JOC Article

BINAP/AgOTf/KF/18-Crown-6 as New Bifunctional Catalysts for Asymmetric Sakurai−Hosomi Allylation and Mukaiyama Aldol Reaction

Manabu Wadamoto,[†,§] Nobuko Ozasa,[†] Akira Yanagisawa,[‡] and Hisashi Yamamoto*[,†,§]

Graduate School of Engineering, Nagoya University, SORST, Japan Science and Technology Corporation (JST), Chikusa, Nagoya 464-8603, Japan, and Department of Chemistry, Faculty of Science, Chiba University, Inage, Chiba 263-8522, Japan

yamamoto@uchicago.edu

Received November 11, 2002

A catalytic amount of KF·18-crown-6 complex is effective as a soluble fluoride source to activate an asymmetric Sakurai−Hosomi allylation with BINAP and silver(I) triflate catalyst. The allylation of a variety of aromatic, α,β-unsaturated and aliphatic aldehydes with allylic trimethoxysilane resulted in high yields and remarkable enantioselectivities. In addition, the asymmetric Mukaiyama-type aldol reaction is achieved by using trimethoxysilyl enol ethers in the presence of the same catalysts. High anti selectivity is obtained from *E*-silyl enol ether, while *Z*-silyl enol ether gives syn selectivity.

Introduction

Enantioselective allylation of carbonyl compounds[1,2] and aldol synthesis[1c,j,3,4] are powerful and important processes based on nucleophilic addition to carbonyl derivatives giving optically active homoallylic alcohols and β-hydroxy carbonyl compounds, respectively. These functional groups are often seen in natural products or biologically active molecules and therefore efficient and enantioselective methods to construct such functional groups are strongly desired. In recent years, numerous chiral Lewis acid catalysts have been developed and applied for these processes.

We have previously shown that the BINAP·AgOTf complex is an excellent chiral catalyst for asymmetric allylation of aldehydes with allyltributyltin[5a,b,e,f] as well as the asymmetric aldol reaction of tributyltin enolates,[5c] and can provide the corresponding optically active products with high diastereo- and enantioselectivities (Figure 1). These reactions, however, have the disadvantage of requiring the use of toxic trialkyltin compounds, and we therefore reported an alternative BINAP·Ag(I)-catalyzed

† Graduate School of Engineering, Nagoya University, SORST.
‡ Department of Chemistry, Faculty of Science, Chiba University.
§ Current address: Department of Chemistry, University of Chicago, 5735 South Ellis Avenue, Chicago, IL 60637.

(1) Reviews for catalytic asymmetric allylations: (a) Roush, W. R. In *Comprehensive Organic Synthesis*; Trost, B. M., Fleming, I., Heathcock, C. H., Eds.; Pergamon Press: Oxford, UK, 1991; Vol. 2, p 1. (b) Yamamoto, Y.; Asao, N. *Chem. Rev.* **1993**, *93*, 2207. (c) Bach, T. *Angew. Chem., Int. Ed. Engl.* **1994**, *33*, 417. (d) Hoppe, D. In *Houben-Weyl*: *Methods of Organic Chemistry*; Helmchen, G., Hoffmann, R. W., Mulzer, J., Schaumann, E., Eds.; Georg Thieme Verlag: Stuttgart, Germany, 1995; Vol. E21, p 1357. (e) Hoveyda, A. H.; Morken, J. P. *Angew. Chem., Int. Ed. Engl.* **1996**, *35*, 1262. (f) Cozzi, P. G.; Tagliavini, E.; Umani-Ronchi, A. *Gazz. Chim. Ital.* **1997**, *127*, 247. (g) Yanagisawa, A. In *Comprehensive Asymmetric Catalysis*; Jacobsen, E. N., Pfaltz, A., Yamamoto, H., Eds.; Springer: Heidelberg, Germany, 1999; Vol. 2, p 965. (h) Denmark, S. E.; Almostead, N. G. In *Modern Carbonyl Chemistry*; Otera, J., Ed.; Wiley-VCH: Weinhein, Germany, 2000; Chapter 10, p 299. (i) Chemler, S. R.; Roush, W. R. In *Modern Carbonyl Chemistry*; Otera, J., Ed.; Wiley-VCH: Weinhein, Germany, 2000; Chapter 11, p 403. (j) *Lewis Acids in Organic Synthesis*; Yamamoto, H., Ed.; Wiley-VCH: Weinheim, Germany, 2000; Vols. 1 and 2.

