Intramolecular Nucleophilic Acyl Substitution Reaction of 3,4-Alkadienyl Carbonates Mediated by Ti(O-*i*-Pr)$_4$/2 *i*-PrMgCl Reagent. Efficient Synthesis of Optically Active β,γ-Unsaturated Esters with an α-Substituent

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Treatment of 3,4-alkadienyl carbonates **2a**−**i** with a low-valent titanium reagent diisopropoxy(η^2-propene)titanium (**1**), readily generated by the reaction of Ti(O-*i*-Pr)$_4$ with 2 *i*-PrMgCl, resulted in an intramolecular nucleophilic acyl substitution (INAS) reaction to afford vinyltitanium compounds **3** which, in turn, reacted with H_3O^+, D_2O, or iodine to give α-substituted β,γ-unsaturated esters **4** in good to excellent yields. The olefin moiety of the hydrolysis product **4** has (*Z*)-geometry mainly except for **4h**. Starting from chiral **2f** or **2g**, the reaction proceeded stereospecifically to give optically active α-substituted β,γ-unsaturated ester **4f** or **4g** having (*Z*)-olefin geometry exclusively.

Asymmetric synthesis based on chirality present in the allene moiety has attracted considerable interest in recent years.[1] These reactions include [2 + 2][2] and [4 + 2][3] cycloaddition reactions, electrophilic addition reactions,[4] nucleophilic addition reactions,[5] and reactions using organometallic compounds having a chiral allenyl moiety.[6,7] We report here a novel application of allenic chirality in asymmetric synthesis which is based on intramolecular nucleophilic acyl substitution (INAS) reaction of allenylic carbonates.

Recently, we[8] and the Cha group[9] have independently developed an INAS reaction mediated by a titanium(II) compound. Thus, for example, treatment of acetylenic or olefinic carbonates with the titanium(II) reagent diisopropoxy(η^2-propene)titanium (**1**),[10] readily generated by the reaction of Ti(O-*i*-Pr)$_4$ with 2 equiv of *i*-PrMgX, resulted in INAS reaction to afford organotitanium compounds having a carbonyl functional group as rep-

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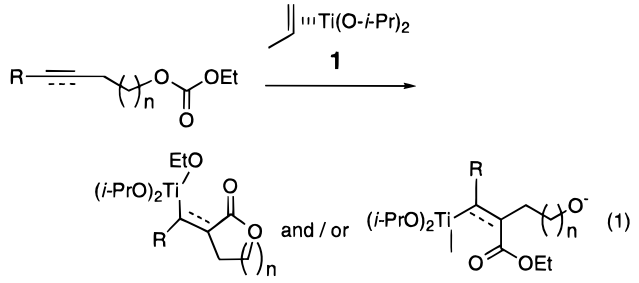
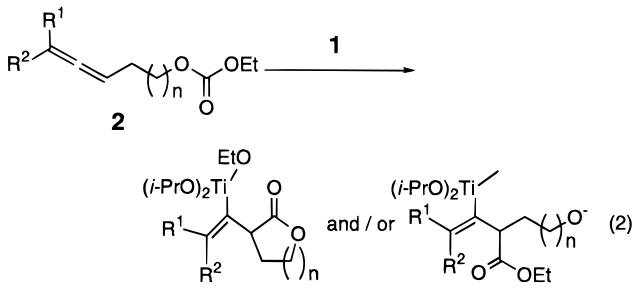
resented by eq 1.[8a,b] These results led us to anticipate that allenylic carbonates of the type **2** might react with



1 in a similar fashion, thus leading to an attractive method for preparing β,γ-unsaturated esters with a substituent at α-position and/or α-alkenyl lactones as shown in eq 2. We were, in particular, interested in synthesizing these compounds in a chiral form by starting with optically active **2**.

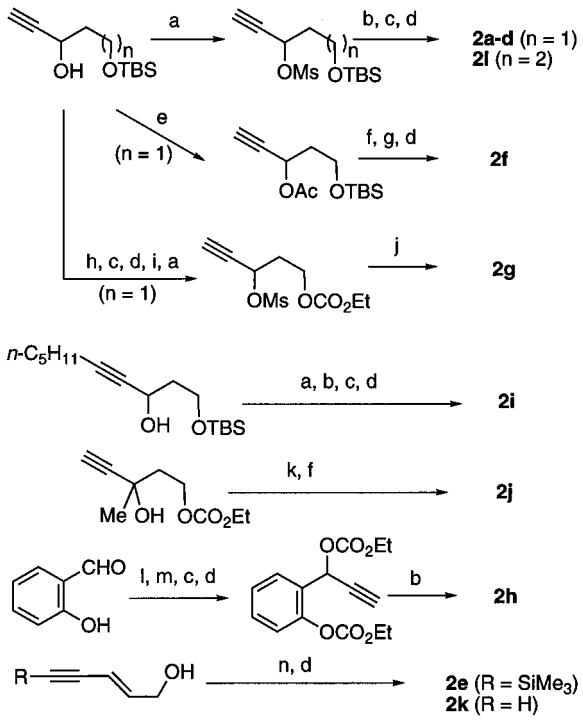


The reaction of a variety of racemic 3,4-alkadienyl carbonates **2a**−**i**, synthesized according to the conventional procedure shown in Scheme 1, with **1** provided the expected INAS products, α-substituted β,γ-unsaturated ester derivatives **3**, in good to excellent yields, which was confirmed by hydrolysis, deuterolysis and/or the reaction with I_2 as summarized in Table 1. However, carbonate **2k** which has a terminal allene moiety gave only a trace amount of the INAS reaction product, but yielded several products including an allenyl-homocoupling product (32% yield, see Experimental Section) (entry 11). The reaction of 4,5-alkadienyl carbonate **2l** with **1** also did not provide the expected INAS product, but gave a complex mixture of products (entry 12),[11] which might be ascribed to the fact that the formation of six-membered transition states leading to the INAS product is disfavored by entropy compared to five-membered ones giving rise to **3** ($n = 1$).

