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Cobalt-Catalyzed Asymmetric Addition of Silylacetylenes to 1,1-Disubstituted Allenes

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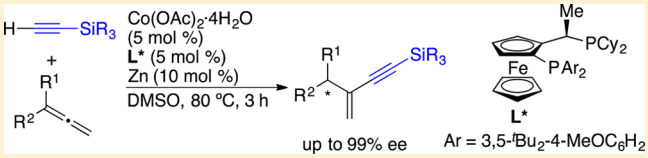
Supporting Information

ABSTRACT: The asymmetric addition of silylacetylenes to 1,1-disubstituted allenes proceeded in the presence of a cobalt/chiral bisphosphine ligand to give the corresponding enynes with high enantioselectivity. The results of deuterium-labeling experiments indicated that a hydrogen atom at the chiral center is originated from the terminal alkyne, and they were in good agreement with the proposed catalytic cycle where enantioselectivity is determined by the reaction of the proposed π-allylcobalt intermediate with the terminal alkyne.



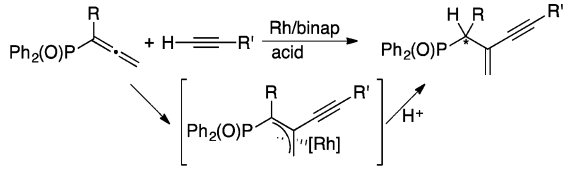
INTRODUCTION

A recent report of the transition-metal-catalyzed asymmetric alkynylation using terminal alkynes provides one of the most efficient ways of preparing chiral internal alkynes in view of high atom efficiency.[1,2] There have been many successful reports on the asymmetric alkynylation of polar unsaturated bonds, such as aldehydes, ketones, and imines.[2a,3] On the other hand, several reports have recently appeared that describe the asymmetric addition of terminal alkynes to less polar C−C double bonds such as α,β-unsaturated carbonyl compounds and related compounds or strained double bonds catalyzed by Cu,[4] Rh,[5] Ir,[6] Ni,[7] and Pd complexes.[8] In this context, we recently reported that cobalt complexes catalyze the asymmetric alkynylation of α,β-unsaturated ketones,[9] oxa- and azabenzonorbornadienes,[10] and $\alpha,\beta,\gamma,\delta$-unsaturated carbonyl compounds.[11,12]

Conjugated enynes are important building blocks found in a variety of biologically active compounds,[13] and the addition of terminal alkynes to alkynes or allenes represents a powerful method for the synthesis of conjugated enynes.[14] There have been several reports on the alkynylation of allenes leading to enynes by use of Pd,[15] Rh,[16] and Ru catalysts.[17] The first asymmetric hydroalkynylation of allenes was reported in the addition of terminal alkynes to 1,1-disubsituted diarylphosphinylallenes in the presence of a chiral rhodium(I) catalyst and an acid, where the enantioselective protonation of a π-allylrhodium(I) intermediate generated by the alkynylation of a central carbon of the allene gives the enantioenriched enynes with high *exo*-selectivity (Scheme 1).[18] Unfortunately, however, applicable substrates have been limited to allenes substituted with a phosphinyl group.

The cobalt-catalyzed reaction has been recently developed as one of the useful tools of carbon−carbon bond formation with the unique reactivity and selectivity.[19,20] During our ongoing investigation into cobalt-catalyzed alkynylation, it was found

Scheme 1. Rh-Catalyzed Asymmetric Addition of Terminal Alkynes to Diphenylphosphinylallenes



that a cobalt/bisphosphine catalytic system displays high catalytic activity in the addition of a silylacetylene to a 1,1-disubstituted allene with high regio- and stereoselectivity. Here we report the asymmetric addition of terminal alkynes to 1,1-disubstituted allenes having a variety of substituents, which is realized by use of a chiral cobalt catalyst.

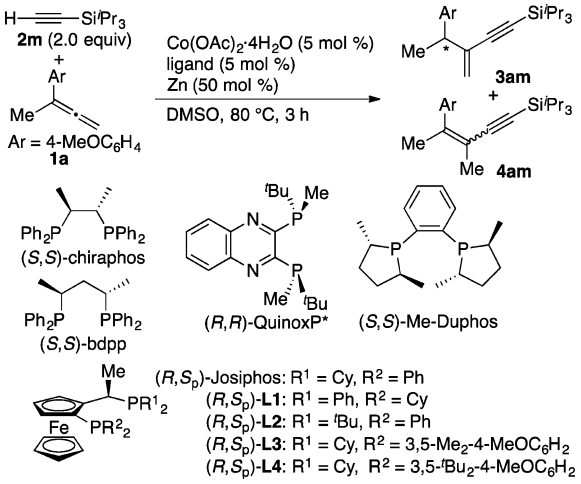
RESULTS AND DISCUSSION

Treatment of 1-(2,3-butadien-2-yl)-4-methoxybenzene (**1a**) with (triisopropylsilyl)acetylene (**2m**) (2.0 equiv) in the presence of $Co(OAc)_2·4H_2O$ (5 mol %), dppe (5 mol %), and zinc powder (50 mol %) in dimethyl sulfoxide (DMSO) at 80 °C for 3 h, which is one of the standard reaction conditions of the cobalt-catalyzed alkynylations,[9] gave a mixture of the addition products in 89% yield, *exo*-enyne **3am** as a major product and its isomer *endo*-enyne **4am** (**3am**/**4am** = 90/10, *E*/*Z* of **4am** = 97/3, Table 1, entry 1). The catalytic system based on the cobalt complex displaying high *exo*-selectivity was promising for the development of asymmetric variant of the reaction. Of several commercially available chiral bisphosphine ligands, (*S*,*S*)-chiraphos,[21] (*S*,*S*)-bdpp,[22] (*R*,*R*)-QuinoxP*,[23] (*S*,*S*)-Me-Duphos,[24] and (R,S_p)-Josiphos[25] (entries 2−6),

Received: July 30, 2013
Published: August 29, 2013

   dx.doi.org/10.1021/jo401604n | J. Org. Chem. 2013, 78, 8986−8993

Table 1. Cobalt-Catalyzed Asymmetric Alkynylation of Allene 1a[a]



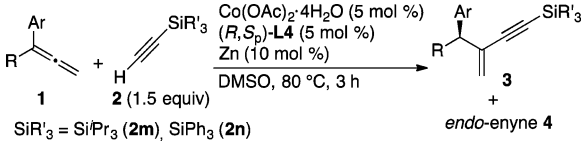
entry	ligand	yield[b] (%)	ee[c] (%)
1	dppe	89 (90/10)	
2	(*S*,*S*)-chiraphos	89 (76/24)	25 (*R*)
3	(*S*,*S*)-bdpp	67 (85/15)	18 (*R*)
4	(*R*,*R*)-QuinoxP*	75 (92/8)	71 (*S*)
5	(*S*,*S*)-Me-Duphos	35 (90/10)	50 (*S*)
6	(R,S_p)-Josiphos	91 (99/1)	82 (*S*)
7	(R,S_p)-**L1**	91 (87/13)	43 (*S*)
8	(R,S_p)-**L2**	10 (30/70)	–[d]
9	(R,S_p)-**L3**	95 (>99/1)	89 (*S*)
10	(R,S_p)-**L4**	83 (98/2)	99 (*S*)
11[e]	(R,S_p)-**L4**	89 (97/3)	99 (*S*)
12[e,f]	(R,S_p)-**L4**	82 (96/4)	98 (*S*)
13[g]	(R,S_p)-**L4**	1 (>99/1)	–[d]

[a]Reaction conditions: allene **1a** (0.20 mmol), (triisopropylsilyl)-acetylene (**2m**) (0.40 mmol), $Co(OAc)_2·4H_2O$ (5 mol %), ligand (5 mol %), Zn (50 mol %), DMSO (0.3 mL) at 80 °C for 3 h. [b]Yield of isomers. The value in parentheses is the ratio of isomers (**3am**/**4am**). [c]The ee of **3am** was determined by chiral HPLC analysis of the desilylated product of **3am**. [d]Not determined. [e]Alkyne (0.30 mmol), Zn (10 mol %). [f]$Co(OAc)_2$ was used instead of $Co(OAc)_2·4H_2O$. [g]Alkyne (0.30 mmol) without Zn. Cy = cyclohexyl. dppe =1,2-bis(diphenylphosphino)ethane.

(R,S_p)-Josiphos displayed both high catalytic activity and enantioselectivity to give **3am** with 82% ee (entry 6). The substituents on two phosphorus atoms of the Josiphos-type ligands have significant influences on both the yield and enantioselectivity. Thus, the use of (R,S_p)-**L1**,[26] which has phosphorus groups replacing each other in the Josiphos ligand, displayed low enantioselectivity (43% ee, entry 7). The ligand (R,S_p)-**L2**[25] bearing bulky *tert*-butyl groups (R^1) gave a low yield of the addition products (entry 8). The ligand **L3**[26] substituted with bulkier aromatic rings than those of the Josiphos ligand, 3,5-dimethyl-4-methoxyphenyl groups on the ferrocenylphosphino group (R^2), increased the enantioselectivity (89% ee, entry 9). Based on these results, we prepared **L4** bearing a bis(3,5-di-*tert*-butyl-4-methoxyphenyl)-phosphinoferrocenyl moiety, and it was found that the use of (R,S_p)-**L4** displays a very high enantioselectivity (99% ee) to give 83% yield of the addition products with high *exo*-selectivity (**3am**/**4am** = 98/2, entry 10). The yield and enantioselectivity of **3am** were kept high (89% yield, **3am**/**4am** = 97/3, *E*/*Z* of **4am** = 22/78, 99% ee of **3am**) in the reaction with a reduced amount of the silylacetylene (1.5 equiv) and zinc powder (10 mol %, entry 11). Anhydrous $Co(OAc)_2$ can also be used as a catalyst precursor giving the addition product with essentially the same yield and ee as that with $Co(OAc)_2·4H_2O$ (entry 12). The reaction without zinc gave only a very low yield (1%) of the addition products (entry 13). The absolute configuration of **3am** obtained with (R,S_p)-**L4** was assigned to be *S*-(+) by X-ray crystallographic analysis of compound **8**, which was derived from **3am** in two steps (vide infra).

