Regio- and Stereocontrolled Synthesis of Allenic and Acetylenic Derivatives. Organotitanium and Boron Reagents

Kyoji FURUTA, Masaharu ISHIGURO, Ryuichi HARUTA, Nobuo IKEDA, and Hisashi YAMAMOTO*
Department of Applied Chemistry, Nagoya University, Chikusa, Nagoya 464
(Received December 26, 1983)

The propargyltitanium reagents derived from 1-alkylpropyne condensed with aldehydes to give α-allenyl alcohol regioselectively, while the allenyltitanium reagents generated from 1-alkyl-1-butyne derivatives gave *threo*-β-acetylenic alcohols with high regio- and stereoselectivities. The course of the reaction was determined by the substitution pattern of starting alkynes. The similar reactions of metallated 1,3-bis(trialkylsilyl)propyne or (trialkylsilyl)acetonitrile with aldehydes were also investigated.

The importance of the propargylic anions in synthetic chemistry emerged from the recognitions of their utility for the extension of the carbon chain and facility in the interconversion of the functionality.[1] Their applicability in organic synthesis, however, has been limited because of the difficulties in controlling the regio- and stereoselectivities of the reaction. As it is often pointed out, the propargylic anion may be in equilibrium with allenic anion.[2] Thus, in the condensation with carbonyl compounds, two products, acetylenic and allenic alcohols, can be formed. Furthermore, each product may consist of two stereoisomers, *i. e.*, *erythro* and *threo* isomers.[3] Under the ordinary reaction conditions, therefore, these four isomers should be produced. Thus, to achieve the selective reaction, it is necessary to solve the regiochemical (allenic and acetylenic) and stereochemical (*erythro* and *threo*) problems at the same time. The similar ambiguity should be observed in the reaction of allylic anions.[4]

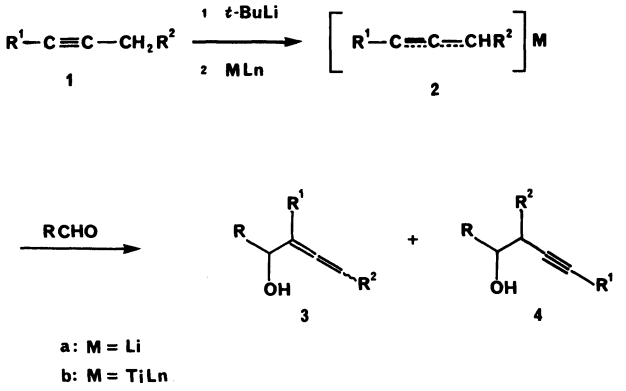
In general, the structure and reactivities of the ambident anion are highly dependent on the nature of the countercations and solvents.[5] In our continuative studies on the organometallic reagents, we found the propargylic titanium reagents partially solved the aforementioned problems. We also investigated the reaction of nitrile anion,[6] which had an analogous structure with propargylic anion, and observed that the boron as a countercation gave the best result in this particular case.

We report here a regio- and stereocontrolled synthesis of allenic and acetylenic alcohols using propargyltitanium reagents. The application of the methodology for the synthesis of enynes and α,β-unsaturated nitriles were also described herein.[7]

Results and Discussion

Synthesis of Allenic and Acetylenic Alcohols. The lithio propargylic derivatives, which were easily generated from substituted propyne derivatives and *t*-butyllithium, were subject to condensation with aldehydes as such or after the exchange of the lithium ion by subsequent treatment with appropriate metal salts (Scheme 1).

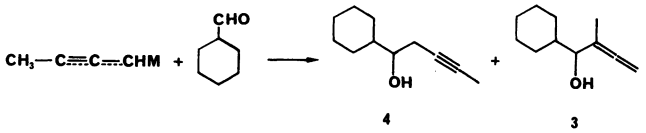
The lithio reagent **2a** (R^1=Me, R^2=H) derived from 2-butyne reacted with cyclohexanecarbaldehyde in tetrahydrofuran (THF) solvent to give a mixture of α-allenic and β-acetylenic alcohol **3** and **4**, respectively, in the ratio of 42:58. On the other hand, the titanium



Scheme 1.

derivative **2b** (R^1=Me, R^2=H) gave the α-allenic alcohol **3** without contamination of any β-acetylenic alcohol **4**. The slight alteration in product distribution was observed by changing the solvent from THF to ether. The effects caused by changing the metal cation and solvent were studied in detail and the results are summarized in Table 1.

TABLE 1. THE REGIOSELECTIVITY OF THE REACTION OF METALLATED 2-BUTYNE WITH CYCLOHEXANECARBALDEHYDE[a]

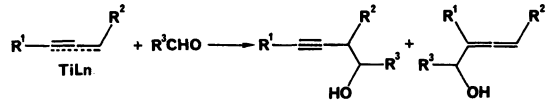


4 3

Entry	Metal[b]	Solvent	4	3[c]
1	*t*-BuLi	Ether	34	66
2	*t*-BuLi	THF	58	42
3	$Ti(OPr^i)_4$	Ether	3	97
4	$Ti(OPr^i)_4$	THF	1	99
5	$B(OPr^i)_3$	Ether	69	31
6	$B(OPr^i)_3$	THF	75	25
7	Et_2AlCl	THF	10	90
8	$Et_2AlCl+H_2O$	THF	7	93
9	MgI_2	THF	19	81
10	$ZnBr_2$	Ether	9	91
11	$ZnBr_2$	THF	17	83
12	$SnCl_2$	THF	7	93

a) The reactions were carried out on 2 mmol scale. The crude products were directly subject to GLC analysis. b) One equivalent of MLn was used for the metal exchange except for entries 7 and 8. Entry 7: Et_2AlCl, 2 equiv; Entry 8: $Et_2AlCl+H_2O$ (2:1), 2 equiv. c) Isomer ratio was determined by GLC analysis.

TABLE 2. THE REGIOSELECTIVITY OF THE REACTION OF TITANIUM REAGENTS WITH ALDEHYDES



Entry	R^1	R^2	R^3	4/3[a,b] Ratio	Yield of 4+3/%
1	$Si(CH_3)_3$	H	Cyclohexyl	1:99 (58:42)[c]	93
2	$Si(CH_3)_3$	H	Phenyl	1:99 (65:35)	87
3	CH_3	H	Cyclohexyl	1:99 (53:47)	90
4	CH_3	H	Phenyl	1:99 (49:51)	80
5	$Si(CH_3)_3$	CH_3	Cyclohexyl	>99: 1	69
6	$Si(CH_3)_3$	CH_3	Phenyl	>99: 1	79
7	CH_3CH_2	CH_3	Cyclohexyl	>99: 1 (84:16)	42
8	Phenyl	CH_3	Cyclohexyl	94: 6 (93: 7)	89
9	Phenyl	CH_3	Phenyl	>99: 1 (98: 2)	92

a) Determined by GLC analysis. b) Values in parenthesis refer to ratios of **4**/**3** obtained in the reactions with lithium reagents. c) 56:44 using Mg ion; 75:25 using Zn ion.

The regioselectivity is heavily dependent on the kind of metal ion. Thus, the titanium reagent showed the highest regioselectivity (entry 4) in a variety of metal ions investigated.[8] In most cases, THF was a superior solvent to ether.

Since the unusual selectivities of the titanium reagents became apparent from the above results, their reactivities were examined in detail. The results were summarized in Table 2.

The titanium reagent generated from 1-substituted propyne (**2b**, R^1=alkyl or trialkylsilyl, R^2=H) condensed with an aldehyde to give the α-allenic alcohol **3** exclusively, similar to that observed in the reaction of 2-butyne (entries 1—4). However, a dramatic alteration in the product distribution occurred when the reactions of the homologous titanium reagents derived from 1,3-disubstituted propyne (**2b**, R^1=alkyl or trialkylsilyl, R^2=Me) were conducted with the same aldehydes. Thus, none of the corresponding α-allenic alcohols were detected, and instead the β-acetylenic alcohols **4** were obtained (entries 5—9). The high regioselectivity appears to be general for a range of acetylenes and aldehydes. Although the corresponding lithio derivatives generally gave the less selective results, in the case of 1,3-disubstituted propyne, even the lithio derivatives showed moderate to fairly high selectivities (entries 7—9).

From the above results, the characteristic features of the reaction may be summarized as follows. The substitution pattern of the starting alkynes plays a dominant role in determining the regioselectivity of the reaction: The alkynes having a substituent on propargylic carbon (**1**, $R^2 \neq H$) produced β-acetylenic alcohols exclusively, while allenic alcohols were obtained from the alkynes not substituted at propargylic carbon (**1**, R^2=H).