(2) Notable examples of chiral Lewis acid-catalyzed asymmetric allylations with allylic trimethylsilanes: (a) Furuta, K.; Mouri, M.; Yamamoto, H. *Synlett* **1991**, 561. (b) Ishihara, K.; Mouri, M.; Gao, Q.; Maruyama, T.; Furuta, K.; Yamamoto, H. *J. Am. Chem. Soc.* **1993**, *115*, 11490. (c) Aoki, S.; Mikami, K.; Terada, M.; Nakai, T. *Tetrahedron* **1993**, *49*, 1783. (d) Gauthier, D. R., Jr.; Carreira E. M. *Angew. Chem., Int. Ed. Engl.* **1996**, *35*, 2363. See also: (e) Duthaler, R. O.; Hafner, A. *Angew. Chem., Int. Ed. Engl.* **1997**, *36*, 43. Notable examples of chiral Lewis base-catalyzed asymmetric allylations with allylic trichlorosilanes: (f) Denmark, S. E.; Coe, D. M.; Pratt, N. E.; Griedel, B. D. *J. Org. Chem.* **1994**, *59*, 6161. (g) Iseki, K.; Kuroki, Y.; Takahashi, M.; Kobayashi, Y. *Tetrahedron Lett.* **1996**, *37*, 5149. (h) Iseki, K.; Kuroki, Y.; Takahashi, M.; Kishimoto, S.; Kobayashi, Y. *Tetrahedron* **1997**, *53*, 3513. (i) Iseki, K.; Mizuno, S.; Kuroki, Y.; Kobayashi, Y. *Tetrahedron Lett.* **1998**, *39*, 2767. (j) Nakajima, M.; Saito, M.; Shiro, M.; Hashimoto, S. *J. Am. Chem. Soc.* **1998**, *120*, 6419. (k) Iseki, K.; Mizuno, S.; Kuroki, Y.; Kobayashi, Y. *Tetrahedron* **1999**, *55*, 977. (l) Denmark, S. E.; Fu, J. *J. Am. Chem. Soc.* **2000**, *122*, 12021. (m) Denmark, S. E.; Fu, J. *J. Am. Chem. Soc.* **2001**, *123*, 9488. (n) Denmark, S. E.; Fu, J. *J. Am. Chem. Soc.* **2001**, *123*, 6199. Catalytic asymmetric Nozaki−Hiyama reactions with chromium catalysts: (o) Bandini, M.; Cozzi, P. G.; Melchiorre, P.; Umani-Ronchi, A. *Angew. Chem., Int. Ed.* **1999**, *38*, 3357. (p) Bandini, M.; Cozzi, P. G.; Umani-Ronchi, A. *Angew. Chem., Int. Ed.* **2000**, *38*, 2327. Asymmetric allyl-transfer reactions; (q) Nokami, J.; Ohga, M.; Nakamoto, H.; Matsubara, T.; Hussain, I.; Kataoka, K. *J. Am. Chem. Soc.* **2001**, *123*, 9168. (r) Loh, T.-P.; Hu, Q.-Y.; Chok, Y.-K.; Tan, K.-T. *Tetrahedron Lett.* **2001**, *42*, 9277.