The results obtained for the cobalt-catalyzed addition of silylacetylenes to 1,1-disubstituted allenes are summarized in Table 2. The reaction of 1,2-butadienes substituted with *p*-, *m*-, and *o*-methoxyphenyl groups (**1a**–**c**) gave the corresponding enynes **3am**–**cm** in good yields with high enantioselectivity (96–99% ee, entries 1–3). Allenes having electron-deficient aryl groups (**1d** and **1e**), phenyl (**1f**), and 1-naphthyl (**1g**) are also good substrates to give the corresponding enynes **3dm**–**gm** with high enantioselectivity (entries 4–7). The alkynylation of allenes substituted with not only methyl on R (**1a**, entry 1) but also ethyl (**1h**), butyl (**1i**), and methoxymethyl (**1j**) proceeded to give the corresponding addition products **3hm**–**jm** in good yields with high enantioselectivity (entries 8–10). The present cobalt-catalyzed alkynylation can introduce bulky silylacetylene **2n** with high enantioselectivity (92% ee, entry 11), but phenylacetylene and 1-octyne were not applicable due to the alkyne oligomerization.

Table 2. Cobalt-Catalyzed Asymmetric Addition of Silylacetylenes 2 to Allenes 1[a]

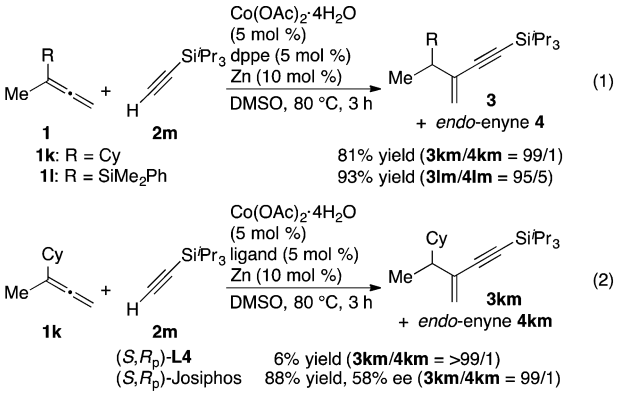


entry	Ar	R	product	yield[b] (%)	ee[c] (%)
1	4-$MeOC_6H_4$	Me (**1a**)	**3am**	89 (97/3)	99
2	3-$MeOC_6H_4$	Me (**1b**)	**3bm**	87 (95/5)	98
3[d]	2-$MeOC_6H_4$	Me (**1c**)	**3cm**	74 (85/15)	96
4	4-FC_6H_4	Me (**1d**)	**3dm**	82 (96/4)	98
5	4-ClC_6H_4	Me (**1e**)	**3em**	81 (95/5)	>99.5
6	Ph	Me (**1f**)	**3fm**	94 (98/2)	98
7	1-naphthyl	Me (**1g**)	**3gm**	88 (89/11)	99
8	4-$MeOC_6H_4$	Et (**1h**)	**3hm**	77 (89/11)	97
9	4-$MeOC_6H_4$	Bu (**1i**)	**3im**	81 (98/2)	96[e]
10	Ph	$MeOCH_2$ (**1j**)	**3jm**	70 (96/4)	96[e]
11	4-$MeOC_6H_4$	Me (**1a**)	**3an**	74 (95/5)	92[e]

[a]Reaction conditions: allene **1** (0.20 mmol), alkyne **2** (0.30 mmol), $Co(OAc)_2·4H_2O$ (5 mol %), (R,S_p)-**L4** (5 mol %), Zn (10 mol %), DMSO (0.3 mL) at 80 °C for 3 h. [b]Yield of isomers. The value in parentheses is the ratio of isomers (**3**/**4**). [c]Determined by chiral HPLC analysis of the desilylated products of **3**. [d]For 10 h. [e]Determined by chiral HPLC analysis of **3**.

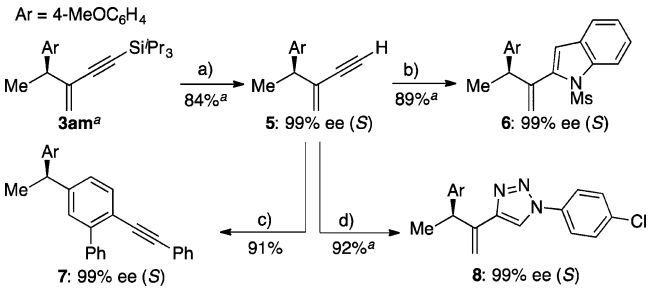
The reactions of allenes substituted with cyclohexyl (**1k**) and dimethylphenylsilyl (**1l**) with alkyne **2m** in the presence of the Co/dppe catalytic system proceeded well to give the corresponding enynes **3km** and **3lm** in high yields with high *exo*-selectivity (eq 1). However, the asymmetric alkynylation of **1k** by use of (R,S_p)-**L4** resulted in a 6% yield with 31% conversion of **1k** (eq 2). A less bulky ligand (R,S_p)-Josiphos displayed higher catalytic activity in the reaction of **1k** to give **3km** in 88% yield, although the ee was modest (58% ee).

dx.doi.org/10.1021/jo401604n | *J. Org. Chem.* 2013, 78, 8986–8993



The enyne **3am** obtained here with high enantioselectivity can be converted into several chiral compounds without loss of the enantiomeric purity (Scheme 2). Thus, removal of a silyl

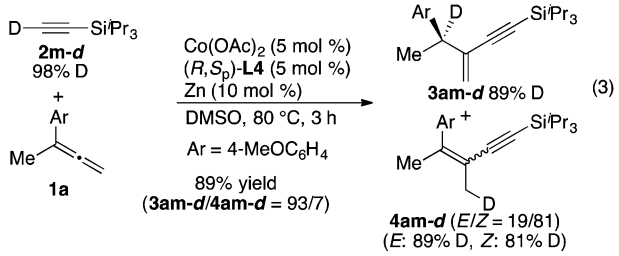
Scheme 2. Transformations of 3am*



*Key: (a) Bu_4NF, MeOH, THF, rt; (b) *N*-mesyl-2-iodoaniline, cat. $Pd(PPh_3)_4$, cat. CuI, 1,8-diazabicyclo[5.4.0]undec-7-ene, EtOH, reflux; (c) 1,4-diphenylbutadiyne, cat. $Pd(PPh_3)_4$, THF, reflux; (d) 1-azido-4-chlorobenzene, cat. $CuSO_4·5H_2O$, Na-(+)-ascorbate, $PhCO_2H$, *t*BuOH, H_2O, rt. [a]Including other isomers (<4%).

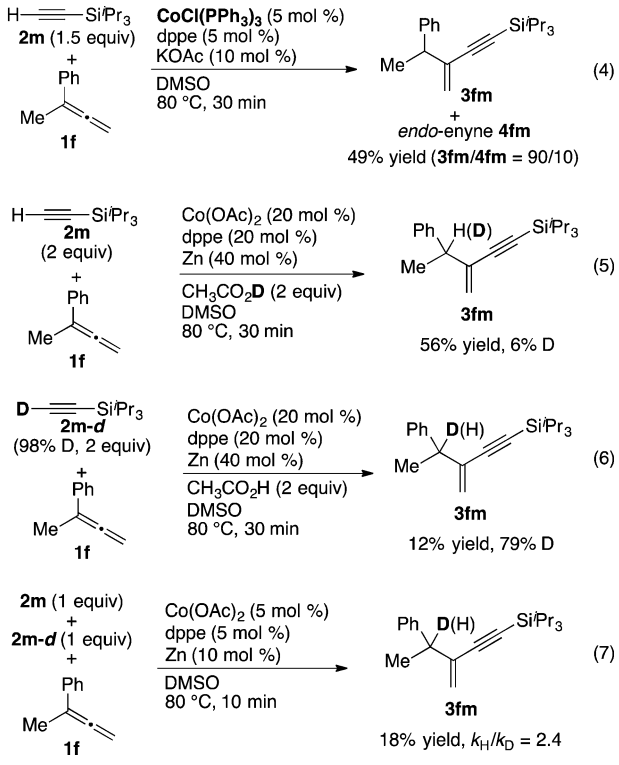
group of **3am** by treatment with tetrabutylammonium fluoride gave **5** in 84% yield (Scheme 2a), which was transformed into indole **6** by the reaction with *N*-mesyl-2-iodoaniline in the presence of a palladium and a copper catalyst (Scheme 2b).[27] The palladium-catalyzed benzannulation[28] of **5** with 1,4-diphenylbutadiyne gave chiral diarylethane **7** in 91% yield (Scheme 2c). The copper-catalyzed cycloaddition[29] of **5** with 1-azido-4-chlorobenzene proceeded to give triazole **8** in 92% yield (Scheme 2d), and its absolute configuration was determined to be *S* by X-ray crystallographic analysis with the Flack parameter (−0.02).[30]

The reaction of allene **1a** with the deuterated alkyne **2m-*d*** in place of **2m** gave the addition product **3am-*d***, where the chiral center was selectively deuterated (eq 3). The *endo*-enyne **4am**



also contained deuterium at the methyl group originated from the allene terminal carbon. These results imply that both the *exo*-enyne and the *endo*-enyne are formed via a protonation of a π-allylcobalt(I) complex and the enantioselective protonation of the π-allylcobalt(I) takes place to give the enantioenriched enyne in the present reaction (vide infra).