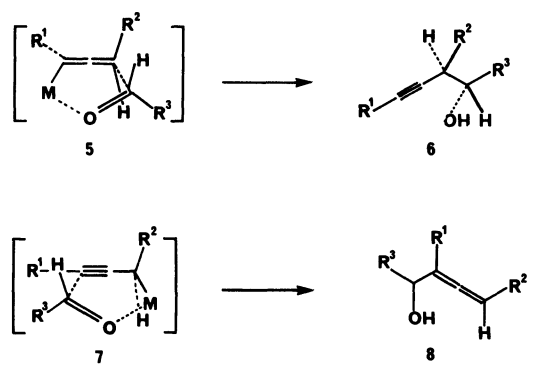


Fig. 1. S_Ei' process.

It is currently assumed that the addition of the allenic and acetylenic organometallics to the carbonyl takes place through an allylic rearrangement of the organometallic by a chelate transition state depicted in Fig. 1.[9]

That is to say, an allenic organometallic produced the β-acetylenic alcohol, while the α-allenic alcohol was derived from an acetylenic reagent. On the basis of these mechanistic considerations, the highly regioselective reaction of the titanium reagents could be explainable as follows. The titanation of the propargylic anion took place with extremely high regioselectivity to produce either allenic or acetylenic titanium derivatives depending on the substitution pattern of the original alkynes. Indeed, the IR spectrum of the titanium reagent in THF derived from 1-(trimethylsilyl)-1-butyne showed a strong absorption at 1898 cm^{-1} characteristic for allenic structure,[10] while that of the reagent derived from 1-(trimethylsilyl)propyne revealed only acetylenic absorption at 2092 cm^{-1},[10] in accord with the above speculation. In contrast to the highly selective formation of either allenic or acetylenic structure with titanium reagent, other metal cations, Li^+, MgX^+, *etc.*, furnished a mixture of the allenic and the acetylenic reagent in a variable ratio depending on the metal cations used. Siteselectivity was assumed to be determind primarily by steric requirements, and the steric repulsion between R^2 and metal centre (Fig. 2) provided conclusive factor of selectivity.

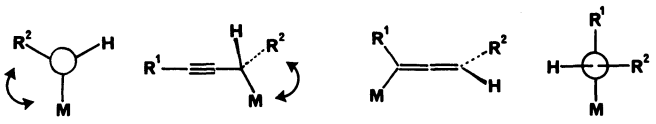
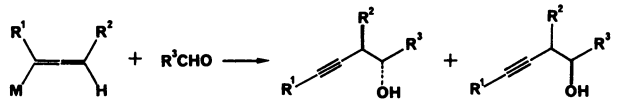


Fig. 2. Steric repulsion.

While the general trend of the regioselectivity of the titanium reagents has become apparent, it was of considerable interest to us to determine whether the tita-

Table 3. Stereoselectivity[a)]



9 10

Entry	R^1	R^2	R^3	Metal[b)]	9/10[c)] Ratio	Yield of 9+10/%
1	Me_3Si	Me	Cyclohexyl	Li	62:38	48
2	Me_3Si	Me	Cyclohexyl	Mg	65:35	42
3	Me_3Si	Me	Cyclohexyl	Ti	89:11 (93:7)[d)]	69(71)[d)]
4	Me_3Si	Me	Phenyl	Ti	30:70	79
5	Phenyl	Me	Cyclohexyl	Li	80:20	67
6	Phenyl	Me	Cyclohexyl	Ti	>99: 1	89
7	Et	Me	Cyclohexyl	Ti	91: 9 (93:7)[d)]	42(35)[d)]
8	Me_3Si	OTHP	Cyclohexyl	Zn	71:29	51[e)]
9	Me_3Si	OTHP	Cyclohexyl	Ti	90:10	67[e)]
10	Me_3Si	OTHP	n-C_5H_{11}	Ti	88:12	65[e)]
11	Me	OTHP	Cyclohexyl	Li	81:19	44[e)]
12	Me	OTHP	Cyclohexyl	Zn	88:12	48[e)]
13	Me	OTHP	Cyclohexyl	Ti	94: 6	81[e)]
14	Me	OTHP	n-C_5H_{11}	Ti	95: 5	76[e)]
15	Me	$OCMe_2OMe$	n-C_5H_{11}	Ti	93: 7	57[e)]
16	Me	OTHF	Cyclohexyl	Ti	95: 5	59[e)]
17	Me	OTHF	n-C_5H_{11}	Ti	95: 5	68[e)]

a) Unless specified, reactions were carried out at −78 °C for 1 h(entries 1—7) or at −78 °C for 0.5 h and 20 °C for 0.5 h (entries 8—17). b) Ti, $Ti(OPr^i)_n$; Mg, MgI; Zn, ZnBr. c) Determined by GLC analysis. Ratios of diacetates for entries 8—17. d) The reaction was carried out at −100°C for 1 h. e) Yields refer to the corresponding diols produced by acid hydrolysis(TsOH in methanol) of the protecting groups.

nium reagents would exhibit an extraordinary diastereoselection for the β-acetylenic alcohol synthesis. Accordingly, we have carefully examined the diastereomeric ratios of the β-acetylenic alcohols (Table 3).

As summarized in Table 3, diastereomeric ratio is influenced significantly by the nature of the counter cation. Thus, the lithium, magnesium, and zinc reagents afforded the mixture of *erythro* and *threo* alcohols with low to moderate stereoselectivities. The enhanced selectivity was now observed with titanium reagents. The titanium reagents afforded predominantly the *threo*-β-acetylenic alcohols (entries 3, 6, and 7) and *erythro*-α,β-acetylenic diols[11] (entries 9—17) with synthetically useful levels of stereoselectivities. The alkoxyl group served as a bulky substituents and did not give a special influence on the regio- and stereoselectivities of the reaction. Such stereoregulation may be understandable simply by considering the same chelate type transition state (Fig. 3).

The titanium reagent which was present as the allenic form with a tight metal-carbon bond, forms the two six-membered ring chelate transition states, T_1 and T_2, according to the direction of the carbonyl approach. As is apparent from the Fig. 3, the steric repulsion between R and R_2 controls the course of the carbonyl approach to the reaction centre. Therefore, the transition state T_1 is more favorable than T_2 and the predominant production of the *threo* adduct *via* T_1 was observed.

Examination of the other data in Table 3 reveals several other trends: (1) Most remarkable is the reaction with benzaldehyde exhibiting an opposite stereoselection,[12] that is, *erythro*-β-acetylenic alcohol was obtained albeit in a lower level of selectivity(entry 4); (2) a trimethylsilyl group at R^1 of the reagents gave

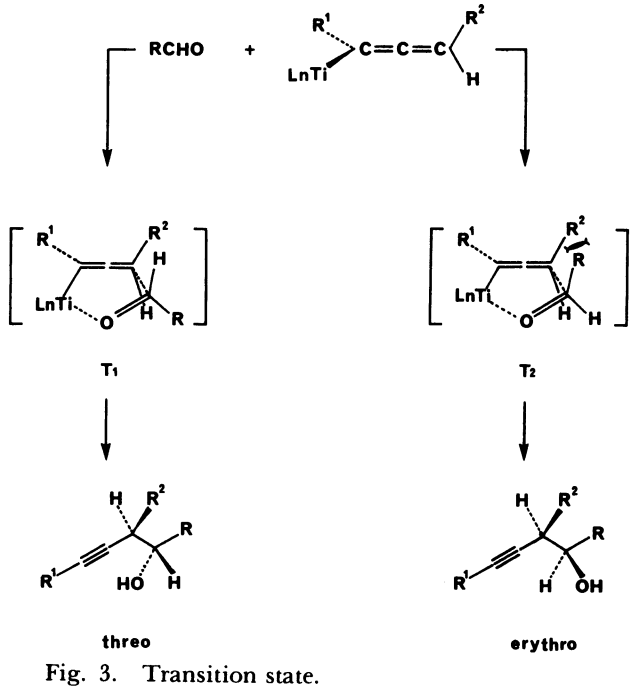


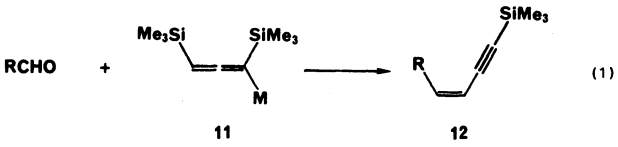
Fig. 3. Transition state.

slightly lower selectivities for the reaction (entries 9 and 10); (3) a lower reaction temperature leads to higher selectivities (entries 3 and 7). The reverse change in stereoselectivity observed in the reaction with benzaldehyde can not be fully explicable at present, but a similar anomaly has been observed elsewhere.[13]

It should be noted that the condensations of the titanium reagent with ketones were unsuccessful, and starting ketones were recovered. Similar chemoselectivities for the titanium reagents were reported.[8]

Synthesis of Enyne and α,β-Unsaturated Nitrile. The regio- and stereoselective behaviours of the propargyltitanium reagents in carbonyl addition have now become apparent in detail. Thus the additional applications of the similar reagents were examined for synthetic purposes.