(3) Review for catalytic asymmetric aldol reactions: (a) Gennari, C. In *Comprehensive Organic Synthesis*; Trost, B. M., Fleming, I., Heathcock, C. H., Eds.; Pergamon Press: Oxford, UK, 1991; Vol. 2, p 629. Reviews for catalytic asymmetric aldol reactions with silyl enol ethers or ketene silyl acetals: (b) Hollis, T. K.; Bosnich, B. *J. Am. Chem. Soc.* **1995**, *117*, 4570. (c) Braun, M. In *Houben-Weyl: Methods of Organic Chemistry*; Helmchen, G., Hoffmann, R. W., Mulzer, J., Schaumann, E., Eds.; Georg Thieme Verlag: Stuttgart, Germany, 1995; Vol. E21, p 1730. (d) Nelson, S. G. *Tetrahedron*: *Asymmetry* **1998**, *9*, 357. (e) Gröger, H.; Vogl, E. M.; Shibasaki, M. *Chem. Eur. J.* **1998**, *4*, 1137. (f) Mahrwald, R. *Chem. Rev.* **1999**, *99*, 1095. (g) Carreira, E. M. In *Comprehensive Asymmetric Catalysis*; Jacobsen, E. N., Pfaltz, A., Yamamoto, H., Eds.; Springer; Heidelberg, Germany, 1999; Vol. 3, p 997. (h) Arya, P.; Qin, H. *Tetrahedron* **2000**, *56*, 917. (i) Machajewski, T. D.; Wong, C.-H. *Angew. Chem., Int. Ed.* **2000**, *39*, 1353. (j) Carreira, E. M. In *Modern Carbonyl Chemistry*; Otera, J., Ed.; Wiley-VCH: Weinheim, Germany, 2000; Chapter 8, p 227.

10.1021/jo020691c CCC: $25.00
Published on Web 06/19/2003

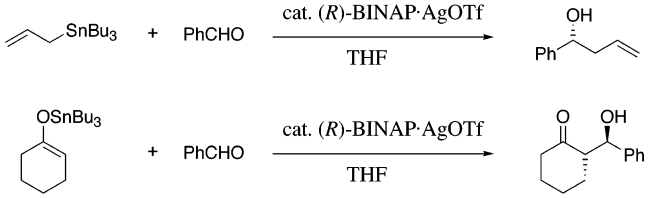


FIGURE 1. Enantioselective allylation and aldol reaction with tin compounds catalyzed by BINAP·AgOTf.

asymmetric aldol reaction of cyclohexanone-derived enol trichloroacetate using a catalytic amount of tributyltin methoxide.[5d]

Unfortunately, we attempted to use less toxic allylic trialkylsilanes or trialkylsilyl enol ethers in the BINAP·Ag(I)-catalyzed reactions but no products were obtained, probably due to less reactivity of the silane compounds than that shown by the corresponding stannanes. Yamagishi and co-workers independently examined the BINAP·Ag(I)-catalyzed asymmetric Mukaiyama aldol reaction using trimethylsilyl enol ether and found that the reaction was accelerated by BINAP·$AgPF_6$ in DMF containing a small amount of water to obtain the aldol product with high enantioselectivity.[6] In contrast, Carreira has shown the utility of metal fluoride−chiral ligand complexes as chiral catalysts in the reactions of silyl compounds including asymmetric Sakurai−Hosomi allylation, and the Mukaiyama-type aldol reaction (eqs 1 and 2 in Figure 2).[2d,7] We also reported that the BINAP·AgF complex is a reactive chiral catalyst of choice for asymmetric allylation and aldol reaction using trimethoxysilanes in methanol (eqs 3 and 4 in Figure 2).[8]

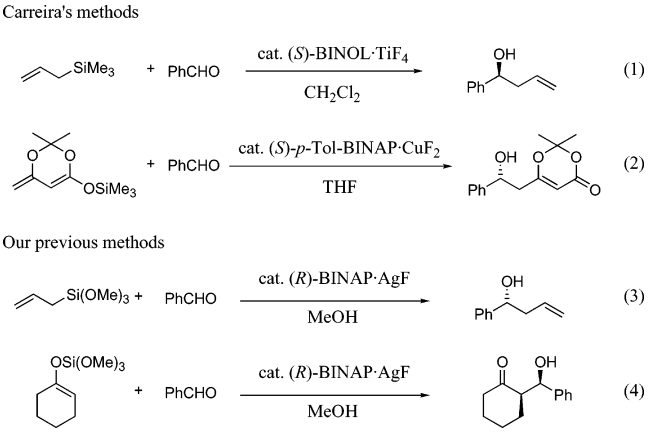


FIGURE 2. Enantioselective allylation and aldol reaction with chiral ligand−metal fluoride complexes as catalysts.