Several aspects exemplified by Table 1 deserve further comments. Firstly, the olefin moiety present in **4** (El = H, hydrolysis product of **3**) has (*Z*)-geometry mainly except for **4h** (entry 8). The *Z* and *E* ratio of the olefin moiety is highly dependent on the bulkiness of the allenic substituent, and the substrates **2** having a sterically more demanding group than *i*-Pr provided (*Z*)-**3** exclusively (entries 3 and 5−7). This stereochemical outcome can be rationalized by the reaction mechanism shown in Scheme 2 which involves the formation of a titanacyclopropane intermediate where **A** is more favorable than **B** due to the steric repulsion between the allenic substituent R and the Ti(O-*i*-Pr)$_2$ moiety and the following INAS reaction. The exceptionally predominant production of **4h** with (*E*)-geometry can be explained by assuming that

(11) The reaction of 2,3-alkadienyl carbonates with **1** affords oxidative addition products (1,3-dien-2-yltitanium compounds), Okamoto, S.; Sato, H.; Sato, F. Unpublished result.

Scheme 1.[a] **Synthesis of Alkadienyl Carbonates 2a−l**



[a] (a) MsCl, Et_3N, CH_2Cl_2; (b) RMgX or RLi, CuBr, LiBr (R = *n*-Bu, *n*-C_5H_{11}, *i*-Pr, *t*-Bu, Ph); (c) TBAF, THF; (d) $ClCO_2Et$, pyridine; (e) AcCl, pyridine, DMAP; (f) $(PhMe_2Si)_2Cu(CN)Li_2$; (g) cat. *p*-TsOH, MeOH; (h) ethyl vinyl ether, cat. *p*-PTS, CH_2Cl_2; (i) aq. 3N HCl, THF; (j) *n*-Bu_3SnLi, CuBr-SMe_2; (k) Ac_2O, Et_3N, cat. DMAP, CH_2Cl_2; (l) TBSCl, imidazole, DMF; (m) acetylene, BuLi, THF (n) $LiAlH_4$, ether.

the transition state **A** becomes less favorable than **B** due to the steric repulsion between the R group and *ortho*-H atom of the phenyl group as shown in Figure 1 which was constructed by using MM2 calculation.

Secondly, although the carbonate **2i** having another substituent at 5-position afforded the corresponding INAS product in excellent yield (entry 9), **2j** which has a substituent at 3-position afforded only a trace amount of the INAS product (entry 10). These results strongly indicate the steric hindrance around the carbon−carbon double bond in **2** which interacts with **1** severely influences the reaction, and **2j** could not form the titanacyclopropane intermediate. Finally, all INAS products obtained here are **3** rather than the corresponding lactone derivatives in contrast to the reaction with olefinic and acetylenic carbonates which provided, in many cases, the lactone derivatives shown in eq 1.

The exclusive production of **3e**−**g** having (*Z*)-geometry as shown in entries 5−7 in Table 1 is particularly noteworthy from the synthetic point of view because (1) alkenyl silanes[12] and alkenyl stannanes[13] with defined stereochemistries are versatile reagents or intermediates in organic synthesis, and (2) it strongly suggested the possibility of effectively synthesizing **3e**−**g** in an optically active form by starting with the corresponding chiral **2**. Next we examined the viability of the latter possibility.

The optically active **2f** and **2g** were prepared from (*R*)-5-[(*tert*-butyldimethylsilyl)oxy]-1-pentyn-3-ol with 89%

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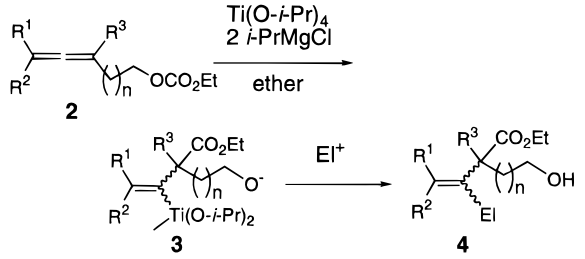
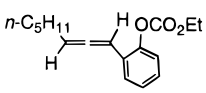
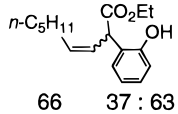
Table 1.[a] Ti(II)-Mediated INAS Reactions of Allenic Carbonates 2



Entry	Substrate 2				Product 4		
		R^1	R^2	R^3	n	El	yield, %[b]	$Z:E$[c]
1	**a** ;	*n*-Bu	H	H	1	H	83	77 : 23
2	**b** ;	*i*-Pr	H	H	1	H	82	92 : 8
3	**c** ;	*t*-Bu	H	H	1	H	88	>98 : 2
4	**d** ;	Ph	H	H	1	H	77	65 : 35
5	**e** ;	Me_3Si	H	H	1	H	56	>98 : 2
						D	54[d]	>98 : 2
						I	49	2 : >98
6	**f** ;	$PhMe_2Si$	H	H	1	H	57	>98 : 2
7	**g** ;	*n*-Bu_3Sn	H	H	1	H	55	>98 : 2
8	**h** ;					H	 66	37 : 63
9	**i** ;	*n*-C_5H_{11} *n*-C_5H_{11}	H		1	H	86[e]	—
10	**j** ;	$PhMe_2Si$	H	Me	1	H	trace[f]	—
11	**k** ;	H	H	H	1	H	trace[g]	—
12	**l** ;	Ph	H	H	2	H	trace[h]	—

[a] Conditions: 1.0 equiv of **2**, 1.4 equiv of Ti(O-*i*-Pr)$_4$, and 2.7 equiv of *i*-PrMgCl in Et_2O at -50 ~ -40 °C for 2 h and then H_2O, D_2O or I_2 at -40 °C. [b] Isolated yield. [c] Stereochemistry of the double bonds and their ratio were determined by 300 MHz ^{1}H-NMR analysis including NOE-difference experiments. [d] Product contained >98% D. [e] 2.0 Equiv of Ti(O-*i*-Pr)$_4$ / 2 *i*-PrMgCl was used. [f] 41% of **2j** was recovered. [g] Allenyl-homocoupling product was obtained in 32% yield; see Experimental Section. [h] The reaction gave a complicated mixture.