We[1h] have already reported an efficient silicon-mediated (*Z*)-enyne synthesis using metallated 1,3-bis(trialkylsilyl)propyne as exemplified in Eq. 1.[1i,14]



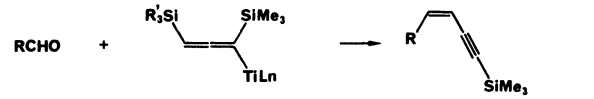
11 12

It was demonstrated that the alkyl groups on silicon provide powerful steric screening effect which plays an important role for the stereochemical course of the reaction. It was also pointed out that the tightness of the bond with counterion has a similar potential as a control element in stereochemistry: In order to maximize the stereoselectivity of the reaction, "a tight chelate transition state" should be achieved. For example, a magnesium chelate may be tighter than that for lithium, thus maximizing the steric effect. Unfortunately, however, the elimination step of Peterson olefination seems to proceed smoothly when lithium, sodium or potassium derivatives are used, the magnesium derivatives being comparatively slow to undergo elimination.[15] Taking these requirements and aforementioned results into account, we have tested the titanium reagents for the enyne synthesis.

1,3-Bis(trialkylsilyl)propyne[16] was treated with *t*-butyllithium and then with titanium tetraisopropoxide. The condensation with aldehydes was then conducted (Table 4). As seen from the Table 4, (*Z*)-enynes were obtained exclusively except for the reaction with benzaldehyde. The anomalous behaviour of benzaldehyde was described previously.[13]

Since the syn elimination mechanism of the β-oxide trialkylsilyl derivatives in Peterson reaction has been accepted,[17] the stereoselectivity of the reaction should be determined by the direction of the initial attack of carbanion to carbonyl.[18] For the diastereoselective addition of the titanium reagents, the similar explanation employed previously may be given again (Fig. 3): With this substituted pattern, the allenic (not acetylenic) titanium reagent was predominantly produced. Therefore, in Fig. 3, one might anticipate that the transition state T_2 might be destabilized relative to T_1 due to the $R \leftrightarrow R^2$ ($R^2 = R_3Si$) steric repulsion. As a result, (*Z*)-enyne was produced selectively *via* transition

TABLE 4. ENYNE SYNTHESIS[a]



Entry	R_3'	R	Z:E[b]	Yield(Z+E)[c]/%
1	Me_3	Cyclohexyl	17:1	87
2	*t*-BuMe$_2$	Cyclohexyl	20:1	73
3	Me_3	Phenyl	1:8	88
4	*t*-BuMe$_2$	Phenyl	1:1	60
5	*t*-BuMe$_2$	Pentyl	>50:1	70

a) All reactions were performed as described in the text. b) Olefin ratio was determined by GLC. c) Values reported are isolated yields.

TABLE 5. SYNTHESIS OF α, β-UNSATURATED NITRILES

Entry	Aldehyde[a]	Reagent	Metal	Condition[b]	Yield[c]/%	*Z*/*E*[d]
1	*c*-$C_6H_{11}CHO$	Me_3SiCH_2CN	Li	A	82	7:1
2			Ti	A	94	11:1
3			B	A	90	12:1
4			B	B	90	16:1
5			B	C	78	23:1
6		Ph_3SiCH_2CN	Mg	D	80	9:1[1h]
7			B	B	90	11:1
8		*t*-$BuMe_2SiCH_2CN$	Mg	D	76	6:1[1h]
9			B	B	85	15:1
10	$C_5H_{11}CHO$	Me_3SiCH_2CN	B	A[e]	72	7:1
11			B	B	68	9:1
12			B	C	52	13:1
13		Ph_3SiCH_2CN	Mg	D	63	5:1[1h]
14			B	B	72	7:1
15	C_5H_9CHO	Me_3SiCH_2CN	Li	B	46	5:1
16			B	B	81	8:1
17			B	C	66	6:1
18		Ph_3SiCH_2CN	Li	A[f]	60	2:1
19			B	B	84	6:1
20		*t*-$BuMe_2SiCH_2CN$	B	B	84	8:1
21	C_6H_5CHO	Me_3SiCH_2CN	Li	A[e]	86	3:1
22			B	A[e]	90	3:1
23			B	C	71	2:1

a) *c*-$C_6H_{11}CHO$: Cyclohexanecarbaldehyde; $C_5H_{11}CHO$: Hexanal; C_5H_9CHO: 2-Hexenal; C_6H_5CHO: Benzaldehyde. b) A: −78 °C, 1 h; 25 °C, 30 min; B: −78 °C, 1 h; C: −78 °C, 30 min; HMPA was added after the addidion of the aldehyde to the anions. D: −78 °C, 5 min; 50 °C, 1 h. c) Values reported are for isolated product. d) *Z*/*E* ratio was determined by GLC. e) 25 °C, 1 h. f) 25 °C, 2 h.

state T_1.

Next we called our attention to the nitrile anion which has analogous structure to the propargyl anion except that it has no substituents at a terminal nitrogen atom. Thus we investigated the reaction of α-silyl-substituted acetonitrile anion which condensed with aldehyde to give α,β-unsaturated nitriles through addition-elimination sequences.[19] Judging from the similarity of the reaction system to the α-silylated propyne, a (*Z*)-olefin may result from this reaction. The α,β-unsaturated nitrile is a useful synthetic intermediate since it is easily converted to the synthetically useful α,β-unsaturated carbonyl compound.[20]

The metallated derivatives of (trialkylsilyl)acetonitrile[21] was condensed with various aldehydes and the results were summarized in Table 5.

Surprisingly, the reaction of simple lithio reagent with aldehyde produced the *Z*-isomer with moderate stereoselectivity (entry 1).[22] The titanium reagents showed a little improvements, but the boron reagents are much superior.[23] In contrast to the previous observations of propargyl anions, the stereochemical course of the reaction showed little dependence on the steric screening effect of the silyl group, but the effects of the reaction temperature and the solvent were crucial. Thus the longer reaction period at room temperature tends to decrease the stereoselectivity of the reaction (entries 3 and 4). Since the presence of excess base (LDA) also decreases the selectivity, secondary isomerization of the produced olefin may be caused by the base particularly at higher temperature.[24] Consequently the quenching of the reaction at low temperature is essential to accomplish the selective reaction.[25]

It should be notable that the addition of HMPA to the reaction mixture remarkably raised the proportion of *Z*-isomer (entry 5). The role of HMPA is not clear, but the rate of the desilylation is clearly accelerated by the addition of HMPA. The lack of the selectivity in the condensation with benzaldehyde was observed as previously, which may be due to the intervention of a competing electron-transfer pathway, or an acyclic transition state.[13]

The regioisomer, ketenimine, which corresponded to the allenyl alcohol for the reaction of propargylic anion, was not detected in a series of this reaction.[26] Since the transition state for this reaction could be regarded as similar to that of propargyl anion, the *Z*-selectivity could be readily understandable. For nitrile anion, however, the site of metallation could be recognized as occurred predominantly at nitrogen atom for all metals studied.[27] This is presumably due to the steric requirement along with the strong affinity of metal-nitrogen bond.

Experimental

General. ^{1}H NMR spectra were taken on a JNM-PMX 60 spectrometer. The chemical shifts are reported in parts per million relative to TMS. The infrared spectra were recorded on a Hitachi 260-10 spectrometer in CCl_4 solution unless otherwise stated. The isomeric ratio of the products was determined by gas-liquid chromatography (GLC) using a Hitachi Model 163 and 164 instruments equipped with a flame ionization detector using nitrogen as carrier gas. For TLC analysis throughout this work, Merck precoated TLC plates (silica gel 60 GF_{254}, 0.25 mm, or silica gel 60 HF_{254} silanized, 0.25 mm) were used. The products were purified by preparative column chromatography on silica gel E. Merck Art. 9385, or silanized silica gel E. Merck Art. 7719. Microanalyses were accomplished at the Institute of Applied Organic Chemistry, Faculty of Engineering, Nagoya University. Unless otherwise specified, all reactions were carried out under an atmosphere of dry argon. In experiments requiring dry solvents, ether and tetrahydrofuran (THF) were distilled from sodium-benzophenone. Benzene, hexane, and toluene were dried over sodium metal. Dichloromethane was dried over 4A Molecular Sieve. Pyridine and triethylamine were stored over potassium hydroxide pellets. Hexamethylphosphoric triamide (HMPA) was used after distillation from CaH_2. Other commercially supplied materials were used as received.

Preparation of 1-(Trimethylsilyl)propyne.[16] To a solution of propyne (20 g, 0.50 mol) in ether (600 ml) was added butyllithium in hexane (1.6 mol dm^{-3} solution, 312 ml, 0.50 mol) at −78 °C under argon. After stirring for 1 h at the same temperature, chlorotrimethylsilane (63 ml, 0.50 mol) was added to this solution. The resulting mixture was stirred at 25 °C for 12 h and then poured into 2 mol dm^{-3} hydrochloric acid. The organic layer was separated and the aqueous layer was extracted with ether. The combined extracts were dried and evaporated. The residue was distilled under atmospheric pressure to give 1-(trimethylsilyl)propyne (34 g, 60%). Bp 94—98 °C; ^{1}H NMR (CCl_4) δ=0.15 (s, 9H), 1.93 (s, 3H).