Further experiments to gain some mechanistic insight were carried out using allene **1f** and dppe as a ligand (eqs 4–6). A



monovalent tetrahedral cobalt(I) complex $CoCl(PPh_3)_3$[31] can be applied as a catalyst precursor without use of zinc, and the reaction in the presence of dppe and KOAc even in a short reaction time of 30 min gave the addition products in 49% yield (eq 4), where both dppe and KOAc were required for the formation of the addition products. As shown in Table 1 (entry 11 vs 13), the use of Zn is essential for the reaction starting with $Co(OAc)_2$. These results indicate that the active catalytic species in the present reaction is a monovalent cobalt in situ generated by reduction of cobalt(II) acetate with zinc.[31a] The formation of a cobalt(I) species by reduction of a cobalt(II) complex with zinc has been proposed in the cobalt-catalyzed reactions using cobalt(II) halides as catalyst precursors with zinc.[20]

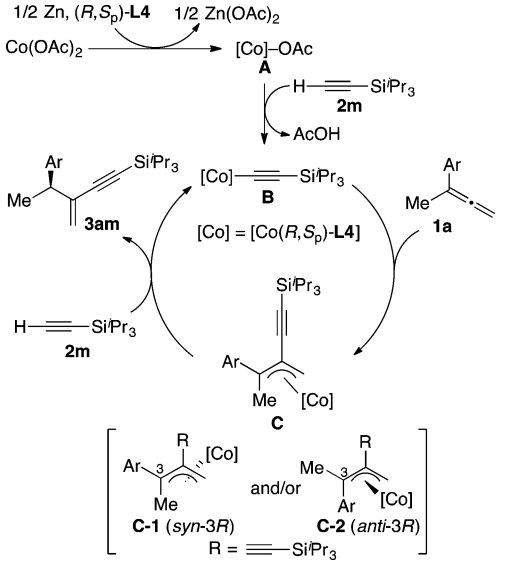
Equations 5 and 6 demonstrate that the hydrogen atom at the chiral center of the product is directly derived from the terminal alkyne not from other possible proton source such as in situ generated acetic acid. Treatment of **1f** with **2m** (2 equiv) in the presence of acetic acid-*d* (2 equiv), $Co(OAc)_2$ (20 mol %), dppe (20 mol %), and zinc powder (40 mol %) at 80 °C for 30 min gave **3fm** in 56% yield, which contains 6% of deuterium at the chiral center (eq 5). On the other hand, the reaction of **1f** with the deuterated alkyne **2m-*d*** in the presence of acetic acid gave 12% yield of **3fm** with 79% D (eq 6). The partial H–D scrambling is probably due to the H–D exchange of the terminal alkyne with acetic acid, which was observed in the reaction of **2m** with acetic acid-*d* under the same reaction conditions except in the absence of **1f** (38% D in the recovered **2m**). The H–D exchange may proceed by way of an alkynylcobalt(I) intermediate, whose formation was also

dx.doi.org/10.1021/jo401604n | J. Org. Chem. 2013, 78, 8986–8993

proposed in our previous studies on the cobalt-catalyzed alkynylation of oxabenzonorbornadienes under similar reaction conditions. The different reactivity between **2m** and **2m-*d*** is demonstrated by the intermolecular competition experiment (eq 7). A positive kinetic isotope effect (k_H/k_D = 2.4) was observed in the reaction of **1f** with **2m** and **2m-*d***.

On the basis of the results described above in eqs 3−7, the catalytic cycle proposed for the present hydroalkynylation of allene **1a** is illustrated in Scheme 3. The catalytic reaction is

Scheme 3. Proposed Catalytic Cycle



initiated by the reduction of cobalt(II) to cobalt(I) by zinc powder giving cobalt(I) acetate **A**, which undergoes the reaction with alkyne **2m** to form alkynylcobalt(I)[32] **B** and acetic acid. The insertion of allene **1a** into the alkynyl cobalt bond results in the formation of π-allylcobalt(I)[33] **C**. Protonation of **C** at the more substituted carbon with the terminal alkyne **2m** leads to enyne **3am** and regenerates alkynylcobalt(I) **B**. Provided that the protonation of the π-allylcobalt(I) intermediate **C** by the terminal alkyne takes place from the same side of cobalt via an oxidative addition/reductive elimination or a σ-bond metathesis pathway, the **C-1** and **C-2** structures are favorable leading to (*S*)-**3am**.[34]

CONCLUSION

In summary, the catalytic asymmetric addition of silylacetylenes to 1,1-disubstituted allenes was realized by use of a chiral cobalt catalyst, giving the corresponding enynes with high enantioselectivity. The results of deuterium-labeling experiments were in good agreement with the proposed catalytic cycle, where enantioselectivity is determined by the reaction of the proposed π-allylcobalt intermediate with the terminal alkyne.

EXPERIMENTAL SECTION

General Methods. All anaerobic and moisture-sensitive manipulations were carried out with standard Schlenk techniques under predried nitrogen or glovebox techniques under argon. NMR spectra were recorded on a NMR spectrometer (500 MHz for ^{1}H, 125 MHz for ^{13}C, and 202 MHz for ^{31}P). Chemical shifts are reported in δ (ppm) referenced to the residual peaks of $CDCl_3$ (δ 7.26) or C_6D_6 (δ 7.16) for ^{1}H NMR, $CDCl_3$ (δ 77.00) or C_6D_6 (δ 128.00) for ^{13}C NMR and an external H_3PO_4 standard for ^{31}P NMR. The following abbreviations are used: s, singlet; d, doublet; t, triplet; q, quartet; quint, quintet; m, multiplet. DMSO was distilled over CaH_2 under N_2. $Co(OAc)_2{\cdot}4H_2O$, $CoCl(PPh_3)_3$, and zinc powder were purchased and used as received. $Co(OAc)_2$ was dried under reduced pressure before use. Allenes[35] **1a** (CAS no. 87959-49-7), **1b** (CAS no. 57532-79-3), **1d** (CAS no. 221312-24-9), **1e** (CAS no. 1037048-15-9), **1f** (CAS no. 22433-39-2), **1g** (CAS no. 1115021-07-2), **1h** (CAS no. 1041791-80-3), **1i** (CAS no. 1020255-02-0), **1j** (CAS no. 343951-53-1), **1k** (CAS no. 59409-49-3), **1l** (CAS no. 252639-93-3), and deuterated alkyne **2m-*d*** (CAS no. 1115020-74-0)[10] were prepared according or analogous to the reported procedures.

1-(Buta-2,3-dien-2-yl)-2-methoxybenzene (1c). To a solution of 1-(2,2-dibromo-1-methylcyclopropyl)-2-methoxybenzene (CAS no. 1064001-03-1)[36] (1.80 g, 5.63 mmol) in Et_2O (5 mL) was added dropwise MeLi (1.12 M Et_2O solution, 6.0 mL, 6.8 mmol) at −40 °C. After the solution was stirred at the same temperature for 1.5 h, water was added. The mixture was extracted with Et_2O, and the combined organic extracts were washed with water until the aqueous layer became neutral, dried (Na_2SO_4), filtered, and concentrated on a rotary evaporator. After evaporation of the solvent, the residue was subjected to flash column chromatography (silica gel, hexane) to give compound **1c** as a pale yellow oil (664 mg, 4.15 mmol, 74%): ^{1}H NMR ($CDCl_3$) δ 2.09 (t, J = 3.2 Hz, 3H), 3.84 (s, 3H), 4.79 (q, J = 3.2 Hz, 2H), 6.88 (d, J = 8.0 Hz, 1H), 6.93 (td, J = 8.0, 1.0 Hz, 1H), 7.20−7.25 (m, 2H); ^{13}C NMR ($CDCl_3$) δ 19.2, 55.5, 73.5, 97.8, 111.3, 120.6, 127.3, 128.2, 129.2, 156.9, 209.3; HRMS (ESI-TOF) calcd for $C_{11}H_{12}NaO$ $(M + Na)^+$ 183.0780, found 183.0779.