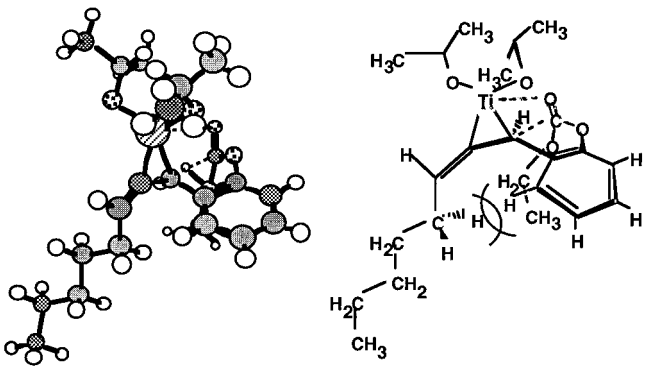
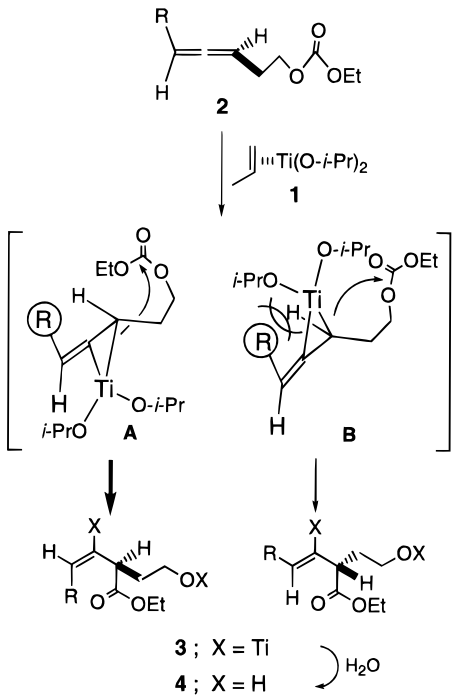


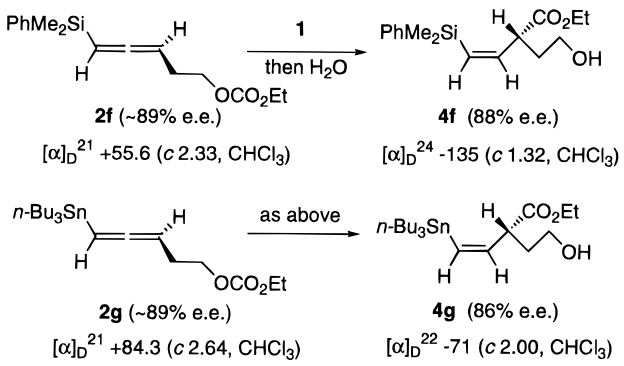
Figure 1. Postulated transition state model **A** for **4h**.

ee[14] according to the procedure shown in Scheme 1 which was reported to proceed stereospecifically.[15] The enantiomeric purities of **4f** and **4g** thus obtained were determined by 300 MHz ^{1}H NMR analysis of the bis-MTPA esters after converting them into (*Z*)-5-(trimethylsilyl)-3-(hydroxymethyl)-4-penten-1-ol and 3-(hydroxymethyl)-4-penten-1-ol, respectively, according to the procedure shown in Scheme 4, and found to be 88 and 86% ee, respectively. These results suggest that essentially no racemization occurs during the reaction. As expected,[10d] the absolute configuration of **4** thus obtained was found to be (*R*) as assigned in Scheme 3 by converting **4g** to the known (*S*)-(−)-2-ethyl-1,4-butandiol[16] as shown in Scheme 4.

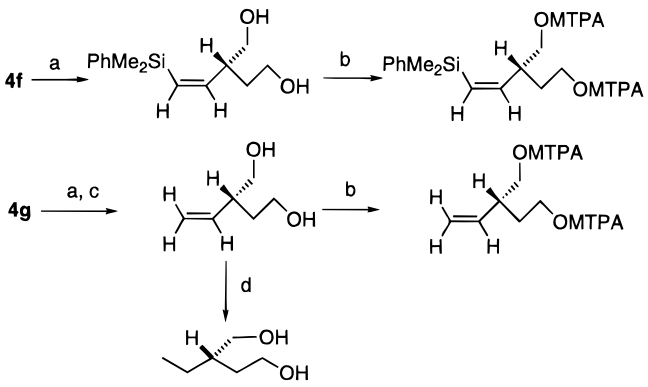
Scheme 2



Scheme 3



Scheme 4[a]



[a] (a) $LiAlH_4$, THF; (b) (*S*)- or (*R*)-MTPA-Cl, pyr., CCl_4; (c) HCl, THF-MeOH; (d) H_2, Pd/C

In conclusion, the INAS reaction of 3,4-alkadienyl carbonates with Ti(O-*i*-Pr)$_4$/2 *i*-PrMgCl reagent proceeds under mild reaction conditions to give good to excellent yields thus providing a useful method for synthesizing α-substituted β,γ-unsaturated esters, including optically active ones. The highly efficient synthesis of the compounds **4e**, **4f**, and **4g** is especially noteworthy because (1) α-substituted β,γ-unsaturated esters often exist in natural compounds and also are versatile synthetic intermediates; however, their synthesis in optically active form is a rather difficult task, and (2) they are of potentially versatile use as synthetic intermediates because they have a vinylsilyl or vinylstannyl moiety as well as a hydroxy group which allows further application of these compounds to organic synthesis.