Preparation of 1-Trimethylsilyl-1-butyne.[28] To a solution of 1-butyne (15 g, 0.28 mol) in ether (500 ml) was added butyllithium in hexane (1.6 mol dm^{-3} solution, 160 ml, 0.26 mol) at −78 °C under argon. After stirring for 1 h at the same temperature, chlorotrimethylsilane (33 ml, 0.26 mol) was added to the reaction mixture. The mixture was stirred at 25 °C for 12 h and then poured into 2 mol dm^{-3} hydrochloric acid. The organic layer was separated and the aqueous layer was extracted with ether. The combined extracts were dried and evaporated. The residue was distilled under atmospheric pressure to give 1-trimethylsilyl-1-butyne (23 g, 70%). Bp 115—116 °C; ^{1}H NMR (CCl_4) δ=0.13 (s, 9H), 1.16 (t, *J*=7 Hz, 3H), 2.21 (q, *J*=7 Hz, 2H).

Preparation of 3-(Tetrahydro-2-pyranyloxy)-1-trimethylsilyl propyne. To a solution of 2-propyn-1-ol (11 g, 0.20 mol) and 3,4-dihydro-2*H*-pyran (22 ml, 0.24 mol) in ether (300 ml) was added *p*-toluenesulfonic acid monohydrate (4 g, 21 mmol) at 0 °C. The mixture was stirred for 0.5 h at 0 °C and 1 h at 25 °C. Then, the reaction mixture was poured into water and the product was extracted with ether. The ether layer was washed with brine, dried over sodium sulfate, and evaporated. Chromatography of the residual crude oil on a silica-gel column (2:1, hexane–ether) afforded 3-(tetrahydro-2-pyranyloxy)propyne (24 g, 86%). ^{1}H NMR (CCl_4) δ=1.3—2.0 (m, 6H), 2.40 (t, *J*=2.5 Hz, 1H), 3.3—4.0 (m, 2H), 4.23 (d, *J*=2.5 Hz, 2H), 4.80 (m, 1H); IR (neat) 3300 cm^{-1}.

To a solution of 3-(tetrahydro-2-pyranyloxy)propyne (5.6 g, 40 mmol) in ether (100 ml) was added butyllithium in hexane (1.6 mol dm^{-3} solution, 25 ml, 40 mmol) at −78 °C. After stirring for 1 h at −78 °C, chlorotrimethylsilane (5.0 ml, 40 mmol) was added to this mixture. The resulting mixture was stirred at 25 °C for 12 h and then poured into 2 mol dm^{-3} hydrochloric acid and extracted with ether. The combined extracts were dried and evaporated. Chromatography of the crude product on a silica-gel column (15:1 hexane–ether) afforded 3-(tetrahydro-2-pyranyloxy)-1-(trimethylsilyl)propyne (6.9 g, 81%). ^{1}H NMR (CCl_4) δ=0.13 (s, 9H), 1.1—2.0 (m, 6H), 3.4—3.9 (m, 2H), 4.03 (s, 2H), 4.63 (t, *J*=2 Hz, 1H); IR (neat) 2190 cm^{-1}. Found: C, 62.38; H, 9.22%. Calcd for $C_{11}H_{20}O_2Si$: C, 62.21; H, 9.49%.

Preparation of 1-(Tetrahydro-2-pyranyloxy)-2-butyne.[29] To a solution of 2-butyn-1-ol (5 ml, 66 mmol) and 3,4-dihydro-2*H*-pyran (9.0 ml, 99 mmol) in ether (130 ml) was added *p*-toluenesulfonic acid monohydrate (1.9 g, 10 mmol) at 0 °C. After stirring for 0.5 h at 0 °C and then 1 h at 25 °C, the reaction mixture was poured into water and extracted with ether. The ether layer was washed with brine, dried, and evaporated. Chromatography of the residual oil on a silica-gel column (10:1 hexane–ether) afforded 1-(tetrahydro-2-pyranyloxy)-2-butyne (10 g, 98%). R_f=0.7 (10:1 hexane–ether); ^{1}H NMR (CCl_4) δ=1.3—1.9 (m, 6H), 1.75 (t, J=2.5 Hz, 3H), 3.2—3.8 (m, 2H), 4.0 (q, J=2.5 Hz, 2H), 4.65 (m, 1H); IR (neat) 2250 cm^{-1}.

Preparation of 1-(1-Methoxy-1-methylethoxy)-2-butyne. To a solution of 2-butyn-1-ol (2.0 ml, 26 mmol) and 2-methoxypropene (3.6 g, 50 mmol) in dichloromethane (30 ml) was added *p*-toluenesulfonic acid monohydrate (0.75 g, 3.9 mmol) at 0 °C. The resulting mixture was stirred at 0 °C for 20 min and treated with triethylamine (1.4 ml, 10 mmol) at 0 °C. The mixture was poured into water and the product was extracted with ether. The organic layer was dried and concentrated. Chromatography of the resulting oil on a silica-gel column (4:1 hexane–ether) afforded 1-(1-methoxy-1-methylethoxy)-2-butyne (2.77 g, 75%). R_f=0.8 (4:1 hexane–ether); ^{1}H NMR (CCl_4) δ=1.33 (s, 6H), 1.83 (t, J=2.5 Hz, 3H), 3.20 (s, 3H), 4.05 (q, J=2.5 Hz, 2H); IR (neat) 2250 cm^{-1}.

Preparation of 1-(Tetrahydro-2-furyloxy)-2-butyne. To a solution of 2-butyn-1-ol (2.0 ml, 26 mmol) and 2,3-dihydrofuran (2.8 g, 40 mmol) in ether (30 ml) was added *p*-toluenesulfonic acid monohydrate (0.75 g, 3.9 mmol) at 0 °C. After stirring for 0.5 h at 0 °C and 1 h at 25 °C, the mixture was poured into water and the product was extracted with ether. The organic layer was dried and concentrated. Chromatography of the crude product on a silica-gel column (10:1 hexane–ether) afforded 1-(tetrahydro-2-furyloxy)-2-butyne (2.8 g, 77%). ^{1}H NMR (CCl_4) δ=1.83 (m, 7H), 3.7—4.0 (m, 2H), 4.15 (m, 2H), 5.27 (m, 1H); IR (neat) 2230 cm^{-1}.

Metallation of Acetylenic Compounds. To a solution of acetylenic compounds (2.0 mmol) dissolved in dry THF (5 ml) was added *t*-butyllithium in pentane (1.8 mol dm^{-3} solution, 1.11 ml, 2.0 mmol) at −78 °C with stirring, and the resulted slightly yellow solution was stirred at 0 °C for 1 h leading to complete lithiation. Corresponding titanium derivatives were prepared by adding titanium tetraisopropoxide (0.60 ml, 2.0 mmol) to a solution of the lithio salt obtained as above at −78 °C. The boron derivatives were similarly prepared with use of one equivalent of boron triisopropoxide. Magnesium, zinc, and tin(II) derivatives were generated by adding one equivalent of magnesium iodide,[30] zinc bromide, or tin(II) chloride, respectively. For the preparation of aluminium reagents, two equivalents of diethylaluminium chloride (hexane solution) were used.

IR Analysis of Metallated Alkyne Derivatives. The lithio derivative of a 1-(trimethylsilyl)propyne solution in THF obtained as above was transferred into IR cell under nitrogen, and the spectrum was measured. IR 1880 cm^{-1} (m, allenic), 2020 cm^{-1} (m, acetylenic). The IR spectra of the other metallated reagents: Titanated 1-(trimethylsilyl)propyne: 2092 cm^{-1}. Titanated 1-trimethylsilyl-1-butyne: 1898 cm^{-1}.

*Reaction of **2b** with Cyclohexanecarbaldehyde.* To a cooled solution (−78 °C) of **2b** (2.0 mmol) in THF was added freshly distilled cyclohexanecarbaldehyde (0.22 ml, 1.8 mmol) over a period of 5 min at −78 °C, and the mixture was stirred at −78 °C for 1 h. The resulting mixture was poured into ice-cooled 1 mol dm^{-3} hydrochloric acid, and the product was extracted with ether repeatedly. The combined ethereal layer was dried and concentrated *in vacuo*. The crude product was purified by silica-gel column chromatography (1:2 ether-heaxne) to give 1-cyclohexyl-3-pentyn-1-ol and 1-cyclohexyl-2-methyl-2,3-butadien-1-ol (269 mg, 90% total yield). GLC analysis of the product revealed the ratio of 1:99.

1-Cyclohexyl-3-pentyn-1-ol: R_f=0.35 (2:1 hexane–ether); ^{1}H NMR (CCl_4) δ=0.7—2.0 (m, 11H), 1.78 (t, J=2.4 Hz, 3H), 2.25 (m, 2H), 3.30 (m, 1H), 4.62 (br s, 1H); IR 2275 cm^{-1}.