(*R*,*S*$_p$)-L4. Reported procedures[37] were modified and used for the preparation of (*R*,*S*$_p$)-**L4**. To a solution of *N*,*N*-diethylphosphoramidous dichloride (CAS no. 1069−08−5)[38] (1.9 mL, 13 mmol) in THF (13 mL) was added dropwise 3,5-di(*tert*-butyl)-4-methoxyphenylmagnesium bromide (1.0 M in THF solution, 39 mL, 39 mmol), prepared from 1-bromo-3,5-di(*tert*-butyl)-4-methoxybenzene and magnesium turnings, at 0 °C, and then the mixture was warmed to room temperature. After being stirred overnight, the mixture was filtered through a pad of Celite with pentane as eluent and the filtrate was concentrated under reduced pressure. The residue was dissolved in pentane and filtered through a pad of Celite. After removal of the solvent under reduced pressure, the residue was dissolved in hexane (65 mL). To the solution was added HCl solution (1 M in Et_2O, 26 mL, 26 mmol) at 0 °C, and the mixture was stirred at 0 °C for 2 h. The mixture was filtered through a pad of Celite with hexane as eluent, and the filtrate was concentrated under reduced pressure to give chlorobis(3,5-di-*tert*-butyl-4-methoxyphenyl)phosphane (**s1**), which was used without further purification. To a solution of (*R*)-*N*,*N*-dimethyl-1-ferrocenylethylamine (CAS no. 31886-58-5)[39] (2.3 g, 9.0 mmol) in Et_2O (13 mL) was added dropwise BuLi (1.64 M in hexane solution, 6.6 mL, 11 mmol) at 0 °C. The mixture was stirred for 1.5 h, and then the solution of **s1** (13 mmol) in Et_2O (8 mL) was added at 0 °C. After being stirred for 1 h, the mixture was warmed to room temperature and aqueous $NaHCO_3$ was added. The mixture was extracted with Et_2O, and the combined organic extracts were dried ($MgSO_4$), filtered, and concentrated under reduced pressure. The residue was subjected to column chromatography (alumina, hexane/Et_2O = 5/1) to give (*R*,*S*$_p$)-2-bis(3,5-di-*tert*-butyl-4-methoxyphenyl)-phosphino-1-(1′-*N*,*N*-dimethylaminoethyl)ferrocene (**s2**) with some impurities (950 mg, 1.3 mmol, 15% yield): ^{1}H NMR ($CDCl_3$) δ 1.26 (d, J = 6.7 Hz, 3H), 1.32 (s, 18H), 1.41 (s, 18H), 1.71 (s, 6H), 3.58 (s, 3H), 3.71 (s, 3H), 3.79−3.82 (m, 1H), 3.94 (s, 5H), 4.12 (qd, J = 6.7 Hz, J_{P-H} = 2.5 Hz, 1H), 4.22 (t, J = 2.1 Hz, 1H), 4.29−4.34 (m, 1H), 7.21 (d, J_{P-H} = 8.4 Hz, 2H), 7.50 (d, J_{P-H} = 7.8 Hz, 2H); ^{31}P NMR ($CDCl_3$) δ −25.3; HRMS (ESI-TOF) calcd for $C_{44}H_{64}FeNO_2P$ $(M)^+$ 725.4019, found 725.4020. A mixture of **s2** (950 mg, 1.3 mmol) and dicyclohexylphosphine (0.29 mL, 1.4 mmol) in acetic acid (11 mL) was stirred at 80 °C overnight. After removal of the solvent under reduced pressure, the residue was subjected to column chromatography (alumina, hexane/Et_2O = 20/1) to give (*R*,*S*$_p$)-**L4** as a yellow solid (1.0 g, 1.2 mmol, 89% yield): mp 82−84 °C; $[\alpha]^{20}_D$ −199 (*c* 0.46, $CHCl_3$); ^{1}H NMR (C_6D_6) δ 1.10−1.43 (m, 12H), 1.45 (s, 18H), 1.47 (s, 18H), 1.55−1.92 (m, 10H), 1.64 (dd, J = 7.2 Hz, J_{P-H} = 4.7 Hz, 3H), 3.39 (s, 3H), 3.44 (s, 3H), 3.66 (qd, J = 7.2 Hz, J_{P-H} = 3.7

dx.doi.org/10.1021/jo401604n | J. Org. Chem. 2013, 78, 8986−8993

Hz, 1H), 3.96 (s, 5H), 4.23 (t, J = 2.4 Hz, 1H), 4.23−4.26 (m, 1H), 4.30−4.35 (m, 1H), 7.63 (d, J_{P-H} = 7.6 Hz, 2H), 7.88 (d, J_{P-H} = 8.1 Hz, 2H); ^{13}C NMR (C_6D_6) δ 16.9 (1C), 26.9−31.8 (m, 11 C), 27.2 (dd, J_{P-C} = 25, 10 Hz, 1C), 32.3 (6C), 32.4 (6C), 33.4 (dd, J_{P-C} = 22, 3 Hz, 1C), 35.98 (2C), 36.03 (2C), 64.2 (2C), 68.6 (1C), 68.8 (dd, J_{P-C} = 4, 3 Hz, 1C), 69.7 (5C), 71.5 (d, J_{P-C} = 5 Hz, 1C), 77.1 (dd, J_{P-C} = 13, 3 Hz, 1C), 102.2 (dd, J_{P-C} = 27, 20 Hz, 1C), 132.3 (d, J_{P-C} = 20 Hz, 2C), 133.9 (dd, J_{P-C} = 8, 2 Hz, 2C), 134.7 (d, J_{P-C} = 24 Hz, 2C), 135.2 (dd, J_{P-C} = 5, 1 Hz, 2C), 142.5 (d, J_{P-C} = 11 Hz, 1C), 143.0 (d, J_{P-C} = 13 Hz, 1C), 159.7 (1C), 160.8 (1C); ^{31}P NMR (C_6D_6) δ −27.8 (d, J = 31 Hz), 14.8 (d, J = 31 Hz); IR (thin film) ν 1410, 1220, 1115, 1011, 810 cm^{-1}; HRMS (ESI-TOF) calcd for $C_{54}H_{80}FeO_2P_2$ $(M)^+$ 878.4977, found 878.4976.

General Procedure for Table 2. A mixture of $Co(OAc)_2{\cdot}4H_2O$ (2.5 mg, 0.010 mmol), (R,S_p)-**L4** (8.8 mg, 0.010 mmol), and Zn powder (1.3 mg, 0.020 mmol) in DMSO (0.3 mL) was stirred at 80 °C for 15 min under N_2. To the mixture were added allene **1** (0.20 mmol) and (triisopropylsilyl)acetylene (**2m**) (68 μL, 0.30 mmol) at room temperature, and it was stirred at 80 °C for 3 h. The mixture was passed through a short column of silica gel with Et_2O as eluent. After removal of the solvent on a rotary evaporator, the residue was subjected to preparative TLC (silica gel, hexane/ethyl acetate = 50/1).

Characterization of the Products. Data for major products **3** are shown below. For *endo*-enyne **4am**, the structure was determined by NOE experiments and the data of ^{1}H NMR are shown below. The ee values of compounds **3am**−**hm** were determined by chiral HPLC analysis of their desilylated products **5** and **3′** (including a small amount of their isomer) of them by tetrabutylammonium fluoride (80−99% yields).

*Table 2, entry 1 ((S)-**3am**):* colorless oil; 89% yield (60.8 mg, **3am**/**4am** = 97/3); $[\alpha]^{20}_D$ +9 (c 0.87, $CHCl_3$) for 99% ee (S); ^{1}H NMR ($CDCl_3$) δ 1.00−1.05 (m, 21H), 1.46 (d, J = 7.0 Hz, 3H), 3.54 (q, J = 7.0 Hz, 1H), 3.78 (s, 3H), 5.27−5.29 (m, 1H), 5.39−5.41 (m, 1H), 6.82 (d, J = 8.7 Hz, 2H), 7.20 (d, J = 8.7 Hz, 2H); ^{13}C NMR ($CDCl_3$) δ 11.2, 18.6, 19.9, 45.2, 55.3, 91.6, 106.7, 113.6, 120.6, 128.4, 136.2, 137.0, 158.2; IR (neat) ν 2943, 2865, 1511, 1462, 1246, 1178, 1037, 882, 830, 676 cm^{-1}; HRMS (ESI-TOF) calcd for $C_{22}H_{34}NaOSi$ $(M + Na)^+$ 365.2271, found 365.2268. **4am**: (*E*)-**4am**, ^{1}H NMR ($CDCl_3$) δ 1.00−1.05 (m, 21H, overlapped with peaks of **3am**), 1.82 (q, J = 1.5 Hz, 3H, CH_3), 2.28 (q, J = 1.5 Hz, 3H, Ar(CH_3)C), 3.82 (s, 3H, OCH_3), 6.88 (d, J = 8.8 Hz, 2H), 7.11 (d, J = 8.8 Hz, 2H); (*Z*)-**4am**, ^{1}H NMR ($CDCl_3$) δ 1.00−1.05 (m, 21H, overlapped with peaks of **3am**), 1.99 (q, J = 1.0 Hz, 3H, Ar(CH_3)C), 2.06 (q, J = 1.0 Hz, 3H, CH_3), 3.81 (s, 3H, OCH_3), 6.85 (d, J = 8.7 Hz, 2H), 7.35 (d, J = 8.7 Hz, 2H). (***S***)-**5**. Colorless oil (**5**/**5′** = 98/2): the ee was measured by HPLC (Chiralpak AD-H column, flow 0.5 mL/min, hexane, 224 nm, t_1 = 17.9 min (R), t_2 = 18.8 min (S)); $[\alpha]^{20}_D$ −6 (c 0.31, $CHCl_3$) for 99% ee (S); ^{1}H NMR ($CDCl_3$) δ 1.46 (d, J = 7.1 Hz, 3H), 2.85 (s, 1H), 3.55 (q, J = 7.1 Hz, 1H), 3.79 (s, 3H), 5.34−5.36 (m, 1H), 5.47−5.49 (m, 1H), 6.85 (d, J = 8.8 Hz, 2H), 7.19 (d, J = 8.8 Hz, 2H); ^{13}C NMR ($CDCl_3$) δ 19.8, 44.9, 55.2, 78.0, 83.4, 113.7, 121.9, 128.4, 135.68, 135.69, 158.2; HRMS (ESI-TOF) calcd for $C_{13}H_{14}NaO$ $(M + Na)^+$ 209.0937, found 209.0942.