Most metal fluorides are difficult to use as catalysts because of their insolubility in common organic solvents.[9] To solve this problem, Carreira documented the use of $(Bu_4N)Ph_3SiF_2$ (TBAT) as a source of fluoride ion for the in situ generation of copper fluoride, whereas we used methanol as a solvent to dissolve AgF. Although methanol is an excellent solvent for various reactions, it sometimes causes undesired protonation of the active species if the reactivity of substrates is high enough. Therefore, a more general method is required that is usable in an aprotic solvent system. In this paper we introduce a new system for the combined use of KF·18-crown-6 ether with the BINAP·AgOTf complex in polar aprotic solvent.

Results and Discussion

First, we examined the (*R*)-BINAP·Ag(I)-catalyzed reaction of allyltrimethoxysilane with benzaldehyde to search for silver salts possessing sufficient catalytic activity. No silver salts other than AgF (AgX; X = OTf, I, BF_4, SbF_6, ClO_4, NTf_2, NO_3, IO_4), however, gave any allylated product in THF or MeOH (entry 1 in Table 1). Next, fluoride compounds were investigated as additives in combination with (*R*)-BINAP·AgOTf catalyst. Adding 1 equiv of KF in methanol gave the desired product in 5% yield and 59% ee (entry 2). Although KF cannot act as an activator of allylsilanes in THF because of its insolubility in this solvent, a catalytic amount of tetrabutylammonium fluoride (TBAF) showed good catalytic activity in this reaction in THF with almost no enantioselectivity (entry 3). 18-Crown-6 is known to improve the

(4) Reviews for chiral Lewis base-catalyzed asymmetric aldol reactions with trichlorosilyl enol ethers: (a) Denmark, S. E.; Stavenger, R. A.; Su, X.; Wong, K.-T.; Nishigaichi, Y. *Pure Appl. Chem.* **1998**, *70*, 1469. (b) Denmark, S. E.; Stavenger, R. A. *Acc. Chem. Res.* **2000**, *33*, 432. Chiral rhodium catalysts: (c) Reetz, M. T.; Vougioukas, A. E. *Tetrahedron Lett.* **1987** *28*, 793. Chiral palladium catalysts: (d) Sodeoka, M.; Ohrai, K.; Shibasaki, M. *J. Org. Chem.* **1995**, *60*, 2648. (e) Sodeoka, M.; Tokunoh, R.; Miyazaki, F.; Hagiwara, E.; Shibasaki, M. *Synlett* **1997**, 463. (f) Sodeoka, M.; Shibasaki, M. *Pure Appl. Chem.* **1998**, *70*, 414. (g) Fujii A.; Sodeoka, M. *Tetrahedron Lett.* **1999**, *40*, 8011. See also: (h) Hagiwara, E.; Fujii, A.; Sodeoka, M. *J. Am. Chem. Soc.* **1998**, *120*, 2474. (i) Fujii, A.; Hagiwara, E.; Sodeoka, M. *J. Am. Chem. Soc.* **1999**, *121*, 5450. Chiral platinum catalysts: (j) Fujimura, O. *J. Am. Chem. Soc.* **1998**, *120*, 10032. Reviews on direct catalytic asymmetric aldol reactions of aldehydes with unmodified ketones: (k) Groger, H.; Wilken, J. *Angew. Chem., Int. Ed.* **2001**, *40*, 529. (l) List, B. *Synlett* **2001**, 1675. Recent examples of direct catalytic asymmetric aldol reactions of aldehydes: (m) Yamada, Y. M. A.; Yoshikawa, N.; Sasai, H.; Shibasaki, M. *Angew. Chem., Int. Ed. Engl.* **1997**, *36*, 1871. (n) Yamada, Y. M. A.; Shibasaki, M. *Tetrahedron Lett.* **1998**, *39*, 5561. (o) Yoshikawa, N.; Yamada, Y. M. A.; Das, J.; Sasai, H.; Shibasaki, M. *J. Am. Chem. Soc.* **1999**, *121*, 4168. (p) List, B.; Lerner, R. A.; Barbas, C. F., III *J. Am. Chem. Soc.* **2000**, *122*, 2395. (q) Notz, W.; List, B. *J. Am. Chem. Soc.* **2000**, *122*, 7386. (r) List, B.; Pojarliev, P.; Castello, C. *Org. Lett.* **2001**, *3*, 573. (s) Saito, S.; Nakadai, M.; Yamamoto, H. *Synlett* **2001**, 1245. (t) Trost, B. M.; Ito, H. *J. Am. Chem. Soc.* **2000**, *122*, 12003. (u) Trost, B. M.; Ito, H.; Silcoff, E. R. *J. Am. Chem. Soc.* **2001**, *123*, 3367. (v) Trost, B. M.; Silcoff, E. R.; Ito, H. *Org. Lett.* **2001**, *3*, 2497. (w) Yoshikawa, N.; Kumagai, N.; Matsunaga, S.; Moll, G.; Ohshima, T.; Suzuki, T.; Shibasaki, M. *J. Am. Chem. Soc.* **2001**, *123*, 2466. (x) Kumagai, N.; Matsunaga, S.; Yoshikawa, N.; Ohshima, T.; Shibasaki, M. *Org. Lett.* **2001**, *3*, 1539. (y) Suzuki, T.; Yamagiwa, N.; Matsuo, Y.; Sakamoto, S.; Yamaguchi, K.; Shibasaki, M.; Noyori, R. *Tetrahedron Lett.* **2001**, *42*, 4669. (z) Yoshikawa, N.; Shibasaki, M. *Tetrahedron* **2001**, *57*, 2569.