1-Cyclohexyl-2-methyl-2,3-butadien-1-ol: R_f=0.43 (2:1 ether–hexane); ^{1}H NMR (CCl_4) δ=0.72—2.22 (m, 11H), 1.62 (t, J=3 Hz, 3H), 2.02 (s, 1H), 3.67 (br d, 1H), 4,63 (m, 2H); IR 1970 cm^{-1}. Found: C, 79.31; H, 10.73%. Calcd for $C_{11}H_{18}O$: C, 79.46; H, 10.91%.

1-Cyclohexyl-4-trimethylsilyl-3-butyn-1-ol:[1g] ^{1}H NMR (CCl_4) δ=0.14 (s. 9H), 0.92—2.0 (m, 12H), 2.32 (d, J=5.4 Hz, 2H), 3.37 (br s, 1H); IR 2180 cm^{-1}.

1-Cyclohexyl-2-trimethylsilyl-2,3-butadien-1-ol:[1g] ^{1}H NMR (CCl_4) δ=0.12 (s, 9H), 0.86—2.03 (m, 12H), 3.81 (br s, 1H), 4.38 (d, J=2 Hz, 2H); IR 1930 cm^{-1}. Found: C, 69.49; H, 10.60%; Calcd for $C_{13}H_{24}OSi$: C, 69.58; H, 10.78%.

1-Phenyl-4-trimethylsilyl-3-butyn-1-ol:[1f,g] ^{1}H NMR (CCl_4) δ=0.08 (s, 9H), 2.47 (d, J=6.2 Hz, 2H), 3.23 (br d, J=3 Hz, 1H), 4.60 (dt, J=3 and 6.2 Hz, 1H), 7.17 (s, 5H); IR 2180 cm^{-1}.

1-Phenyl-2-trimethylsilyl-2,3-butadien-1-ol:[1f,g] ^{1}H NMR (CCl_4) δ=0.02 (s, 9H), 3.33 (br s, 1H), 4.45 (d, J=3 Hz, 2H), 5.17 (t, J=3 Hz, 1H), 7.19 (s, 5H); IR 1930 cm^{-1}; MS m/z: 218 (M^+).

1-Phenyl-3-pentyn-1-ol:[1f] ^{1}H NMR (CCl_4) δ=1.70(t, J=2.5 Hz, 3H), 2.42 (dq, J=2.5 and 6 Hz, 2H), 2.77 (br s, 1H), 4.60 (t, J=6 Hz, 1H), 7.18 (s, 5H).

2-Methyl-1-phenyl-2,3-butadien-1-ol:[1f,31] ^{1}H NMR (CCl_4) δ= 1.47 (t, J=3 Hz, 3H), 3.04 (br s, 1H), 4.68 (m, 2H), 4.98 (br s, 1H), 7.16 (s, 5H); IR 1960 cm^{-1}; MS m/z: 160 (M^+).

1,4-Diphenyl-2-methyl-3-butyn-1-ol (Mixture of erythro *and* threo *Isomers)*: ^{1}H NMR (CCl_4) δ=1.06 and 1.14 (2d, J=7 Hz each, 3H), 2.85 (quintet, J=7 Hz, 1H), 3.08 (br s, 1H), 4.45 (m, 1H), 7.17 (m, 10H); IR 2250 cm^{-1}. Found: C, 86.16; H, 7.07%; Calcd for $C_{17}H_{16}O$: C, 86.41; H, 6.82%.

erythro-*1-Cyclohexyl-2-methyl-4-trimethylsilyl-3-butyn-1-ol*:[32] ^{1}H NMR (CCl_4) δ=0.13 (s, 9H), 0.78—2.03 (m, 12H), 1.13 (d, J=6.5 Hz, 3H), 2.52 (quintet, J=6.5 Hz, 1H), 3.20 (t, J=5 Hz, 1H); IR 2170 cm^{-1}.

threo-*1-Cyclohexyl-2-methyl-4-trimethylsilyl-3-butyn-1-ol*:[32] ^{1}H NMR (CCl_4) δ=0.15 (s, 9H), 0.87—2.08 (m, 12H), 1.18 (d, J= 7 Hz, 3H), 2.60 (dq, J=2 and 7 Hz, 1H), 2.95 (m, 1H); IR 2160 cm^{-1}. Found: C, 70.70; H, 10.81%; Calcd for $C_{14}H_{26}OSi$: C, 70.52; H, 10.99%.

erythro-*2-Methyl-1-phenyl-4-trimethylsilyl-3-butyn-1-ol*:[33] ^{1}H NMR (CCl_4) δ=0.07 (s, 9H), 1.07 (d, J=7 Hz, 3H), 2.28 (br s, 1H), 2.67 (quintet, J=7 Hz, 1H), 4.51 (d, J=6.2 Hz, 1H), 7.21 (s, 5H); IR 2180 cm^{-1}.

threo-*2-Methyl-1-phenyl-4-trimethylsilyl-3-butyn-1-ol*):[33] ^{1}H NMR (CCl_4) δ=0.14 (s, 9H), 1.05 (d, J=7 Hz, 3H), 2.35 (br s, 1H), 2.68 (quintet, J=7 Hz, 1H), 4.38 (d, J=7 Hz, 1H), 7.23 (s, 5H); IR 2180 cm^{-1}. Found: C, 72.48; H, 8.95%. Calcd for $C_{14}H_{20}OSi$: C, 72.36; H, 8.67%.

threo-*1-Cyclohexyl-2-methyl-3-hexyn-1-ol*:[32] ^{1}H NMR (CCl_4) δ=0.57—2.20 (m, 13H), 1.10 (t, J=7 Hz, 3H), 1.13 (d, J=6.8 Hz, 3H), 2.57 (m, 1H), 2.92 (m, 1H), 3.22 (br s, 1H).

erythro-*1-Cyclohexyl-2-methyl-3-hexyn-1-ol*:[32] ^{1}H NMR (CCl_4) δ=0.87—2.37 (m, 14H), 1.11 (d, J=7 Hz, 3H), 1.13 (t, J=7.5 Hz, 3H), 2.49 (m, 1H), 3.17 (m, 1H).

erythro-*1-Cyclohexyl-2-methyl-4-phenyl-3-butyn-1-ol*:[32] ^{1}H NMR (CCl_4) δ=0.69—2.35 (m, 12H), 1.24 (d, J=6.4 Hz, 3H), 2.74 (quintet, J=6.4 Hz, 1H), 3.32 (t, J=6.4 Hz, 1H), 7.22 (br s, 5H); IR 2250 cm^{-1}.

threo-*1-Cyclohexyl-2-methyl-4-phenyl-3-butyn-1-ol*:[32] ^{1}H NMR (CCl_4) δ=0.67—2.34 (m, 12H), 1.27 (d, J=6.8 Hz, 3H), 2.80 (dq, J=4 and 6.8 Hz, 1H), 3.03 (br s, 1H), 7.20 (m, 5H); IR 2240 cm^{-1}. Found: C, 84.16; H, 9.23%. Calcd for $C_{17}H_{22}O$: C, 84.25; H, 9.15%.

Reaction of Metallated Alkoxyalkyne Reagents with Aldehydes. The following procedure is representative for these type

of reagents (entries 8—17 in Table 3). *t*-Butyllithium in pentane (1.8 mol dm^{-3} solution, 0.83 ml, 1.5 mmol) was added dropwise to a solution of 1-(tetrahydro-2-pyranyloxy)-2-butyne (231 mg, 1.5 mmol) in dry THF (4 ml) with stirring under argon at −78 °C. After 40 min at −78 °C, titanium tetraisopropoxide (0.45 ml, 1.5 mmol) was added dropwise to the resulting orange solution of the anion, and the slightly darkened solution was stirred there for 10 min. Freshly distilled hexanal (0.155 ml, 1.3 mmol) was added over a period of 5 min at −78 °C, and the mixture was stirred at −78 °C for 30 min and then at 20 °C for 30 min. The reaction mixture was poured into ice-cooled 1 mol dm^{-3} hydrochloric acid, and the product was extracted with ether repeatedly. The combined ethereal layer was concentrated *in vacuo* to give a crude hydroxy ether, which was dissolved in dry methanol (5 ml) at 0 °C. *p*-Toluenesulfonic acid monohydrate (5 mg) was added, and the mixture was stirred at 20 °C for 30 min. After the consumption of all tetrahydropyranyl ether by TLC assay, the reaction was terminated by the addition of excess sodium hydrogencarbonate (10 mg). The suspension was concentrated *in vacuo*, and the slurry was directly subjected to column chromatography on silica gel (2:1 ether–hexane) to afford 2-decyne-4,5-diol (168 mg, 76%). The diol was acetylated by Ac_2O–pyridine, and the GLC analysis of the diacetate revealed the isomeric ratio of 95:5 (*erythro*:*threo*).[34]

2-Decyn-4,5-diol: ^{1}H NMR (CCl_4) δ=0.5—1.67 (m, 11H), 1.87 (d, *J*=3 Hz, 3H), 2.97 (br s, 2H), 3.63 (m, 1H), 4.28 (dq, *J*=3 and 3 Hz, 1H); IR 3400, 2260 cm^{-1}. Found: C, 70.32; H, 10.68%. Calcd for $C_{10}H_{18}O_2$: C, 70.55; H, 10.65%.