Experimental Section

General. Infrared (IR) spectra are reported in wave numbers (cm^{-1}). ^{1}H NMR (300 MHz) and ^{13}C NMR (75 MHz) spectra were measured with $CDCl_3$ as the solvent, and chemical shifts are reported in parts per million (δ value).

Materials. Diethyl ether and tetrahydrofuran (THF) were distilled from sodium benzophenone ketyl. Dichloromethane was distilled from CaH_2. Ti(O-*i*-Pr)$_4$ and L-(+)-DIPT were distilled and stored under argon atmosphere. Pyridine was dried over CaH_2. *i*-PrMgCl was prepared as a 1.2−1.6 M ethereal solution from 2-chloropropane and magnesium turnings by the conventional procedure, titrated, and stored under argon atmosphere. All other reagents were available from commercial sources and were used without further purification.

Starting carbonates **2a**−**l** were prepared by the conventional methods as follows (see also Scheme 1); allenic carbonates **2a**−**d** were prepared from 3-[(methanesulfonyl)oxy]-1-[(*tert*-butyldimethylsilyl)oxy]-4-pentyne by the reaction with RCuX−MgX−LiX (R = *n*-Bu or Ph)[17] followed by desilylation (TBAF, THF, 0 °C) and the reaction with ethyl chloroformate and pyridine. Similarly, **2h**, **2i**, and **2k** were prepared from ethyl 2-[1-[(ethoxycarbonyl)oxy]-2-propynyl]phenyl carbonate, 3-[(methanesulfonyl)oxy]-1-[(*tert*-butyldimethylsilyl)oxy]-4-decyne, and 4-[(methanesulfonyl)oxy]-1-[(*tert*-butyldimethylsilyl)-oxy]-5-hexyne, respectively. Compound **2j** was synthesized by the reaction of 3-acetoxy-3-methyl-1-[(*tert*-butyldimethylsilyl)-oxy]-4-pentyne with $(PhMe_2Si)_2Cu(CN)Li_2$[15] followed by desilylation and ethoxycarbonylation of the primary alcohol group. Allenic carbonates **2e** (racemic) and **2k** were prepared from 5-(trimethylsilyl)pent-2-en-4-yn-1-ol and pent-2-en-4-yn-1-ol by $LiAlH_4$ reduction[18] followed by ethoxycarbonylation. Optically active allenic carbonates **2f** and **2g** were synthesized starting with the corresponding propargyl alcohol [89% ee, determined by ^{1}H NMR analysis of the MTPA esters],[19] which were readily obtained from (*E*)-5-[(*tert*-butyldimethylsilyl)oxy]-2-penten-1-ol by the Yadav procedure,[14] by the reaction with $(PhMe_2Si)_2Cu(CN)Li_2$ or *n*-Bu_3SnLi/CuBr-SMe_2[14] after conversion into its mesylate or acetate, respectively. ^{1}H NMR data of **2a**−**l** thus prepared are indicated as follows:

Ethyl 3,4-nonadienyl carbonate (2a): ^{1}H NMR δ 0.90 (t, *J* = 7.2, 3H), 1.26−1.45 (m, 4H), 1.31 (t, *J* = 7.1, 3H), 1.98 (ddt, *J* = 3.0, 7.1, 7.1, 2H), 2.35 (ddt, *J* = 3.1, 6.7, 6.8, 2H), 4.18 (t, *J* = 6.8, 2H), 4.20 (q, *J* = 7.1, 2H), 5.02−5.20 (m, 2H).

Ethyl 6-methyl-3,4-heptadienyl carbonate (2b): ^{1}H NMR δ 1.00 (d, *J* = 6.7, 3H), 1.31 (t, *J* = 7.1, 3H), 2.20−2.41 (m, 3H), 4.18 (t, *J* = 6.9, 2H), 4.19 (q, *J* = 7.1, 2H), 5.08−5.22 (m, 2H).

Ethyl 6,6-dimethyl-3,4-heptadienyl carbonate (2c): ^{1}H NMR δ 1.03 (s, 9H), 1.31 (t, *J* = 7.1, 3H), 2.36 (ddt, *J* = 4.8, 4.8, 6.9, 2H), 4.19 (t, *J* = 7.1, 2H), 4.19 (q, *J* = 7.1, 2H), 5.15 (d, *J* = 4.7, 1H), 5.16 (d, *J* = 4.7, 1H).

Ethyl 5-phenyl-3,4-pentadienyl carbonate (2d): ^{1}H NMR δ 1.28 (t, *J* = 7.1, 3H), 2.51 (ddt, *J* = 2.8, 6.7, 6.6, 2H), 4.07−4.34 (m, 4H), 5.58 (dt, *J* = 6.4, 6.6, 1H), 6.19 (dt, *J* = 6.4, 3.1, 1H), 7.15−7.34 (m, 5H).

Ethyl 5-(trimethylsilyl)-3,4-pentadienyl carbonate (2e): ^{1}H NMR δ 0.08 (s, 9H), 1.29 (t, *J* = 7.1, 3H), 2.32 (ddt, *J* = 3.6, 7.0, 6.9, 2H), 4.14 (t, *J* = 7.0, 2H), 4.18 (q, *J* = 7.1, 2H), 4.75 (dt, *J* = 7.0, 6.8, 1H), 4.85 (dt, *J* = 7.0, 3.6, 1H).