*Table 2, entry 2 ((S)-**3bm**):* colorless oil, 87% yield (59.6 mg, **3bm**/**4bm** = 95/5); $[\alpha]^{20}_D$ +5 (c 0.51, $CHCl_3$) for 98% ee (S); ^{1}H NMR ($CDCl_3$) δ 0.98−1.04 (m, 21H), 1.48 (d, J = 7.1 Hz, 3H), 3.55 (q, J = 7.1 Hz, 1H), 3.79 (s, 3H), 5.30−5.32 (m, 1H), 5.42−5.44 (m, 1H), 6.74 (dd, J = 8.1, 2.2 Hz, 1H), 6.83 (t, J = 2.2 Hz, 1H), 6.87−6.91 (m, 1H), 7.19 (t, J = 8.1 Hz, 1H); ^{13}C NMR ($CDCl_3$) δ 11.2, 18.6, 19.8, 46.0, 55.1, 91.7, 106.6, 111.6, 113.5, 120.0, 121.0, 129.1, 136.4, 145.6, 159.5; IR (neat) ν 2941, 2865, 1601, 1463, 1248, 1178, 1046, 882, 674 cm^{-1}; HRMS (ESI-TOF) calcd for $C_{22}H_{34}NaOSi$ $(M + Na)^+$ 365.2271, found 365.2261. (***S***)-**3bm′**: colorless oil (**3bm′**/**4bm′** = 93/7); the ee was measured by HPLC (Chiralpak AD-H column ×2, flow 0.5 mL/min, hexane, 224 nm, t_1 = 48.7 min (S), t_2 = 50.4 min (R)); $[\alpha]^{20}_D$ +0.8 (c 0.33, $CHCl_3$) for 98% ee (S); ^{1}H NMR ($CDCl_3$) δ 1.47 (d, J = 7.2 Hz, 3H), 2.87 (s, 1H), 3.57 (q, J = 7.2 Hz, 1H), 3.80 (s, 3H), 5.37−5.39 (m, 1H), 5.50−5.52 (m, 1H), 6.77 (ddd, J = 8.1, 2.4, 0.9 Hz, 1H), 6.84 (t, J = 2.4 Hz, 1H), 6.86−6.89 (m, 1H), 7.23 (t, J = 8.1 Hz, 1H); ^{13}C NMR ($CDCl_3$) δ 19.7, 45.7, 55.1, 78.1, 83.3, 111.6, 113.5, 119.9, 122.3, 129.2, 135.1, 145.3, 159.6; HRMS (ESI-TOF) calcd for $C_{13}H_{14}NaO$ $(M + Na)^+$ 209.0937, found 209.0940.

*Table 2, entry 3 ((R)-**3cm**):* colorless oil, 74% yield (50.7 mg, **3cm**/**4cm** = 85/15); $[\alpha]^{20}_D$ +23 (c 0.82, $CHCl_3$) for 96% ee (R); ^{1}H NMR ($CDCl_3$) δ 0.98−1.05 (m, 21H), 1.42 (d, J = 7.1 Hz, 3H), 3.81 (s, 3H), 4.08 (q, J = 7.1 Hz, 1H), 5.29−5.32 (m, 1H), 5.42−5.44 (m, 1H), 6.83 (dd, J = 7.8, 1.0 Hz, 1H), 6.90 (td, J = 7.8, 1.0 Hz, 1H), 7.16 (td, J = 7.8, 1.6 Hz, 1H), 7.31 (dd, J = 7.8, 1.6 Hz, 1H); ^{13}C NMR ($CDCl_3$) δ 11.3, 18.6, 19.2, 37.9, 55.4, 90.9, 107.2, 110.4, 120.4, 120.9, 127.2, 127.7, 132.5, 136.0, 156.8; IR (neat) ν 2942, 2864, 1492, 1462, 1243, 883, 750, 675 cm^{-1}; HRMS (ESI-TOF) calcd for $C_{22}H_{34}NaOSi$ $(M + Na)^+$ 365.2271, found 365.2268. (***R***)-**3cm′**: colorless oil (**3cm′**/**4cm′** = 94/6); the ee was measured by HPLC (Chiralcel OD-H column, flow 0.5 mL/min, hexane, 224 nm, t_1 = 24.8 min (R), t_2 = 29.9 min (S)); $[\alpha]^{20}_D$ +4 (c 0.47, $CHCl_3$) for 96% ee (R). ^{1}H NMR ($CDCl_3$) δ 1.42 (d, J = 7.2 Hz, 3H), 2.84 (s, 1H), 3.82 (s, 3H), 4.07 (q, J = 7.2 Hz, 1H), 5.33−5.36 (m, 1H), 5.49−5.51 (m, 1H), 6.86 (dd, J = 7.8, 1.0 Hz, 1H), 6.94 (td, J = 7.8, 1.0 Hz, 1H), 7.21 (td, J = 7.8, 1.7 Hz, 1H), 7.27 (dd, J = 7.8, 1.7 Hz, 1H); ^{13}C NMR ($CDCl_3$) δ 19.0, 37.8, 55.5, 77.4, 83.9, 110.6, 120.5, 122.2, 127.4, 127.5, 132.0, 134.7, 156.9; HRMS (ESI-TOF) calcd for $C_{13}H_{14}NaO$ $(M + Na)^+$ 209.0937, found 209.0939.

*Table 2, entry 4 ((S)-**3dm**):* colorless oil, 82% yield (53.9 mg, **3dm**/**4dm** = 96/4); $[\alpha]^{20}_D$ +9 (c 0.81, $CHCl_3$) for 98% ee (S); ^{1}H NMR ($CDCl_3$) δ 0.98−1.02 (m, 21H), 1.46 (d, J = 7.1 Hz, 3H), 3.57 (q, J = 7.1 Hz, 1H), 5.30−5.32 (m, 1H), 5.41−5.44 (m, 1H), 6.92−6.99 (m, 2H), 7.21−7.26 (m, 2H); ^{13}C NMR ($CDCl_3$) δ 11.2, 18.5, 19.9, 45.3, 92.0, 106.3, 114.8 (d, J_{F-C} = 21 Hz), 120.9, 128.9 (d, J_{F-C} = 8 Hz), 136.4, 139.7 (d, J_{F-C} = 3 Hz), 161.6 (d, J_{F-C} = 244 Hz); IR (neat) ν 2943, 2865, 1509, 1226, 882, 836, 675 cm^{-1}; HRMS (ESI-TOF) calcd for $C_{21}H_{31}FNaSi$ $(M + Na)^+$ 353.2071, found 353.2074. (***S***)-**3dm′**: colorless oil (**3dm′**/**4dm′** = 97/3); the ee was measured by HPLC (Chiralcel OJ-H column, flow 0.5 mL/min, hexane, 224 nm, t_1 = 26.3 min (R), t_2 = 27.6 min (S)); $[\alpha]^{20}_D$ +3 (c 0.47, $CHCl_3$) for 98% ee (S). ^{1}H NMR ($CDCl_3$) δ 1.46 (d, J = 7.2 Hz, 3H), 2.86 (s, 1H), 3.58 (q, J = 7.2 Hz, 1H), 5.36−5.38 (m, 1H), 5.49−5.51 (m, 1H), 6.96−7.02 (m, 2H), 7.20−7.26 (m, 2H); ^{13}C NMR ($CDCl_3$) δ 19.8, 45.0, 78.3, 83.1, 115.0 (d, J_{F-C} = 21 Hz), 122.2, 128.9 (d, J_{F-C} = 8 Hz), 135.2, 139.2 (d, J_{F-C} = 4 Hz), 161.6 (d, J_{F-C} = 244 Hz); HRMS (APCI-TOF) calcd for $C_{12}H_{11}F$ $(M)^+$ 174.0839, found 174.0839.

*Table 2, entry 5 ((S)-**3em**):* colorless oil, 81% yield (56.4 mg, **3em**/**4em** = 95/5); $[\alpha]^{20}_D$ +8 (c 0.66, $CHCl_3$) for >99.5% ee (S); ^{1}H NMR ($CDCl_3$) δ 0.99−1.03 (m, 21H), 1.46 (d, J = 7.1 Hz, 3H), 3.56 (q, J = 7.1 Hz, 1H), 5.31−5.33 (m, 1H), 5.42−5.44 (m, 1H), 7.21 (d, J = 8.7 Hz, 2H), 7.24 (d, J = 8.7 Hz, 2H); ^{13}C NMR ($CDCl_3$) δ 11.2, 18.5, 19.7, 45.4, 92.1, 106.2, 121.1, 128.3, 128.9, 132.1, 136.1, 142.5; IR (neat) ν 2942, 2865, 1493, 1462, 1092, 1014, 881, 830, 674 cm^{-1}; HRMS (ESI-TOF) calcd for $C_{21}H_{31}ClNaSi$ $(M + Na)^+$ 369.1776, found 369.1780. (***S***)-**3em′**: colorless oil (**3em′**/**4em′** = 94/6); the ee was measured by HPLC (Chiralcel OD-H column, flow 0.5 mL/min, hexane, 224 nm, t_1 = 13.3 min (S), t_2 = 14.2 min (R)); $[\alpha]^{20}_D$ +1 (c 0.60, $CHCl_3$) for >99.5% ee (S). ^{1}H NMR ($CDCl_3$) δ 1.45 (d, J = 7.1 Hz, 3H), 2.85 (s, 1H), 3.57 (q, J = 7.1 Hz, 1H), 5.37−5.39 (m, 1H), 5.50−5.52 (m, 1H), 7.21 (d, J = 8.5 Hz, 2H), 7.28 (d, J = 8.5 Hz, 2H); ^{13}C NMR ($CDCl_3$) δ 19.6, 45.1, 78.4, 83.0, 122.4, 128.4, 128.8, 132.3, 134.8, 142.1; HRMS (APCI-TOF) calcd for $C_{12}H_{11}Cl$ $(M)^+$ 190.0544, found 190.0543.