1-Cyclohexyl-4-trimethylsilyl-3-butyn-1,2-diol:[35] ^{1}H NMR (CCl_4) δ=0.16 (s, 9H), 0.75—2.17 (m, 11H), 2.78 (br s, 2H), 3.17 (dd, *J*=4 and 6 Hz, 1H), 4.22 (d, *J*=4 Hz, 1H); IR 3400, 2200 cm^{-1}.

1-Trimethylsilyl-1-nonyn-3,4-diol:[35] ^{1}H NMR (CCl_4) δ=0.16 (s, 9H), 0.66—1.58 (m, 11H), 2.14 (br m, 1H), 2.69 (m, 1H), 3.48 (m, 1H), 4.13 (m, 1H); IR 3400, 2230cm^{-1}.

1-Cyclohexyl-3-pentyn-1,2-diol: ^{1}H NMR (CCl_4) δ=0.67—2.33 (m, 11H), 1.88 (d, *J*=2 Hz, 3H), 2.83 (br s, 2H), 3.32 (dd, *J*=3 and 7 Hz, 1H), 4.41 (dq, *J*=3 and 4 Hz, 1H); IR (neat) 3400, 2280 cm^{-1}. Found: C, 72.34; H, 10.10%. Calcd for $C_{11}H_{18}O_2$: C, 72.49; H, 9.95%.

Preparation of 1,3-Bis(trimethylsilyl)propyne.[16] To a solution of 1-(trimethylsilyl)propyne (13.5 g, 120 mmol) in ether (200 ml) were added *N,N,N′,N′*-tetramethylethylenediamine (21.1 ml, 140 mmol) and butyllithium in hexane (1.6 mol dm^{-3} solution, 87.5 ml, 140 mmol) at −5 °C under argon. After stirring for 30 min, chlorotrimethylsilane (17 ml, 134 mmol) was added and the mixture was stirred at 25 °C for 12 h. The resulting mixture was poured into ice-cooled water and the product was extracted with ether. The combined extracts were dried and evaporated. The residue was distilled under reduced pressure to give 1,3-bis(trimethylsilyl)propyne (16.6 g 75%). Bp 75—76 °C (34 mmHg†): ^{1}H NMR ($CDCl_3$) δ=0.17 and 0.24 (2s, 9H each), 1.61 (s, 2H).[16]

Preparation of 3-(t-Butyldimethylsilyl)-1-(trimethylsilyl)propyne. To a solution of 1-(trimethylsilyl)propyne (22.4 g, 200 mmol) in ether (300 ml) was added *t*-butyllithium[36] in pentane (1.8 mol dm^{-3} solution, 111 ml, 200 mmol) at −5 °C. After stirring for 30 min, *t*-butyldimethylsilyl chloride (30.1 g, 200 mmol) was added and the mixture was stirred for 12 h. The resulting mixture was poured into ice-cooled water and the product was extracted with ether. The combined extracts were dried and concentrated. The residue was distilled under reduced pressure to give 3-(*t*-butyldimethylsilyl)-1-(trimethylsilyl)propyne (24.4 g, 54%). Bp 106—107 °C (31 mmHg); ^{1}H NMR ($CDCl_3$) δ=0.14 and 0.19 (2s, 15H), 0.98 (s, 9H), 1.63 (s, 2H); MS *m/z*: 226 (M^+).

† 1 mmHg≈133.322 Pa.

Reaction of Metallated 1,3-Bis(trialkylsilyl)propyne with Aldehydes.[37] The following experimental procedure is representative. To a solution of 1,3-bis(trimethylsilyl)propyne (368 mg, 2.0 mmol), in THF (4 ml) was added *t*-butyllithium in pentane (1.8 mol dm^{-3} solution, 1.1 ml, 2.0 mmol) at −78 °C. After 1 h at −78 °C, titanium tetraisopropoxide (0.60 ml, 2.0 mmol) was added to the mixture and the solution was stirred for 10 min at −78 °C. Cyclohexanecarbaldehyde (0.22 ml, 1.8 mmol) was added to the solution and the resulting mixture was stirred at −78 °C for 30 min and then at 25 °C for 1 h. The reaction mixture was poured into 1 mol dm^{-3} hydrochloric acid, and the product was extracted with ether repeatedly. The combined ethereal layer was concentrated *in vacuo* to give a crude oil, which was subjected to column chromatography on silica gel (hexane) to afford 4-cyclohexyl-1-trimethylsilyl-3-buten-1-yne (323 mg, 87%). GLC analysis of the product revealed the isomeric ratio of 17:1 (*Z*:*E*).[38]

(Z)-4-Cyclohexyl-1-trimethylsilyl-3-buten-1-yne:[37] ^{1}H NMR (CCl_4) δ=0.17 (s, 9H), 0.77—1.95 (m, 10H), 2.57 (br m, 1H), 5.27 (d, *J*=11 Hz, 1H), 5.72 (dd, *J*=8.5 and 11 Hz, 1H); IR 2150, 1450, 1255, 1015, 700 cm^{-1}.

(E)-4-Cyclohexyl-1-trimethylsilyl-3-buten-1-yne:[37] ^{1}H NMR (CCl_4) δ=0.13 (s, 9H), 5.28 (d, *J*=16 Hz, 1H), 6.02 (dd, *J*=7 and 16 Hz, 1H), 0.65—2.0 (m, 11H); IR 2150, 1450, 1250, 960 cm^{-1}.

(Z)-1-Trimethylsilyl-3-nonen-1 yne:[39] ^{1}H NMR (CCl_4) δ=0.17 (s, 9H), 0.8—1.5 (m, 9H), 2.27 (m, 2H), 5.33 (d, *J*=11 Hz, 1H), 5.80 (dt, *J*=7 and 11 Hz, 1H); IR 2150, 1250, 1050, 700 cm^{-1}.

(E)-1-Trimethylsilyl-3-nonen-1-yne:[39] ^{1}H NMR(CCl_4) δ=0.13 (s, 9H), 0.76—1.58 (m, 9H), 2.10 (m, 2H), 5.32 (d, *J*=16 Hz, 1H), 6.08 (dt, *J*=7 and 16 Hz, 1H); IR 2150, 1260, 1095, 960 cm^{-1}.

(Z)-4-Phenyl-1-trimethylsilyl-3-buten-1-yne:[37] ^{1}H NMR(CCl_4) δ=0.22 (s, 9H), 5.56 (d, *J*=11 Hz, 1H), 6.53 (d, *J*=11 Hz, 1H), 7.18 (m, 3H), 7.72 (m, 2H).

(E)-4-Phenyl-1-trimethylsilyl-3-buten-1-yne:[37] ^{1}H NMR (CCl_4) δ=0.20 (s, 9H), 6.05 (d, *J*=16 Hz, 1H), 6.93 (d, *J*=16 Hz, 1H), 7.27 (s, 5H).

Preparation of (Trimethylsilyl)acetonitrile.[19b] To a mixture of chlorotrimethylsilane (36 g, 0.33 mol) and activated granular zinc (38 g, 0.58 mol), in THF–benzene (1:1, 400 ml) was added a solution of chloroacetonitrile (22 g, 0.29 mol) in benzene (20 ml). The resulting mixture was heated under reflux for 30 h and then poured into a buffer solution (AcONa–AcOH, 300 ml). The organic layer was separated and the aqueous layer was extracted with benzene. The combined extracts were dried and concentrated. The residue was distilled under reduced pressure to give (trimethylsilyl)acetonitrile (13.5 g, 41%). Bp 65 °C (20 mmHg); ^{1}H NMR (CCl_4) δ=0.23 (s, 9H), 1.53 (s, 2H); IR (neat) 2215 cm^{-1}. This compound was also prepared from bromoacetonitrile in the similar manner.[19b]

Preparation of (Triphenylsilyl)acetonitrile. To a solution of acetonitrile (4.1 g, 0.10 mol) in THF (200 ml) was added butyllithium in hexane (1.6 mol dm^{-3}, 62.5 ml, 0.10 mol) at −78 °C. After stirring for 20 min, chlorotriphenylsilane (29.5 g, 0.10 mol) in THF (50 ml) was added at −78 °C and the mixture was stirred at −78 °C for 30 min and then 25 °C for 5 h. The resulting mixture was poured into water and the product was extracted with ether. The combined extracts were dried and concentrated to give a crude product. Recrystallization from acetone–methanol gave colourless crystals of (triphenylsilyl)acetonitrile (16.7 g, 56%). Mp 135.5—136 °C (acetone); ^{1}H NMR ($CDCl_3$) δ=2.30 (s, 2H), 7.45 (br s, 15H); IR 2250 cm ; MS *m/z*: 299 (M^+).