Ethyl 2-(1,2-octadienyl)phenyl carbonate (2h): ^{1}H NMR δ 0.89 (t, *J* = 7.0, 3H), 1.24−1.54 (m, 6H), 1.39 (t, *J* = 7.1, 3H), 2.12 (ddt, *J* = 3.0, 6.7, 7.0, 2H), 4.31 (q, *J* = 7.1, 2H), 5.57 (dt,*J* = 6.6, 6.7, 1H), 6.24 (dt, *J* = 6.6, 3.0, 1H), 7.07−7.24 (m, 3H), 7.38−7.47 (m,1H).

Ethyl 5-pentyl-3,4-decadienyl carbonate (2i): ^{1}H NMR δ 0.88 (t, *J* = 6.8, 6H), 1.20−1.46 (m, 12H), 1.31 (t, *J* = 7.1, 3H), 1.85−1.95 (m, 4H), 2.33 (dt, *J* = 6.7, 7.0, 2H), 4.16 (t, *J* = 7.0, 2H), 4.19 (q, *J* = 7.1, 2H), 5.01−5.11 (m, 1H).

Ethyl 5-(dimethylphenylsilyl)-3-methyl-3,4-pentadienyl carbonate (2j): ^{1}H NMR δ 0.34 (s, 6H), 1.29 (t, *J* = 7.1, 3H), 1.69 (d, *J* = 3.7, 3H), 2.16−2.40 (m, 2H), 4.09−4.24 (m, 4H), 5.00−5.10 (m, 1H), 7.30−7.43 (m, 3H), 7.48−7.59 (m, 2H).

Ethyl 3,4-pentadienyl carbonate (2k): ^{1}H NMR δ 1.31 (t, *J* = 7.1, 3H), 2.31−2.43 (m, 2H), 4.19 (t, *J* = 6.8, 2H), 4.19 (qqq, *J* = 7.1, 2H), 4.68−4.75 (m, 2H), 5.05−5.17 (m, 1H).

Ethyl 6-phenyl-3,4-hexadienyl carbonate (2l): ^{1}H NMR δ 1.30 (t, *J* = 7.1, 3H), 1.77−1.96 (m, 2H), 2.23 (ddt, *J* = 3.2, 6.4, 7.4, 2H), 4.13−4.24 (m, 4H), 5.59 (dt, *J* = 6.5, 6.4, 1H), 6.17 (dt, *J* = 6.5, 3.2, 1H), 7.12−7.36 (m, 5H).

Ethyl (*S*)-5-(phenyldimethylsilyl)-3,4-pentadienyl carbonate (2f): $[\alpha]^{21}_D$ +55.6 (*c* 2.33, $CHCl_3$); ^{1}H NMR δ 0.37 (s, 6H), 1.30 (t, *J* = 7.1, 3H), 2.34 (ddt, *J* = 3.4, 6.8, 6.9, 2H), 4.13 (t, *J* = 6.9, 2H), 4.18 (dt, *J* = 7.0, 6.8, 1H), 5.12 (dt, *J* = 7.0, 3.4, 1H), 7.33−7.41 (m, 3H), 7.50−7.58 (m, 2H).

Ethyl (*S*)-5-(tributylstannyl)-3,4-pentadienyl carbonate (2g): $[\alpha]^{21}_D$ +84.3 (*c* 2.64, $CHCl_3$); ^{1}H NMR δ 0.80−1.10 (m, 15H), 1.31 (t, *J* = 7.1, 3H), 1.20−1.65 (m, 12H), 2.32 (ddt, *J* = 3.5, 7.1, 7.2, 2H), 4.15 (t, *J* = 7.2, 2H), 4.58 (dt, *J* = 6.9, 7.1, 1H), 5.07 (dt, *J* = 6.9, 3.5, 1H).

General Procedure for Ti(II)-Mediated INAS Reactions of Allenic Carbonates 2. To a solution of allenic carbonate **2** (1.0 mmol) and Ti(O-*i*-Pr)$_4$ (1.4 mmol) in ether (10 mL) was added dropwise *i*-PrMgCl (1.2 - 1.6 M in ether, 2.7 mmol) at −78 °C. The resulting mixture was allowed to warm up to −50 °C over 1 h and stirred for 2 h at −50 °C to −40 °C to afford a solution of the organotitanium compound **3**. **Hydrolysis or Deuterolysis:** To the solution of the organotitanium **3** prepared above from 1.0 mmol of **2** was added H_2O (0.5 mL) or D_2O (1.0 mL) at −40 °C. The mixture was warmed up to 0 °C, and to this were added NaF (0.5 g) and then Celite (0.5 g). The mixture was filtered through a pad of Celite, and the filtrate was concentrated under reduced pressure and chromatographed on silica gel (hexane−ether) to afford α-substituted-β,γ-unsaturated ester **4**. Olefin geometries of **4** and their ratio were determined by ^{1}H NMR analysis including an NOE-difference experiment. Deuterolysis gave **4** containing >98% D at the olefinic position (β-position of the resulting ester) which was determined by ^{1}H NMR analysis. **Iodolysis:** To the solution of the organotitanium **3** prepared above was added dropwise a solution of iodine (3.0 mmol) in THF (3 mL) at −40 °C. The resulting mixture was warmed up to 0 °C over 1 h. After addition of H_2O (0.5 mL), to this were added NaF (0.5 g) and then Celite (0.5 g) and similar workup gave the crude product which was purified by column chromatography on silica gel to give the β-iodo-β,γ-unsaturated ester.

