349.
6. Corey, E.J.; Fuchs, P.L. Tetrahedron Lett., 1972, 3769.
7. Combret, J.C.; Villieras, J.; Lavielle, G. Tetrahedron Lett., 1971, 1035.
8. Garin, D.L. J. Org. Chem., 1969, 34, 2355.
9. Chan, J.H.-H.; Rickborn, B. J. Am. Chem. Soc., 1968, 90, 6406.
10. Wiley, G.A.; Hershkowitz, R.L.; Rein, B.M.; Chung, B.C. J. Am. Chem. Soc., 1964, 86, 964.
11. Perry, R.A.; Chen, S.C.; Menon, B.C.; Hanaya, K.; Chow, Y.L. Can. J. Chem., 1976, 54, 2385.
12. Smith, W.N.; Beumel, O.F. Synthesis, 1974, 441.
13. We are very grateful to Professor L. Weiler and Dr. P.E. Sum for a generous sample of the tetrahydropyranyl ether of this compound, which was readily hydrolyzed (HCl, H_2O, MeOH, room temperature) to the ester alcohol.
14. Fischer, B.; Grob, C.A. Helv. Chim. Acta, 1956, 39, 417.
15. Logue, M.W.; Teng, K. J. Org. Chem., 1982, 47, 2549.
16. Miyashita, M.; Yoshikoshi, A.; Grieco, P.A. J. Org. Chem., 1977, 42, 3772.
17. Tufariello, J.J.; Trybulski, E.J. J. Org. Chem., 1974, 39, 3378.
18. Sonnett, P.E. Synth. Commun., 1976, 6, 21.
19. It has been established that (trimethylstannyl)copper(I) reagents are very weak bases in THF and react very slowly, if at all, with weak proton donors such as MeOH.[2,20]
20. Cox, S.D.; Wudl, F. Organometallics, 1983, 2, 184.
21. Davidson, R.S.; Gunther, W.H.H.; Waddington-Feather, S.M.; Lythgoe, B. J. Chem. Soc., 1964, 4907.
22. Leusink, A.J.; Marsman, J.W.; Budding, H.A. Recl. Trav. Chim. Pay-Bas, 1965, 84, 689.
23. Leusink, A.J.; Budding, H.A.; Marsman, J.W. J. Organometal. Chem., 1967, 9, 285.
24. Normant, J.F.; Alexakis, A. Synthesis, 1981, 841.
25. Erdik, E. Tetrahedron, 1984, 40, 641.
26. The structural formulas 32 and 33, which are undoubtedly simplistic representations of the structures of these intermediates, are used in the interest of clarity. It may be noted that both vinylcopper(I) and allenoate species have been proposed as intermediates in the addition of organocopper(I) reagents to α,β-acetylenic esters.[1a,i,j,m,p]
27. The initial addition of (trimethylstannyl)copper(I) reagents to α,β-acetylenic esters has been shown[20,28] to be reversible.
28. Piers, E.; Chong, J.M. Unpublished work.
29. The Me_3Sn group would be expected to hinder the approach of an external reagent and, therefore, protonation of 33 might be expected to occur from the side opposite the Me_3Sn function, to give 11. However, particularly if R is large, another factor may be important. Due to the length of carbon-tin bonds (~0.22 nm) the steric demand of a Me_3Sn group within a molecule is not particularly large. For example, the conformational free energy of this function in trimethylstannylcyclohexane is about 1 kcal/mol.[30] On this basis, one would predict that compounds 11 would be thermodynamically more stable than 10. Consequently, if the transition state for protonation of 33 has (some) product-like character, the formation of 11 would be favored over the production of 10.
30. Kitching, W.; Olszowy, H.A.; Harvey, K. J. Org. Chem., 1982, 47, 1893.
31. Piers, E.; Chong, J.M.; Keay, B.A. Tetrahedron Lett., 1985, 26, 6265.
32. Piers, E.; Urech, R. Unpublished work.
33. Piers, E.; Chong, J.M. J. Org. Chem., 1982, 47, 1602.
34. Piers, E.; Tse, H.L.A. Tetrahedron Lett., 1984, 25, 3155.
35. Piers, E.; Karunaratne, V. J. Org. Chem. 1983, 48, 1774; Piers, E.; Gavai, A.V. J. Chem. Soc., Chem. Commun., 1985, 1241; Piers, E.; Friesen, R.W. J. Org. Chem., 1986, 51, 3405; Piers, E.; Friesen, R.W. Can. J. Chem., 1987, 65, 1681.
36. Kuivila, H.G.; Tsai, K.-H.; Kingston, D.G.I. J. Organomet. Chem., 1970, 23, 129.
37. Still, W.C.; Kahn, M.; Mitra, A. J. Org. Chem., 1978, 43, 2923.