Preparation of (t-Butyldimethylsilyl)acetonitrile. To a solution of acetonitrile (4.1 g, 0.10 mol) in THF (200 ml) was added butyllithium in hexane (1.6 mol dm^{-3}, 62.5 ml, 0.10 mol) at −78 °C. After stirring for 20 min, *t*-butyldimethylsilyl chloride (15.1 g, 0.10 mol) in THF (50 ml) was

added at −78 °C and the mixture was stirred at −78 °C for 30 min and 25 °C for 5 h. The resulting mixture was poured into water and the product was extracted with ether. The combined extracts were dried and concentrated. The residue was distilled under reduced pressure to give (*t*-butyldimethylsilyl) acetonitrile (7.75 g, 50%). Bp 102 °C (30 mmHg); ^{1}H NMR ($CDCl_3$) δ=0.19 (s, 6H), 0.95 (s, 9H), 1.54 (s, 2H); IR 2250 cm^{-1}; Mp 71—72 °C; MS *m/z*: 155 (M^+).

Reaction of Metallated (Trialkylsilyl)acetonitrile with Aldehydes.[19b] The following experimental procedure provides details of the typical preparation of (*Z*)-unsaturated nitriles: To a solution of (trimethylsilyl)acetonitrile (113 mg, 1.0 mmol) in THF (2 ml) was added dropwise butyllithium in hexane (1.6 mol dm^{-3} solution, 0.63 ml, 1.0 mmol) at −78 °C. After 10 min, boron triisopropoxide (0.231 ml, 1.0 mmol) was added at −78 °C and the solution was stirred there for an additional 10 min. Cyclohexanecarbaldehyde (0.121 ml, 1.0 mmol) in THF (0.5 ml) was added slowly and after 2 min, dry HMPA (0.4 ml) was added to the reaction mixture and stirring was continued for 1 h. Addition of water to the mixture at −78 °C, then the product was extracted with ether. The combined organic layer was dried and concentrated. Chromatography of the crude product on silica-gel column (1:6 ether-hexane) gave 3-cyclohexylacrylonitrile (105 mg, 78%). GLC analysis of the product revealed 23:1 (*Z*)-isomer.[38]

(Z)-3-Cyclohexylacrylonitrile (Contains ca. 4% of the (E)-Isomer):[19c] R_f=0.46 (1:6 ether-hexane); ^{1}H NMR (CCl_4) δ= 0.72—3.0 (m, 11H), 5.15 (d, *J*=11 Hz, 1H), 6.23 (dd, *J*=10 and 11 Hz, 1H); IR 2910, 2840, 2210, 1625, 740 cm^{-1}. Found: C, 80.08; H, 9.73; N, 10.18%. Calcd for $C_9H_{13}N$: C, 79.95; H, 9.69; N, 10.36%.

(Z)-2-Octenenitrile (Contains ca. 7% of the (E)-Isomer):[19c] R_f=0.44 (1:5 ether-hexane); ^{1}H NMR (CCl_4) δ=0.63—2.0 (m, 9H), 2.0—2.67 (m, 2H), 5.22 (d, *J*=11 Hz, 1H), 6.37 (dt, *J*=7 and 11 Hz, 1H); IR 2960, 2940, 2860, 2230, 1630, 740 cm^{-1}; Found: C, 78.17; H, 10.56; N, 10.92%. Calcd for $C_8H_{13}N$: C, 78.00; H, 10.63; N, 11.37%.

(2Z,4E)-2,4-Octadienenitrile (Contains ca. 11% of the (E,E)-Isomer):[40] R_f=0.35 (1:5 ether-hexane); ^{1}H NMR (CCl_4) δ=0.94 (t, *J*=7 Hz, 3H), 1.17—1.83 (m, 2H), 1.92—2.5 (m, 2H), 5.00 (d, *J*=10 Hz, (*Z*)-isomer), 5.20 (d, *J*=15 Hz, (*E*)-isomer), 5.83—7.0 (m, 3H); IR 2975, 2940, 2875, 2225, 1645, 740 cm^{-1}.

(Z)-3-Phenylacrylonitrile (Contains ca. 25% of the (E)-Isomer):[19b,c] R_f=0.31 (1:5 ether-hexane); ^{1}H NMR (CCl_4) δ= 5.33 (d, *J*=12 Hz, (*Z*)-isomer), 5.76 (d, *J*=17 Hz, (*E*)-isomer), 7.00 (d, *J*=12 Hz, 1H), 7.33 and 7.72 (m, 5H); IR 3050, 3030, 2220, 1615, 970, 775, 750, 685 cm^{-1}.

We thank the Asahi Glass Foundation for financial support of this work.

References

1) Recent reviews: a) "The Chemistry of the Carbon–Carbon Triple Bond," ed by S, Patai, Wiley, New York (1978); b) "The Chemistry of Ketenes, Allenes, and Related Compounds," ed by S. Patai, Wiley, New York (1980); c) L. Brandsma and H. D. Verkruijsse, "Synthesis of Acetylenes, Allenes and Cumulenes," Elsevier, Amsterdam (1981); d) "The Chemistry of the Allenes," ed by S. R. Landor, Academic Press, London (1982), Vol. 1—3; Recent efforts: e) G. Eyring, B. Curry, A. Brock, and J. Lugtenburg, *J. Am. Chem. Soc.*, **102**, 5392 (1980); f) T. Mukaiyama and T. Harada, *Chem. Lett.*, **1981**, 621; g) R. G. Daniels and L. A. Paquette, *Tetrahedron Lett.*, **22**, 1579 (1981); h) Y. Yamakado, M. Ishiguro, N. Ikeda, and H. Yamamoto, *J. Am. Chem. Soc.*, **103**, 5568 (1981); i) E. J. Corey and C. Rücken, *Tetrahedron Lett.*, **23**, 719 (1982); j) N. R. Pearson, G. Hahn, G. Zweifel, *J. Org. Chem.*, **47**, 3364 (1982); k) R. Haruta, M. Ishiguro, N. Ikeda, and H. Yamamoto, *J. Am. Chem. Soc.*, **104**, 7667 (1982).

2) For example, see pp. 343—379 of Ref. 1a.

3) For a definition of "*erythro-threo*," see R. Noyori, I. Nishida, and J. Sakata, *J. Am. Chem. Soc.*, **103**, 2106 (1981).

4) For recent reviews: J.-F. Biellmann, *Org. React.*, **27**, 1 (1982); Y. Yamamoto, Y. Naruta, "Yuki Kinzoku Kagaku," Maruzen, Tokyo (1983); R. W. Hoffmann, *Angew. Chem., Int. Ed. Engl.*, **21**, 555 (1982).

5) S. A. Shevelev, *Russ. Chem. Rev. (Engl. Transl.)*, **39**, 844 (1970); L. M. Jackman and B. C. Lange, *Tetrahedron*, **33**, 2737 (1977); D. Seebach and K.-H. Geiss, "New Applications of Organometallic Reagents in Organic Chemistry," Elsevier, Amsterdam (1976), p. 22; see also, P. W. K. Lau and T. H. Chan, *Tetrahedron Lett.*, **1978**, 2383.

6) D. S. Watt, *Tetrahedron Lett.*, **1974**, 707 and references are cited therein.

7) For preliminary accounts of the present work, see: a) M. Ishiguro, N. Ikeda, and H. Yamamoto, *J. Org. Chem.*, **47**, 2225 (1982); **48**, 142 (1983); b) R. Haruta, M. Ishiguro, K. Furuta, A. Mori, N. Ikeda, and H. Yamamoto, *Chem. Lett.*, **1982**, 1093.

8) For recent reviews: M. T. Reetz, "Topics in Current Chemistry," Springer, Berlin (1982), pp. 1—54; B. Weidmann and D. Seebach, *Angew. Chem., Int. Ed. Engl.*, **22**, 31 (1983); D. Seebach, B. Weidmann, and L. Widler, "Modern Synthetic Methods 1983," ed by R. Scheffold, Wiley, New York and Salle/Sauerländer, Aarau (1983), pp. 217—353.

9) a) M. Saniere-Karila, M. L. Capmau, and W. Chodkiewicz, *Bull. Soc. Chim. Fr.*, **1973**, 3371; b) E. Favre and M. Gaudemar, *J. Organomet. Chem.*, **92**, 17 (1975).

10) See pp. 367—368 of Ref. 1b.

11) For a similar approach to prepare *erythro* diols, see: F. Mercier, N. Le Goff, and R. Epsztein, *C. R. Acad. Sci., Ser. C*, **279**, 525 (1974); *J. Organomet. Chem.* **108**, 165 (1976).

12) We thank Professor Y. Yamamoto for bringing the error of our preliminary report, see Ref. 7a.