Ethyl (*E*)- and (*Z*)-2-(2-hydroxyethyl)-3-octenoate (4a) (entry 1 in Table 1): a 77:23 mixture of *Z* and *E* isomers); ^{1}H NMR δ 0.81−0.94 (m, 3H), 1.17−1.41 (m, 4H), 1.23 (t, *J* =

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7.1, 3H, *Z* isomer), 1.24 (t, J = 7.1, 3H, *E* isomer), 1.62−1.82 (m, 1H), 1.91−2.17 (m, 3H), 3.14 (dt, J = 7.4, 8.4, 1H, *E* isomer), 3.51 (dt, J = 7.3, 9.6, 1H, *Z* isomer), 3.55−3.74 (m, 2H), 4.12 (q, J = 7.1, 2H, *Z* isomer), 4.13 (qq, J = 7.1, 2H, *E* isomer), 5.35 (ddt, J = 9.6, 10.9, 1.7, 1H, *Z* isomer), 5.41 (ddt, J = 8.4, 15.4, 1.5, 1H, *E* isomer), 5.55 (dt, J = 7.2, 10.9, 1H, *Z* isomer), 5.57 (dt, J = 6.6, 15.4, 1H, *E* isomer); ^{13}C NMR δ 13.85, 13.91 (*Z*), 14.13 (*Z* and *E*), 22.09, 22.28 (*Z*), 27.25 (*Z*), 31.29, 31.62 (*Z*), 32.08, 35.14, 35.36 (*Z*), 40.94 (*Z*), 46.04, 60.50 (*Z* and *E*), 60.63 (*Z* and *E*), 126.62 (*Z*), 126.99, 133.38 (*Z*), 134.02, 174.53 (*Z*), 174.62; IR (neat) 3430, 2970, 2940, 2880, 1740, 1660, 1475, 1375, 1265, 1165, 1060, 975, 905, 865, 715; Anal. Calcd for $C_{12}H_{22}O_3$: C, 67.26; H, 10.35. Found: C, 67.42; H, 10.41.

Ethyl (*E*)- and (*Z*)-2-(2-hydroxyethyl)-5-methyl-3-pentenoate (4b) (entry 2 in Table 1): ^{1}H NMR δ 0.97 (d, J = 6.6, 3H), 0.98 (d, J = 6.6, 3H), 1.25 (t, J = 7.1, 3H), 1.53−1.82 (m, 3H), 1.94−2.09 (m, 1H), 2.20−2.35 (m, 1H, *E* isomer), 2.56−2.76 (m, 1H, *Z* isomer), 3.14 (dt, J = 7.7, 8.6, 1H, *E* isomer), 3.53 (dt, J = 7.3, 9.9, *Z* isomer), 3.50−3.78 (m, 2H), 4.14 (q, J = 7.14, 2H *Z* isomer), 4.15 (q, J = 7.0, 2H, *E* isomer), 5.23 (dd, J = 9.9, 10.2, 1H, *Z* isomer), 5.38 (dd, J = 10.2, 10.2, 1H, *Z* isomer), 5.56 (dd, J = 6.4, 15.3, 1H, *E* isomer); ^{13}C NMR δ 14.0, 22.9, 26.8, 35.3, 41.0, 60.2, 60.5, 124.2, 140.6, 174.5; IR (neat) 3423, 2960, 2870, 2362, 1734, 1466, 1369, 1259, 1174, 1055, 918, 735. Anal. Calcd for $C_{11}H_{20}O_3$: C, 65.97; H, 10.06. Found: C, 66.24; H, 10.09.

Ethyl (*Z*)-2-(2-hydroxyethyl)-5,5-dimethyl-3-pentenoate (4c) (entry 3 in Table 1): ^{1}H NMR δ 1.15 (s, 9H), 1.25 (t, J = 7.2, 3H), 1.60−1.83 (m, 2H), 1.92−2.06 (m, 1H), 3.60−3.74 (m, 2H), 3.80 (dt, J = 10.9, 7.1, 1H), 4.15 (q, J = 7.1, 2H), 5.18, (dd, J = 10.9, 11.5, 1H), 5.51 (d, J = 11.5, 1H); ^{13}C NMR δ 14.1, 31.2, 33.5, 36.1, 41.6, 60.5, 60.6, 125.4, 142.7, 174.5; IR (neat) 3448, 2956, 2871, 1734, 1477, 1410, 1365, 1336, 1205, 1161, 1053, 908, 858, 733. Anal. Calcd for $C_{12}H_{22}O_3$: C, 67.26; H, 10.35. Found: C, 66.81; H, 10.16.

Ethyl (*E*)- and (*Z*)-2-(2-hydroxyethyl)-4-phenyl-3-butenoate (4d) (entry 4 in Table 1): a 65:35 mixture of *Z* and *E* isomers; ^{1}H NMR δ 1.27 (t, J = 7.1, 3H, *E* isomer), 1.28 (t, J = 7.1, 3H, *Z* isomer), 1.60−1.96 (m, 2H), 1.98−2.19 (m, 1H), 3.39 (dt, J = 7.6, 8.7, 1H, *E* isomer), 3.52−3.76 (m, 2H), 3.78 (dt, J = 7.2, 10.6, 1H, *Z* isomer), 4.17 (q, J = 7.1, 2H, *E* isomer), 4.18 (q, J = 7.1, 2H, *Z* isomer), 5.67 (dd, J = 10.6, 11.3, 1H, *Z* isomer), 6.21 (dd, J = 8.7, 15.9, 1H, *E* isomer), 6.52 (d, J = 15.9, 1H, *E* isomer), 6.63 (d, J = 11.3, 1H, *Z* isomer), 7.18−7.42 (m, 5 H); ^{13}C NMR δ 14.15 (2 peaks), 35.18, 35.65, 41.56, 46.28, 60.27 (2 peaks), 60.86 (2 peaks), 126.32, 126.93, 127.22, 127.62, 128.37, 128.52, 128.60, 129.01, 131.77, 132.57, 136.43, 136.67, 174.07, 174.13; IR (neat) 3430, 3070, 3030, 2940, 2880, 1730, 1650, 1605, 1500, 1455, 1375, 1260, 1180, 1050, 970, 920, 860, 770, 735, 700. Anal. Calcd for $C_{14}H_{18}O_3$: C, 71.77; H, 7.74. Found: C, 72.37; H, 7.67.