(5) (a) Yanagisawa, A.; Nakashima, H.; Ishiba, A.; Yamamoto, H. *J. Am. Chem. Soc.* **1996**, *118*, 4723. (b) Yanagisawa, A.; Nakashima, H.; Nakatsuka, Y.; Ishiba, A.; Yamamoto, H. *Bull. Chem. Soc. Jpn.* **2001**, 1129. (c) Yanagisawa, A.; Matsumoto, Y.; Nakashima, H.; Asakawa, K.; Yamamoto, H. *J. Am. Chem. Soc.* **1997**, *119*, 9319. (d) Yanagisawa, A.; Matsumoto, Y.; Asakawa, K.; Yamamoto, H. *J. Am. Chem. Soc.* **1999**, *121*, 892. Since these communications appeared, other papers on chiral silver-catalyzed asymmetric allylation have been reported: (e) Shi, M.; Sui, W.-S. *Tetrahedron*: *Asymmetry* **2000**, *11*, 773. (f) Loh, T.-P.; Zhou, J.-R. *Tetrahedron Lett.* **2000**, *41*, 5261.

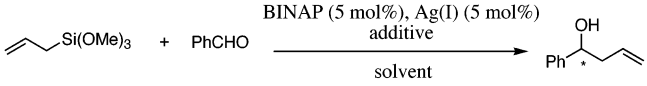
(6) (a) Ohkouchi, M.; Yamaguchi, M.; Yamagishi, T. *Enantiomer* **2000**, *5*, 71. (b) Ohkouchi, M.; Masui, D.; Yamaguchi, M.; Yamagishi, T. *J. Mol. Catal. A*: *Chemical* **2001**, *170*, 1.

(7) (a) Krüger, J.; Carreira, E. M. *J. Am. Chem. Soc.* **1998**, *120*, 837. (b) Pagenkopf, B. L.; Krüger, J.; Stojanovic, A.; Carreira, E. M. *Angew. Chem., Int. Ed.* **1998**, *37*, 3124.