13) The lack of stereoselectivity of the condensation of α-silyl anions with aromatic aldehydes was observed previously, see Ref. 1h and 1i. An electron transfer pathway or an acyclic transition state may be proposed for these anomalous results of aromatic aldehydes, see: E. C. Ashby and A. B. Goel, *J. Am. Chem. Soc.*, **103**, 4983 (1981); S. Murata, M. Suzuki, and R. Noyori, *ibid.*, **102**, 3248 (1980).

14) For recent reviews of Peterson olefination, see: a) T.-H. Chan, *Acc. Chem. Res.*, **10**, 442 (1977); b) A. W. P. Jarvie, *Organomet. Chem. Rev., Sect A*, **6**, 153 (1970).

15) I. Fleming, "Comprehensive Organic Chemistry," ed by D. N. Jones, Pergamon Press, Oxford (1979), Vol. 3, pp. 640—644.

16) Prepared from 1-(trimethylsilyl)propyne, see: E. J. Corey and H. A. Kirst, *Tetrahedron Lett.*, **1968**, 5041. For another preparation of this compound, see: F. Jaffe, *J. Organomet. Chem.*, **23**, 53 (1970); M. Laguerre, J. Dunogues, and R. Calas, *ibid.*, **145**, C34 (1978).

17) P. E. Hudrlik, D. Peterson, and R. J. Rona, *J. Org. Chem.*, **40**, 2263 (1975).

18) V. Rautenstrauch, *Helv. Chim. Acta*, **57**, 496 (1974); F. Mercier, R. Epsztein, and S. Holand, *Bull. Soc. Chim. Fr.*, **1972**, 690.

19) a) I. Ojima, M. Kumagai, and Y. Nagai, *Tetrahedron Lett.*, **1974**, 4005; b) I. Matsuda, S. Murata, and Y. Ishii, *J. Chem. Soc., Perkin Trans. 1*, **1978**, 26; c) Y. Sato and Y. Niinomi, *J. Chem. Soc., Chem. Commun.*, **1982**, 56; d) H. Okada, I. Matsuda, and Y. Izumi, *Chem. Lett.*, **1983**, 97. See also, D. N. Brattesani and C. H. Heathcock, *Tetrahedron Lett.*, **1974**, 2279; D. Danion and R. Carrie, *Tetrahedron*, **28**, 4223 (1972).

20) For a general review, see: "The Chemistry of the Cyano Group," ed by S. Patai, Wiley, New York (1970); A. J. Fatiadi, "Preparation and Synthetic Applications of Cyano Com-

pounds," in press.

21) (Trimethylsilyl)acetonitrile was reported to undergo clean metallation with lithium diisopropylamide at low temperature (Ref. 19). Butyllithium was found to be equally effective for the above transformation.

22) The similar reactions of lithio propionitrile or phenylacetonitrile with aldehydes gave β-hydroxy nitrile in modest stereoselectivities.

23) The reactions of corresponding magnesium derivatives were previously reported, see Ref. 1h.

24) Addition of excess base (LDA) to the reaction mixture after treatment with the aldehyde resulted in a lower selectivity.

25) Slightly higher temperature was necessary in the case of magnesio reagents.

26) G. Tennant, "Comprehensive Organic Chemistry," ed by I. O. Sutherland, Pergamon Press, Oxford (1979), Vol. 2, p. 545.

27) G. Stork, L. D. Cama, and D. R. Coulson, *J. Am. Chem. Soc.*, **96**, 5268 (1974); G. Stork and J. F. Cohen, *ibid.*, **96**, 5270 (1974); J. B. Moffat, *J. Chem. Soc., Chem. Commun.*, **1980**, 1108.

28) C. C. Shen and C. Ainsworth, *Tetrahedron Lett.*, **1979**, 87.

29) L. Gouin, M. C. Faroux, O. Riobe, *Bull. Soc. Chim. Fr.*, **1966**, 2320.

30) Freshly prepared from magnesium and iodine in ether.

31) J. Pornet, B. Randrianoelina, and L. Miginiac, *J. Organomet. Chem.*, **174**, 15 (1979).

32) The stereochemical assignment of the acetylenic alcohols was based on the NMR analyses and GLC behaviour in comparison with the authentic sample prepared independently. *threo*-1-Cyclohexyl-2-methyl-4-trimethylsilyl-3-butyn-1-ol was prepared as follows. Wittig reaction of cyclohexanecarbaldehyde with triphenylphosphonium ethylide gave (*Z*)-1-cyclohexylpropene as a major product.[41] Oxidation of the olefin with *m*-CPBA followed by ring opening with diethyl(trimethylsilylethynyl)aluminium[42] afforded the mixture of *threo*-1-cyclohexyl-2-methyl-4-trimethylsilyl-3-butyn-1-ol and 3-cyclohexyl-5-trimethylsilyl-4-pentyn-2-ol (regioisomer). GLC behaviour of the former product was in complete coincidence with the major product of the reaction of titanium reagents. *erythro*-1-Cyclohexyl-2-methyl-4-trimethylsilyl-3-butyn-1-ol was prepared as follows.

Treatment of the (*E*)-1-cyclohexylpropene, which was prepared by the established procedure[43] from the reaction of cyclohexanecarbaldehyde and triphenylphosphonium ethylide, with *m*-CPBA followed by ring opening with the above aluminium reagent gave the *erythro*-1- cyclohexyl-2-methyl-4-trimethylsilyl-3-butyn-1-ol and its regioisomer, 3-cyclohexyl-5-trimethylsilyl-4-pentyn-2-ol. Both isomers of 1-cyclohexyl-2-methyl-4-phenyl-3-butyn-1-ol and 1-cyclohexyl-2-methyl-3-hexyn-1-ol were prepared in a similar manner.

33) The stereochemistry of this compound was determined by the NMR analysis after the conversion to the corresponding aldol product:[44] Treatment of this acetylenic alcohol with mercury(II) sulfate and sulfuric acid gave 4-hydroxy-3-methyl-4-phenyl-2-butanone. ^{1}H NMR spectrum of this product (CCl_4) revealed absorptions at 4.5 (d, J= 8 Hz, weak) and 4.9 ppm (d, J=4 Hz, strong) arising from the benzyl protons. The smaller coupling constant may be expected to belong to *erythro*-isomer.[45]

34) The stereochemistry of this compound was determined as follows. Epoxidation of 1-hexen-3-ol with *t*-BuOOH-VO(acac)$_2$ followed by ring opening with lithium dibutylcuprate-(I) reagent (excess) gave the *erythro*-4,5-decanediol.[46] The NMR analysis and GLC behaviour were identical with the hydrogenation product from entries 14, 15, and 17.

35) The stereochemical assignment of this compound was based on the NMR analysis and GLC behaviour in comparison with the authentic sample prepared independently. Treatment of (*Z*)-4-cyclohexyl-1-trimethylsilyl-3-buten-1-yne, which was prepared by the reported procedure,[1h] with osmium tetraoxide[47] gave *erythro*-1-cyclohexyl-4-trimethylsilyl-3-butyn-1,2-diol. The acetylated product (acetic anhydride–pyridine) of this diol was identical with the major isomer from entries 8 and 9. *erythro*-1-Trimethylsilyl-1-nonyn-3,4-diol was prepared in a similar manner.

36) The butyllithium-*N,N,N',N'*-tetramethylethylenediamine method may cause the rearrangement of acetylenic bond.

37) E. J. Corey and R. A. Ruden, *Tetrahedron Lett.*, **1973**, 1495.

38) The *Z*-isomer was characterized by an infrared absorption at ≈700 cm^{-1} and coupling constant between the vicinal olefinic hydrogens of ≈11 Hz observed in the ^{1}H NMR spectrum. On the other hand, the *E*-isomer was characterized by an infrared absorption at 960—970 cm^{-1} and a coupling constant of ≈16 Hz.

39) H. Kleijn, H. Westmize, K. Kruithof, and P. Vermeer, *Recl. Trav. Chim. Pays-Bas*, **98**, 27 (1979).

40) K. Utimoto, N. Sakai, H. Nozaki, *J. Am. Chem. Soc.*, **96**, 5601 (1974).

41) I. Gosney and A. G. Rowley, "Organophosphorus Reagents in Organic Synthesis," ed by J. I. G. Cadogon, Academic Press, New York (1979), pp. 17—153; M. Schlosser, *Top. Stereochem.*, **5**, 1 (1970).

42) T. Mole and E. A. Jeffery, "Organoaluminium Compounds," Elsevier, Amsterdam (1972).

43) M. Schlosser and K. F. Christmann, *Liebigs Ann., Chem.* **708**, 1 (1967).

44) D. A. McCrae and L. Dolby, *J. Org. Chem.*, **42**, 1607 (1977).

45) C. H. Heathcock, C. T. Buse, W. A. Kleschick, M. C. Pirrung, J. E. Sohn, and J. Lampe, *J. Org. Chem.*, **45**, 1066 (1980).

46) A. Yasuda, S. Tanaka, H. Yamamoto, and H. Nozaki, *Bull. Chem. Soc. Jpn.*, **52**, 1701 (1979).

47) Review: M. Schröder, *Chem. Rev.*, **80**, 187 (1980).