Ethyl (*Z*)-2-(2-hydroxyethyl)-4-(trimethylsilyl)-3-butenoate (4e) (entry 5 in Table 1): ^{1}H NMR δ 0.16 (s, 9H), 1.26 (t, J = 7.1, 3H), 1.54 (br s, 1H), 1.70−1.88 (m, 1H), 1.95−2.11 (m, 1H), 3.40 (dt, J = 7.2, 10.3, 1H), 3.58−3.76 (m, 2H), 4.15 (q, J = 7.1, 2H), 5.71 (d, J = 13.8, 1H), 6.24 (dd, J = 10.3, 13.8, 1H); ^{13}C NMR δ 0.09, 14.10, 35.52, 46.77, 60.46, 60.72, 133.07, 144.72, 174.02; IR (neat) 3450, 2970, 1740, 1615, 1375, 1255, 1165, 1060, 850, 770, 695, 665. Anal. Calcd for $C_{11}H_{22}O_3Si$: C, 57.35; H, 9.62. Found: C, 56.85; H, 9.85. Deuterolysis product: ^{1}H NMR δ 3.40 (t, J = 7.1, 1H), 5.71 (s, 1H); ^{13}C NMR δ 0.09, 14.09, 35.53, 46.68, 60.44, 60.69, 132.85, 144.40 (t, J = 24.7), 174.00.

Ethyl (*E*)-3-iodo-2-(2-hydroxyethyl)-4-(trimethylsilyl)-3-butenoate. The title compound is not stable enough to be stored for elemental analysis: ^{1}H NMR δ 0.18 (s, 9H), 1.27 (t, J = 7.1, 3H), 1.71 (br s, 1H), 1.70−1.87 (m, 1H), 2.10−2.25 (m, 1H), 3.35 (t, J = 6.9, 1H), 3.56−3.80 (m, 2H), 4.17 (q, J = 7.1, 2H), 6.63 (s, 1H); ^{13}C NMR δ −0.07, 14.08, 35.64, 52.98, 59.62, 61.36, 114.72, 148.65, 171.02; IR (neat) 3450, 2970, 2910, 1740, 1590, 1455, 1375, 1260, 1210, 1170, 1060, 1025, 915, 855, 770, 740, 700.

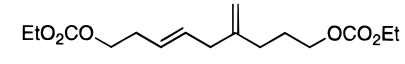
Ethyl (*R*)-(*Z*)-2-(2-hydroxyethyl)-4-(phenyldimethylsilyl)-3-butenoate (4f) (entry 6 in Table 1): $[\alpha]^{24}_D$ −135 (*c* 1.32, $CHCl_3$); ^{1}H NMR δ 0.41 (s, 3H), 0.47 (s, 3H), 1.10 (br s, 1H), 1.22 (t, J = 7.1, 3H), 1.51−1.67 (m, 1H), 1.83−1.99 (m, 1H), 3.25 (dt, J = 7.1, 10.4, 1H), 3.31−3.53 (m, 2H), 4.10 (q, J = 7.1, 2H), 5.88 (d, J = 13.8, 1H), 6.32 (dd, J = 10.4, 13.8, 1H), 7.30−7.44 (m, 3H), 7.50−7.64 (m, 2H); ^{13}C NMR δ −1.42, −0.86, 14.07, 35.31, 46.61, 60.23, 60.67, 127.90, 129.14, 131.08, 133.78, 138.99, 146.38, 173.81; IR (neat) 3450, 3080, 3060, 2970, 1735, 1615, 1435, 1375, 1340, 1255, 1165, 1120, 1055, 825, 785, 735, 705, 675. Anal. Calcd for $C_{16}H_{24}O_3Si$: C, 65.71; H, 8.27. Found: C, 66.27; H, 8.69.

Ethyl (*R*)-(*Z*)-2-(2-hydroxyethyl)-4-tributylstannyl-3-butenoate (4g) (entry 7 in Table 1): $[\alpha]^{22}_D$ −71 (*c* 2.00, $CHCl_3$); ^{1}H NMR δ 0.80−1.08 (m, 15H), 1.16−1.66 (m, 12H), 1.25 (t, J = 7.0, 3H), 1.71−1.81 (m, 1H), 1.96−2.12 (m, 1H), 2.99 (ddd, J = 6.5, 7.8, 9.8, 1H), 3.56−3.76 (m, 2H), 4.13 (qq, J = 7.1, 2H), 6.02 (d, J = 12.5, J_{Sn-H} 61.2Hz, 1H), 6.47 (dd, J = 9.8, 12.5, J_{Sn-H} 128.5, 1H); ^{13}C NMR δ 10.32, 13.65, 14.14, 27.30, 29.12, 35.78, 50.50, 60.66, 60.70, 132.69, 145.56, 174.16; IR (neat) 3440, 2960, 2930, 2880, 1740, 1600, 1470, 1425, 1380, 1340, 1260, 1155, 1050, 960, 865, 770, 685, 665. Anal. Calcd for $C_{20}H_{40}O_3Sn$: C, 53.71; H, 9.01. Found: C, 53.57; H, 9.23.