(8) (a) Yanagisawa, A.; Kageyama, H.; Nakatsuka, Y.; Asakawa, K.; Matsumoto, Y.; Yamamoto, H. *Angew. Chem., Int. Ed.* **1999**, *38*, 3701. (b) Yanagisawa, A.; Nakatsuka, Y.; Asakawa, K.; Kageyama, H.; Yamamoto, H. *Synlett* **2001**, 69. (c) Yanagisawa, A.; Nakatsuka, Y.; Asakawa, K.; Wadamoto, M.; Kageyama, H.; Yamamoto, H. *Bull. Chem. Soc. Jpn.* **2001**, 1477.

(9) Pagenkopf, B. L.; Carreira, E. M. *Chem. Eur. J.* **1999**, *5*, 3437.

TABLE 1. Effects of Additives on Chemical Yield and Enantioselectivity[a]



entry	solvent	Ag(I)	allylsilane [equiv]	additive (mol %)	yield[b] [%]	ee[c] [%]
1	THF	AgX[d]	1.8		<1	
2	MeOH	AgOTf	1.0	KF (100)	5	59
3	THF	AgOTf	2.0	TBAF (5)	92	1
4	THF	AgOTf	1.0	KF,18-crown-6 (5)	61	90
5	THF	AgOTf	1.8	KF (5)	<1	
6	THF	AgOTf	1.8	18-crown-6 (5)	<1	
7	THF	AgOTf	1.0	KF (50), 18-crown-6 (5)	56	3
8	THF	AgOTf	1.0	KF (5), 18-crown-6 (50)	82	58

[a] Unless otherwise noted, the reaction was carried out with allyltrimethoxysilane (1.8 equiv) and benzaldehyde (1 equiv) with (*R*)-BINAP (5 mol %) and silver salt (5 mol %) at −20 °C for 4 h. [b] Yield of isolated product. [c] Determined by HPLC analysis (Chiral OD-H, Daicel Chemical Industries, Ltd.). [d] AgOTf, AgI, $AgBF_4$, $AgSbF_6$, $AgClO_4$, $AgNTf_2$, $AgNO_3$, and $AgIO_4$ were used.

TABLE 2. The Optimum Reaction Conditions of Asymmetric Allylation of Benzaldehyde: Concerning the Amount of BINAP[a]

entry	(*R*)-BINAP [mol %]	allylsilane [equiv]	yield[b] [%]	ee[c] [%]
1	5	1.0	61	90
2	5	3.0	90	69
3	3	3.0	92	93
4	2	3.0	91	95
5	10	3.0	21	2
6	0	3.0	<1	

[a] Unless otherwise specified, the reaction was carried out with AgOTf (5 mol %), KF (5 mol %), and 18-crown-6 (5 mol %) at −20 °C for 4 h in THF. [b] Yield of isolated product. [c] Determined by HPLC analysis (Chiral OD-H, Daicel Chemical Industries, Ltd.).

solubility of KF in THF or other aprotic polar organic solvents and also to generate a reactive fluoride species. In fact, when a catalytic amount of KF and 18-crown-6 was added, the reaction proceeded smoothly in THF with 90% ee (entry 4). In the absence of KF, however, the product was not obtained at all (entry 6). Use of an increased amount of 18-crown-6 improved the chemical yield but the enantioselectivity was lower (entry 8).

The optimum reaction conditions of (*R*)-BINAP, AgOTf, KF, and 18-crown-6 catalyzed asymmetric allylation with benzaldehyde are shown in Table 2. Three equivalents of allyltrimethoxysilane raised the yield but resulted in a decrease of the enantioselectivity (entry 2). We recently showed that the ratio of BINAP to a silver salt is a very important factor in obtaining better yield and better enantioselectivity, because a significant amount of a 2:1 complex of (*R*)-BINAP and silver(I) salt was formed in addition to a 1:1 complex when (*R*)-BINAP was mixed with an equimolar amount of silver(I) salt at room temperature.[8,10] In fact, a mixture of 10 mol % of (*R*)-BINAP and 5 mol % of AgOTf gave only a 21% yield of the product with 2% ee (entry 5). When this reaction was carried out by changing the ratio of (*R*)-BINAP to AgOTf, it was found that an excess amount of silver triflate

(10) Yamagishi et al. also detected the 2:1 complex by ^{31}P NMR; see ref 6b.