*Table 2, entry 6 ((S)-**3fm**):* colorless oil, 94% yield (58.8 mg, **3fm**/**4fm** = 98/2); $[\alpha]^{20}_D$ −0.9 (c 0.54, $CHCl_3$) for 98% ee (S); ^{1}H NMR ($CDCl_3$) δ 0.99−1.04 (m, 21H), 1.49 (d, J = 7.1 Hz, 3H), 3.58 (q, J = 7.1 Hz, 1H), 5.30−5.32 (m, 1H), 5.42−5.44 (m, 1H), 7.16−7.21 (m, 1H), 7.24−7.31 (m, 4H); ^{13}C NMR ($CDCl_3$) δ 11.3, 18.6, 19.8, 46.0, 91.7, 106.6, 120.9, 126.3, 127.5, 128.2, 136.6, 144.0; IR (neat) ν 2942, 2865, 1462, 997, 881, 698, 675 cm^{-1}; HRMS (ESI-TOF) calcd for $C_{21}H_{32}NaSi$ $(M + Na)^+$ 335.2165, found 335.2159. (***S***)-**3fm′**: colorless oil (**3fm′**/**4fm′** = 98/2); the ee was measured by HPLC (Chiralcel OJ-H column, flow 0.5 mL/min, hexane, 224 nm, t_1 = 44.9 min (S), t_2 = 49.2 min (R)); $[\alpha]^{20}_D$ −4 (c 0.75, $CHCl_3$) for 98% ee (S); ^{1}H NMR ($CDCl_3$) δ 1.48 (d, J = 7.1 Hz, 3H), 2.86 (s, 1H), 3.60 (q, J = 7.1 Hz, 1H), 5.36−5.39 (m, 1H), 5.49−5.52 (m, 1H), 7.20−7.25 (m, 1H),

dx.doi.org/10.1021/jo401604n | J. Org. Chem. 2013, 78, 8986−8993

7.25−7.34 (m, 4H); ^{13}C NMR ($CDCl_3$) δ 19.7, 45.7, 78.1, 83.3, 122.2, 126.5, 127.5, 128.3, 135.3, 143.6; HRMS (APCI-TOF) calcd for $C_{12}H_{13}$ $(M + H)^+$ 157.1012, found 157.1012.

*Table 2, entry 7 ((R)-**3gm**):* colorless oil, 88% yield (63.6 mg, **3gm**/**4gm** = 89/11); $[\alpha]^{20}_D$ +28 (*c* 0.92, $CHCl_3$) for 99% ee (*R*); ^{1}H NMR ($CDCl_3$) δ 0.95−1.02 (m, 21H), 1.65 (d, *J* = 7.0 Hz, 3H), 4.41 (q, *J* = 7.0 Hz, 1H), 5.27−5.30 (m, 1H), 5.47−5.50 (m, 1H), 7.38−7.54 (m, 4H), 7.72 (d, *J* = 8.2 Hz, 1H), 7.84 (d, *J* = 8.0 Hz, 1H), 8.11 (d, *J* = 8.4 Hz, 1H); ^{13}C NMR ($CDCl_3$) δ 11.2, 18.5, 20.1, 41.1, 91.5, 107.1, 121.5, 123.5, 124.4, 125.2, 125.4, 125.7, 127.0, 128.8, 131.7, 133.9, 136.4, 139.7; IR (neat) ν 2941, 2863, 1462, 881, 775, 664 cm^{-1}; HRMS (ESI-TOF) calcd for $C_{25}H_{34}NaSi$ $(M + Na)^+$ 385.2322, found 385.2324. (***R***)-**3gm**′: colorless oil (**3gm**′/**4gm**′ = 99/1); the ee was measured by HPLC (Chiralcel OJ-H column, flow 0.5 mL/min, hexane, 224 nm, t_1 = 45.1 min (*R*), t_2 = 51.1 min (*S*)); $[\alpha]^{20}_D$ +7 (*c* 0.30, $CHCl_3$) for 99% ee (*R*); ^{1}H NMR ($CDCl_3$) δ 1.63 (d, *J* = 7.1 Hz, 3H), 2.86 (s, 1H), 4.41 (q, *J* = 7.1 Hz, 1H), 5.30 (s, 1H), 5.56 (s, 1H), 7.42−7.54 (m, 4H), 7.75 (d, *J* = 7.9 Hz, 1H), 7.86 (d, *J* = 8.1 Hz, 1H), 8.08 (d, *J* = 8.5 Hz, 1H); ^{13}C NMR ($CDCl_3$) δ 19.9, 40.8, 77.8, 83.9, 122.9, 123.5, 124.2, 125.35, 125.42, 125.9, 127.3, 128.9, 131.6, 133.9, 135.1, 139.2; HRMS (ESI-TOF) calcd for $C_{16}H_{14}Na$ $(M + Na)^+$ 229.0988, found 229.0995.

*Table 2, entry 8 ((S)-**3hm**):* colorless oil, 77% yield (55.1 mg, **3hm**/**4hm** = 89/11); $[\alpha]^{20}_D$ +25 (*c* 0.72, $CHCl_3$) for 97% ee (*S*); ^{1}H NMR ($CDCl_3$) δ 0.89 (t, *J* = 7.4 Hz, 3H), 1.03−1.07 (m, 21H), 1.70−1.83 (m, 1H), 1.94−2.07 (m, 1H), 3.19 (t, *J* = 7.6 Hz, 1H), 3.78 (s, 3H), 5.30−5.34 (m, 1H), 5.39−5.41 (m, 1H), 6.81 (d, *J* = 8.8 Hz, 2H), 7.22 (d, *J* = 8.8 Hz, 2H); ^{13}C NMR ($CDCl_3$) δ 11.3, 12.4, 18.6, 26.6, 53.4, 55.2, 91.8, 106.4, 113.6, 121.7, 128.7, 135.4, 135.8, 158.2; IR (neat) ν 2942, 2864, 1510, 1463, 1248, 1178, 1038, 881, 825, 675 cm^{-1}; HRMS (ESI-TOF) calcd for $C_{23}H_{36}NaOSi$ $(M + Na)^+$ 379.2428, found 379.2421. (***S***)-**3hm**′: colorless oil (**3hm**′/**4hm**′ = 98/2); the ee was measured by HPLC (Chiralpak AD-H column, flow 0.3 mL/min, hexane, 224 nm, t_1 = 27.8 min (*R*), t_2 = 29.4 min (*S*)); $[\alpha]^{20}_D$ −2 (*c* 0.66, $CHCl_3$) for 97% ee (*S*); ^{1}H NMR ($CDCl_3$) δ 0.89 (t, *J* = 7.3 Hz, 3H), 1.73−1.83 (m, 1H), 1.93−2.03 (m, 1H), 2.87 (s, 1H), 3.21 (t, *J* = 7.7 Hz, 1H), 3.79 (s, 3H), 5.37−5.40 (m, 1H), 5.47−5.48 (m, 1H), 6.85 (d, *J* = 8.8 Hz, 2H), 7.20 (d, *J* = 8.8 Hz, 2H); ^{13}C NMR ($CDCl_3$) δ 12.3, 26.3, 53.1, 55.2, 78.1, 83.1, 113.7, 122.7, 128.7, 134.5, 134.7, 158.2; HRMS (ESI-TOF) calcd for $C_{14}H_{16}NaO$ $(M + Na)^+$ 223.1093, found 223.1094.

*Table 2, entry 9 ((S)-**3im**):* colorless oil, 81% yield (62.6 mg, **3im**/**4im** = 98/2). the ee was measured by HPLC (Chiralcel OD-H column, flow 0.5 mL/min, hexane, 224 nm, t_1 = 15.2 min (*R*), t_2 = 17.8 min (*S*)); $[\alpha]^{20}_D$ +18 (*c* 0.78, $CHCl_3$) for 96% ee (*S*); ^{1}H NMR ($CDCl_3$) δ 0.88 (t, *J* = 7.2 Hz, 3H), 0.97−1.15 (m, 21H), 1.15−1.38 (m, 4H), 1.67−1.79 (m, 1H), 1.95−2.05 (m, 1H), 3.28 (t, *J* = 7.6 Hz, 1H), 3.78 (s, 3H), 5.29−5.32 (m, 1H), 5.37−5.40 (m, 1H), 6.81 (d, *J* = 8.6 Hz, 2H), 7.22 (d, *J* = 8.6 Hz, 2H); ^{13}C NMR ($CDCl_3$) δ 11.3, 14.0, 18.6, 22.6, 29.9, 33.4, 51.5, 55.2, 91.8, 106.4, 113.6, 121.5, 128.6, 135.6, 136.0, 158.1; IR (neat) ν 2942, 2865, 1511, 1463, 1247, 1177, 1036, 882, 830, 676 cm^{-1}; HRMS (ESI-TOF) calcd for $C_{25}H_{40}NaOSi$ $(M + Na)^+$ 407.2741, found 407.2742.

*Table 2, entry 10 ((S)-**3jm**):* colorless oil, 70% yield (47.8 mg, **3jm**/**4jm** = 96/4); the ee was measured by HPLC (Chiralcel OD-H column, flow 0.5 mL/min, hexane, 224 nm, t_1 = 16.2 min (*R*), t_2 = 17.4 min (*S*)); $[\alpha]^{20}_D$ +21 (*c* 0.51, $CHCl_3$) for 96% ee (*S*); ^{1}H NMR ($CDCl_3$) δ 0.97−1.10 (m, 21H), 3.38 (s, 3H), 3.68−3.77 (m, 2H), 3.88−3.96 (m, 1H), 5.39−5.41 (m, 1H), 5.52−5.54 (m, 1H), 7.22 (t, *J* = 7.4 Hz, 1H), 7.28 (t, *J* = 7.4 Hz, 2H), 7.34 (d, *J* = 7.4 Hz, 2H); ^{13}C NMR ($CDCl_3$) δ 11.3, 18.6, 52.1, 58.9, 74.6, 92.4, 105.9, 123.5, 126.9, 127.9, 128.3, 132.7, 140.1; IR (neat) ν 2943, 2865, 1512, 1463, 1248, 997, 882, 699, 676 cm^{-1}; HRMS (ESI-TOF) calcd for $C_{22}H_{34}NaOSi$ $(M + Na)^+$ 365.2271, found 365.2269.