Ethyl (*E*)- and (*Z*)-2-(2-hydroxyphenyl)-3-octenoate (4h) (entry 8 in Table 1): a 37:63 mixture of *Z* and *E* isomers; ^{1}H NMR δ 0.86 (t, J = 6.7, 3H), 1.15−1.45 (m, 6H), 1.28 (t, J = 7.1, 3H), 1.97−2.20 (m, 2H), 4.12−4.28 (m, 2H), 4.32 (d, J = 7.6, *E* isomer), 4.65 (d, J = 9.3, 1H, *Z* isomer), 5.54−5.70 (m, 1H), 5.87 (ddt, J = 7.6, 15.3, 1.7, 1H, *E* isomer), 5.99 (ddt, J = 9.3, 10.7, 1.5, 1H, *Z* isomer), 6.80−7.00 (m, 2H), 7.03−7.24 (m, 2H), 7.83 (br s, 1H, *E* isomer), 7.86 (br s, 1H, *Z* isomer); ^{13}C NMR δ 13.98 (4 peaks), 22.43, 22.47, 27.48, 28.63, 28.85, 31.32, 31.41, 32.35, 47.81, 53.08, 61.96, 62.02, 118.13 (2 peaks), 120.68, 120.77, 124.17, 120.40, 124.57 (2 peaks), 128.94, 129.09, 129.83, 130.13, 134.04, 134.74, 154.79, 154.89, 175.52; IR (neat) 3400, 2970, 2940, 2860, 1710, 1600, 1515, 1495, 1465, 1375, 1280, 1195, 1100, 1030, 975, 900, 855, 755. Anal. Calcd for $C_{17}H_{24}O_3$: C, 73.88; H, 8.75. Found: C, 73.73; H, 8.95.

Ethyl 2-(2-hydroxyethyl)-4-pentyl-3-octenoate (4i) (entry 9 in Table 1): ^{1}H NMR δ 0.88 (t, J = 7.0, 3H), 0.89 (t, J = 6.8, 3H), 1.15−1.46 (m, 12H), 1.24 (t, J = 7.1, 3H), 1.62 (br s, 1H), 1.67−1.81 (m, 1H), 1.92−2.15 (m, 5H), 3.45 (dt, J = 7.2, 9.9, 1H), 3.56−3.74 (m, 2H), 4.12 (q, J = 7.1, 2H), 5.10 (d, J = 9.9, 1H); ^{13}C NMR δ 14.01, 14.04, 14.16, 22.52, 22.57, 27.72, 28.12, 30.35, 31.52, 31.96, 35.74, 36.68, 41.46, 60.47, 60.68, 121.73, 143.75, 174.99; IR (neat) 3430, 2970, 2940, 2860, 1740, 1660, 1475, 1375, 1260, 1165, 1105, 1060, 910, 865, 730. Anal. Calcd for $C_{18}H_{34}O_3$: C, 72.44; H, 11.48. Found: C, 72.38; H, 11.54.

Results of the Reaction of Entry 11 in Table 1. ^{1}H NMR analysis of the crude mixture showed that the reaction provided several products but less than 5% of **4k**. One of these products was the allenyl-homocoupling product shown below (32% yield).



^{1}H NMR δ 1.31 (t, J = 7.1, 6H), 1.70−1.88 (m, 2H), 2.03−2.16 (m, 4H), 2.73 (2d, J = 5.6, 2H), 4.118 and 4.123 (2t, J = 6.8 and J = 6.7, 4H), 4.19 (q, J = 7.1, 4H), 4.78 (br s, 2H), 5.30−5.60 (m, 2H).

Determination of Optical Purities of 4f and 4g. The compound **4f** was reduced by using $LiAlH_4$ (THF, 0 °C to room temperature), and the resulting diol [(*Z*)-5-(trimethylsilyl)-3-(hydroxymethyl)-4-penten-1-ol] was converted to bis-MTPA esters by treatment with (*R*)- or (*S*)-MTPA-Cl and pyridine in CCl_4. Optical purity of **4f** was confirmed by 300 MHz ^{1}H NMR of these bis-MTPA esters; olefinic proton at the α-position of the silyl group, δ 5.844 (d, J = 14.1, 1H) vs 5.817 (d, J = 14.1, 1H).

The diol [(*Z*)-5-(tributylstannyl)-3-(hydroxymethyl)-4-penten-1-ol] derived from **4g** by the reaction with $LiAlH_4$ was destannylated by treatment with aqueous diluted HCl-MeOH to give 3-(hydroxymethyl)-4-penten-1-ol in essentially quantitative yield. The bis-MTPA esters of this compound were analyzed by 300 MHz ^{1}H NMR to determine optical purity of **4g**; olefinic protons of the terminal position, [δ 5.054 (d, J =

17.0, 1H) and 5.132 (d, J = 10.3, 1H)] vs [δ 5.002 (d, J = 17.2, 1H) and 5.112 (d, J = 10.4, 1H)].

Preparation of the Graphic Formula A for 2h. Figure 1 shown in the text is a postulated transition state model **A** for **2h** (see, Scheme 2 in the text) which was constructed by using MM2 calculation (CAChe calculation system, with an extended parameter set, CAChe Scientific, Inc.). In these calculations we locked parameters on a dihedral angle for Ti−C_{sp^3}−$C_{carbonyl}$−$O_{carbonyl}$ (within ±20°) and an atom distance for $C_{sp^3(attached\ to\ Ti)}$−$C_{carbonyl}$ (2.0−2.5 Å) as a conformational arrangement for carbonyl addition.

Acknowledgment. This work was suported in part by a grant from the Ministry of Education of Japan (No. 07455359 and 07216223).

Supporting Information Available: ^{1}H NMR spectra of **2a**−**l** and **4a**−**i** (12 pages). This material is contained in libraries on microfiche, immediately follows this article in the microfilm version of the journal, and can be ordered from the ACS; see any current masthead page for ordering information.

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