*Table 2, entry 11 ((S)-**3an**):* colorless oil, 70% yield (65.5 mg, **3an**/**4an** = 95/5); the ee was measured by HPLC (Chiralcel OD-H column, flow 0.5 mL/min, hexane/2-propanol = 500/1, 224 nm, t_1 = 24.4 min (*R*), t_2 = 25.3 min (*S*)); $[\alpha]^{20}_D$ +1 (*c* 0.44, $CHCl_3$) for 92% ee (*S*); ^{1}H NMR ($CDCl_3$) δ 1.49 (d, *J* = 7.0 Hz, 3H), 3.62 (q, *J* = 7.0 Hz, 1H), 3.79 (s, 3H), 5.42−5.44 (m, 1H), 5.55−5.57 (m, 1H), 6.81 (d, *J* = 8.8 Hz, 2H), 7.19 (d, *J* = 8.8 Hz, 2H), 7.34 (t, *J* = 7.5 Hz, 6H), 7.40 (tt, *J* = 7.5, 1.5 Hz, 3H), 7.55 (dd, *J* = 7.5, 1.5 Hz, 6H); ^{13}C NMR ($CDCl_3$) δ 19.9, 45.1, 55.2, 90.0, 109.5, 113.7, 122.0, 127.9, 128.5, 129.8, 133.6, 135.5, 135.8, 136.5, 158.2; IR (neat) ν 2943, 2867, 1510, 1428, 1246, 1178, 1112, 1032, 830, 696 cm^{-1}; HRMS (ESI-TOF) calcd for $C_{31}H_{28}NaOSi$ $(M + Na)^+$ 467.1802, found 467.1803.

*Equation 2 ((S)-**3km**):* colorless oil, 88% yield (56.0 mg, **3km**/**4km** = 99/1); the ee obtained with (R,S_p)-Josiphos was determined by chiral HPLC analysis of (*S*)-1-chloro-4-(4-cyclohexyl-3-methylene-pent-1-yn-1-yl)benzene (**3km**′) derived from **3km**; $[\alpha]^{20}_D$ +4 (*c* 0.70, $CHCl_3$) for 58% ee (*S*); ^{1}H NMR ($CDCl_3$) δ 0.80−0.92 (m, 2H), 0.98−1.28 (m, 27H), 1.35−1.45 (m, 1H), 1.58−1.85 (m, 5H), 1.95 (quint, *J* = 7.2 Hz, 1H), 5.18 (d, *J* = 1.8 Hz, 1H), 5.32 (d, *J* = 1.8 Hz, 1H); ^{13}C NMR ($CDCl_3$) δ 11.3, 17.1, 18.6, 26.5, 26.58, 26.61, 30.1, 31.6, 41.1, 47.1, 90.9, 106.5, 120.9, 137.0; IR (neat) ν 2922, 2864, 1462, 996, 882, 675 cm^{-1}; HRMS (APCI-TOF) calcd for $C_{21}H_{38}Si$ $(M)^+$ 318.2737, found 318.2736. (***S***)-**3km**′. To a solution of **3km** (42.1 mg, 0.132 mmol, **3km**/**4km** = >99/1) in THF (1.3 mL) were added MeOH (11 μL, 0.26 mmol) and tetrabutylammonium fluoride (1.0 M solution in THF, 0.40 mL, 0.40 mmol) at room temperature, and the mixture was stirred for 2 h. To the mixture were added 1-chloro-4-iodobenzene (37.3 mg, 0.158 mmol), $Pd(PPh_3)_4$ (7.6 mg, 0.0066 mmol), CuI (1.3 mg, 0.0066 mmol), and triethylamine (37 μL, 0.26 mmol) at room temperature, and the mixture was stirred for 10 h. The mixture was passed through a short column of silica gel with Et_2O as eluent. After evaporation of the solvent, the residue was subjected to preparative TLC (silica gel, hexane) to give **3km**′ as a colorless oil (30.4 mg, 0.111 mmol, 84% yield): the ee was measured by HPLC (Chiralcel OJ-H column × 2, flow 0.5 mL/min, hexane, 224 nm, t_1 = 19.0 min (*R*), t_2 = 20.3 min (*S*)); $[\alpha]^{20}_D$ +12 (*c* 0.59, $CHCl_3$) for 58% ee (*S*); ^{1}H NMR ($CDCl_3$) δ 0.85−0.98 (m, 2H), 1.05−1.30 (m, 6H), 1.33−1.45 (m, 1H), 1.60−1.87 (m, 5H), 2.06 (quint, *J* = 7.3 Hz, 1H), 5.26 (d, *J* = 1.9 Hz, 1H), 5.40 (d, *J* = 1.9 Hz, 1H), 7.29 (d, *J* = 8.4 Hz, 2H), 7.36 (d, *J* = 8.4 Hz, 2H); ^{13}C NMR ($CDCl_3$) δ 17.1, 26.47, 26.54, 26.6, 30.1, 31.6, 41.1, 47.0, 88.8, 89.9, 121.1, 122.1, 128.6, 132.8, 134.0, 136.3; HRMS (APCI-TOF) calcd for $C_{18}H_{22}Cl$ $(M + H)^+$ 273.1405, found 273.1406.

*Equation 1 (**3lm**):* colorless oil, 93% yield (69.2 mg, **3lm**/**4lm** = 95/5); ^{1}H NMR ($CDCl_3$) δ 0.35 (s, 3H), 0.36 (s, 3H), 1.00−1.13 (m, 21H), 1.15 (d, *J* = 7.4 Hz, 3H), 1.98 (q, *J* = 7.4 Hz, 1H), 4.98 (s, 1H), 5.29 (s, 1H), 7.30−7.38 (m, 3H), 7.47−7.55 (m, 2H); ^{13}C NMR ($CDCl_3$) δ −5.3, −3.8, 11.4, 14.3, 18.7, 30.3, 90.6, 108.2, 119.4, 127.6, 129.0, 134.0, 134.8, 137.8; IR (neat) ν 2944, 2865, 1252, 1119, 1061, 882, 830, 699, 675 cm^{-1}; HRMS (APCI-TOF) calcd for $C_{23}H_{39}Si_2$ $(M + H)^+$ 371.2585, found 371.2589.

Procedure for Scheme 2a. To a solution of a mixture of **3am** and **4am** (115 mg, 0.337 mmol, **3am**/**4am** = 97/3) in THF (1.7 mL) were added MeOH (27 μL, 0.67 mmol) and tetrabutylammonium fluoride (1.0 M solution in THF, 1.0 mL, 1.0 mmol) at room temperature. The mixture was stirred for 1.5 h, and then it was passed through a short column of silica gel with Et_2O as eluent. After evaporation of the solvent, the residue was subjected to preparative TLC (silica gel, hexane/ethyl acetate = 50/1) to give a mixture of **5** and **5**′ as a colorless oil (52.6 mg, 0.282 mmol, 84% yield, **5**/**5**′ = 97/3, 99% ee of **5**).

Procedure for Scheme 2b.[27] To a mixture of *N*-mesyl-2-iodoaniline (CAS no. 116547−92−3)[39] (29.7 mg, 0.100 mmol), CuI (3.8 mg, 0.020 mmol), $Pd(PPh_3)_4$ (2.3 mg, 0.0020 mmol), and DBU (75 μL, 0.50 mmol) in EtOH (0.4 mL) was added a mixture of **5** and **5**′ (22.4 mg, 0.120 mmol, **5**/**5**′ = 97/3, 99% ee of **5**) at room temperature. After the mixture was stirred under reflux for 2 h, water was added, and the mixture was extracted with ethyl acetate. After the organic extracts were concentrated on a rotary evaporator, the residue was subjected to preparative TLC (hexane/ethyl acetate = 5/1) to give a mixture of **6** and **6**′ as a yellow oil (31.8 mg, 0.0895 mmol, 89% yield, **6**/**6**′ = 98/2). (***S***)-**6**: the ee was measured by HPLC (Chiralpak AD-H column, flow 0.5 mL/min, hexane/2-propanol = 98/2, 224 nm, t_1 = 24.9 min (*R*), t_2 = 29.8 min (*S*)); $[\alpha]^{20}_D$ −6 (*c* 1.24, $CHCl_3$) for 99% ee (*S*); ^{1}H NMR ($CDCl_3$) δ 1.44 (d, *J* = 7.1 Hz, 3H), 2.72 (s, 3H), 3.76 (s, 3H), 4.08 (q, *J* = 7.1 Hz, 1H), 5.29−5.31 (m, 1H), 5.31−5.33

dx.doi.org/10.1021/jo401604n | *J. Org. Chem.* 2013, 78, 8986−8993

(m, 1H), 6.32 (s, 1H), 6.78 (d, J = 8.7 Hz, 2H), 7.15 (d, J = 8.7 Hz, 2H), 7.26 (td, J = 7.3, 0.8 Hz, 1H), 7.31 (td, J = 8.0, 1.3 Hz, 1H), 7.44 (d, J = 7.3 Hz, 1H), 8.03 (dd, J = 8.0, 0.8 Hz, 1H); ^{13}C NMR ($CDCl_3$) δ 20.5, 38.8, 44.5, 55.2, 112.5, 113.6, 115.3, 116.0, 121.0, 124.3, 124.9, 128.8, 130.4, 136.2, 137.6, 142.7, 147.6, 158.0; IR (neat) ν 1509, 1363, 1245, 1169, 1032, 957, 830, 769, 747 cm^{-1}; HRMS (ESI-TOF) calcd for $C_{20}H_{21}NNaO_3S$ $(M + Na)^+$ 378.1134, found 378.1133.

Procedure for Scheme 2c.[28] To a solution of $Pd(PPh_3)_4$ (5.8 mg, 0.0050 mmol) in THF (0.4 mL) were added a mixture of **5** and **5′** (18.6 mg, 0.100 mmol, **5**/**5′** = 97/3, 99% ee of **5**) and 1,4-diphenylbutadiyne (20.2 mg, 0.100 mmol) at room temperature. The mixture was stirred under reflux for 24 h, and then it was passed through a short column of silica gel with Et_2O as eluent. After removal of the solvent on a rotary evaporator, the residue was subjected to preparative TLC (silica gel, hexane/ethyl acetate = 40/1) to give compound **7** as a yellow oil (35.5 mg, 0.914 mmol, 91% yield). (***S***)-**7**: the ee was measured by HPLC (Chiralcel OD-H column, flow 0.5 mL/min, hexane/2-propanol = 100/1, 224 nm, t_1 = 21.8 min (*S*), t_2 = 24.2 min (*R*)); $[\alpha]^{20}_D$ +9 (c 1.42, $CHCl_3$) for 99% ee (*S*); ^{1}H NMR ($CDCl_3$) δ 1.65 (d, J = 7.2 Hz, 3H), 3.79 (s, 3H), 4.16 (q, J = 7.2 Hz, 1H), 6.85 (d, J = 8.6 Hz, 2H), 7.17 (d, J = 8.6 Hz, 2H), 7.14−7.20 (m, 1H), 7.23−7.34 (m, 6H), 7.38 (t, J = 7.8 Hz, 1H), 7.44 (t, J = 7.8 Hz, 2H), 7.55 (d, J = 8.0 Hz, 1H), 7.64 (d, J = 7.8 Hz, 2H); ^{13}C NMR ($CDCl_3$) δ 21.9, 43.9, 55.2, 89.5, 91.7, 113.8, 119.2, 123.6, 126.3, 127.4, 127.8, 127.9, 128.2, 128.5, 128.7, 129.4, 131.3, 132.9, 137.9, 140.7, 143.9, 147.4, 158.0; IR (neat) ν 1509, 1244, 1176, 1033, 829, 754, 690 cm^{-1}; HRMS (ESI-TOF) calcd for $C_{29}H_{24}NaO$ $(M + Na)^+$ 411.1719, found 411.1714.

Procedure for Scheme 2d.[29b] To a mixture of $CuSO_4{\cdot}5H_2O$ (2.5 mg, 0.010 mmol), Na-(+)-ascorbate (4.0 mg, 0.020 mmol), and benzoic acid (12.2 mg, 0.10 mmol) in *t*-BuOH (0.2 mL) and H_2O (0.4 mL) were added a mixture of **5** and **5′** (18.6 mg, 0.100 mmol, **5**/**5′** = 97/3, 99% ee of **5**) and 1-azido-4-chlorobenzene (CAS no. 3296-05-7)[41] (16.9 mg, 0.110 mmol) at room temperature. After being stirred for 18 h, the mixture was extracted with dichloromethane and the combined organic extracts were concentrated on a rotary evaporator. The residue was subjected to preparative TLC (silica gel, hexane/dichloromethane = 1/1) to give a mixture of **8** and **8′** as a white solid (31.3 mg, 0.0921 mmol, 92% yield, **8**/**8′** = 99/1). (***S***)-**8**: the ee was measured by HPLC (Chiralpak IB column, flow 0.5 mL/min, hexane/chloroform/ethanol = 90/30/1, 254 nm, t_1 = 11.3 min (*R*), t_2 = 12.0 min (*S*)); $[\alpha]^{20}_D$ +2 (c 1.57, $CHCl_3$) for 99% ee (*S*); mp 156−158 °C; ^{1}H NMR ($CDCl_3$) δ 1.52 (d, J = 6.9 Hz, 3H), 3.77 (s, 3H), 4.02 (q, J = 6.9 Hz, 1H), 5.35−5.38 (m, 1H), 6.07−6.10 (m, 1H), 6.83 (d, J = 8.7 Hz, 2H), 7.23 (d, J = 8.7 Hz, 2H), 7.44 (d, J = 9.0 Hz, 2H), 7.50 (s, 1H), 7.56 (d, J = 9.0 Hz, 2H); ^{13}C NMR ($CDCl_3$) δ 21.3, 42.4, 55.2, 113.0, 114.0, 118.0, 121.5, 128.4, 129.8, 134.2, 135.5, 136.6, 141.3, 149.0, 158.1; IR (thin film) ν 1499, 1246, 1176, 1034, 913, 823 cm^{-1}; HRMS (ESI-TOF) calcd for $C_{19}H_{18}ClN_3NaO$ $(M + Na)^+$ 362.1031, found 362.1030. Colorless crystals of **8** suitable for X-ray crystallographic analysis were obtained by recrystallization from hexane/ethyl acetate. The crystal structure has been deposited at the Cambridge Crystallographic Centre (deposition number: CCDC 922867). The data can be obtained free of charge via www.ccdc.cam.ac.uk/data_request/cif.

Procedure for Equation 3. A mixture of $Co(OAc)_2$ (1.8 mg, 0.010 mmol), (R,S_p)-**L4** (8.8 mg, 0.010 mmol), and Zn powder (1.3 mg, 0.020 mmol) in DMSO (0.3 mL) was stirred at 80 °C for 15 min under N_2. To the mixture were added allene **1a** (32.0 mg, 0.200 mmol) and deuterated alkyne **2m**-***d*** (55.0 mg, 0.300 mmol, 98% D) at room temperature, and it was stirred at 80 °C for 3 h. The mixture was passed through a short column of silica gel with Et_2O as eluent. After removal of the solvent on a rotary evaporator, the residue was subjected to preparative TLC (silica gel, hexane/ethyl acetate = 50/1) to give a mixture of **3am**-***d*** and **4am**-***d*** as a colorless oil (61.1 mg, 0.178 mmol, 89% yield, **3am**-***d***/**4am**-***d*** = 93/7). The deuterium contents were determined by ^{1}H NMR (89% D for **3am**-***d***, 81% D for (*Z*)-**4am** and 89% D for (*E*)-**4am**-***d***). Compound **3am**-***d***: ^{1}H NMR ($CDCl_3$) δ 0.98−1.05 (m, 21H), 1.46 (s, 3H), 3.78 (s, 3H), 5.28 (d, J = 1.7 Hz, 1H), 5.40 (d, J = 1.7 Hz, 1H), 6.82 (d, J = 8.6 Hz, 2H), 7.20 (d, J = 8.6 Hz, 2H).

Procedure for Equation 4. A mixture of $CoCl(PPh_3)_3$ (8.8 mg, 0.010 mmol), dppe (4.0 mg, 0.010 mmol), and KOAc (2.0 mg, 0.020 mmol) in DMSO (0.3 mL) was stirred at room temperature for 15 min. To the mixture were added allene **1f** (26.0 mg, 0.200 mmol) and alkyne **2m** (67 μL, 0.30 mmol), and it was stirred at 80 °C for 30 min. The mixture was passed through a short column of silica gel with Et_2O as eluent and concentrated on a rotary evaporator. The yields of **3fm** and **4fm** were determined by ^{1}H NMR using nitromethane as an internal standard.

Procedure for Equation 5. A mixture of $Co(OAc)_2$ (3.5 mg, 0.020 mmol), dppe (8.0 mg, 0.020 mmol), and Zn powder (2.6 mg, 0.040 mmol) in DMSO (0.3 mL) was stirred at 80 °C for 15 min under N_2. To the mixture were added allene **1f** (13.0 mg, 0.100 mmol), alkyne **2m** (36.5 mg, 0.200 mmol), and acetic acid-***d*** (12.2 mg, 0.200 mmol, 99.9% D) at room temperature, and it was stirred at 80 °C for 30 min. The mixture was passed through a short column of silica gel with Et_2O as eluent and concentrated on a rotary evaporator. The yield of **3fm** was determined by ^{1}H NMR using nitromethane as an internal standard. The deuterium content of **3fm** was determined by ^{1}H NMR (6% D) after isolation of the mixture of **3fm** and **4fm** by preparative TLC (silica gel, hexane).

Procedures for Equation 6. A mixture of $Co(OAc)_2$ (3.5 mg, 0.020 mmol), dppe (8.0 mg, 0.020 mmol), and Zn powder (2.6 mg, 0.040 mmol) in DMSO (0.3 mL) was stirred at 80 °C for 15 min under N_2. To the mixture were added allene **1f** (13.0 mg, 0.100 mmol), deuterated alkyne **2m**-***d*** (36.7 mg, 0.200 mmol, 98% D), and acetic acid (11.8 mg, 0.200 mmol) at room temperature, and it was stirred at 80 °C for 30 min. The mixture was passed through a short column of silica gel with Et_2O as eluent and concentrated on a rotary evaporator. The yield of **3fm** was determined by ^{1}H NMR using nitromethane as an internal standard. The deuterium content of **3fm** was determined by ^{1}H NMR (79% D) after isolation of the mixture of **3fm** and **4fm** by preparative TLC (silica gel, hexane).

Procedure for Equation 7. A mixture of $Co(OAc)_2$ (1.8 mg, 0.010 mmol), dppe (4.0 mg, 0.010 mmol), and Zn powder (1.3 mg, 0.020 mmol) in DMSO (0.3 mL) was stirred at 80 °C for 15 min under N_2. To the mixture were added allene **1f** (26.0 mg, 0.200 mmol), alkyne **2m** (36.5 mg, 0.200 mmol), and deuterated alkyne **2m**-***d*** (36.7 mg, 0.200 mmol, 98% D) at room temperature, and it was stirred at 80 °C for 10 min. The mixture was passed through a short column of silica gel with Et_2O as eluent and concentrated on a rotary evaporator. The yield of **3fm** was determined by ^{1}H NMR using nitromethane as an internal standard. The deuterium content of **3fm** was determined by ^{1}H NMR (29% D) after isolation of the mixture of **3fm** and **4fm** by preparative TLC (silica gel, hexane).

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

^{1}H and ^{13}C NMR spectra of all new compounds, chiral HPLC charts, and crystallographic data (CIF). This material is available free of charge via the Internet at http://pubs.acs.org.

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Notes

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

This work has been supported by a Grant-in-Aid for Scientific Research from the MEXT, Japan. T.S. thanks the JSPS for a research Fellowship for Young Scientists.

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