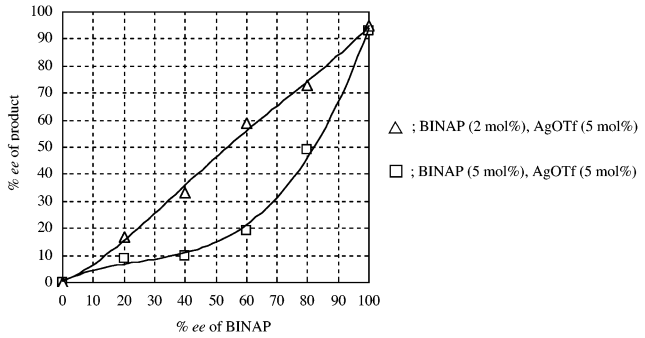


FIGURE 3. Plot of ee dependence of allylation as a function of ee of BINAP.

raised the ee of the product and a combination of 2 or 3 mol % of BINAP and 5 mol % of silver triflate gave the best results with 3 equiv of allyltrimethoxysilane (entries 3 and 4).

To substantiate the effect of these ratios, the enantioselectivity of homoallyl alcohol obtained from the reaction of allyltrimethoxysilane and benzaldehyde was plotted against the ee of BINAP using the two different ratios of BINAP and AgOTf (Figure 3).[11] When the reaction was performed in the presence of a catalyst prepared from a 1:1 mixture of (*R*)-BINAP and AgOTf, a negative nonlinear effect was observed (□). In contrast, the linear behavior was observed with a 1:0.4 mixture of (*R*)-BINAP and AgOTf (△). These phenomena support the hypothesis that at least two BINAP·silver complexes have certain catalytic activity and contribute to the allylation when a 1:1 mixture of BINAP and AgOTf is used as a catalyst, and a single BINAP silver complex is formed with use of the 1:0.4 mixture. Moreover, these experiments support the inference that a 1:1 complex is a key species to promote the reaction highly enantioselectively.

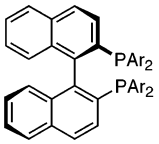
To obtain higher enantioselectivity, we screened various BINAP derivatives and other related chiral bisphosphines as chiral ligands (Table 3). When the (*R*)-Tol-BINAP was used for this allylation, the enantioselectivity was slightly higher than that obtained with the (*R*)-BINAP catalyst (entries 1 and 2). (*S*)-DM-BINAP also gave high enantioselectivity though in low yield (entry 4). Among the chiral bisphosphines resulting, H_8-BINAP showed the highest reactivity; however, (*R*)-H_8-DM-BINAP did not give good results in either yield or enantioselectivity (entries 5 and 6). Use of (*R*)-MeO-BIPHEP and (*R*)-SEGPHOS[12] resulted in moderate yields and enantioselectivity (entries 7 and 8).

Some reaction temperatures were examined, and allylation at −20 °C gave a satisfactory result with respect to both chemical yield and ee of the product (Table 4, entries 1−3). Among the solvents tested, aprotic and polar solvents proved to be effective for the reaction, and THF provided the best result (entries 1 and 4−6). Allylation at high concentration improved the chemical yield and the reaction could be achieved with a reduced amount of allyltrimethoxysilane without decreasing the yield. In fact, the reaction of benzaldehyde with an

(11) Kagan, H. B.; Luukas, T. O. In *Comprehensive Asymmetric Catalysis*; Jacobsen, E. N., Pfaltz, A., Yamamoto, H., Eds.; Springer: Heidelberg, Germany, 1999; Vol. 1, p 102.

(12) Saito, T.; Yokozawa, T.; Ishizaki, T.; Moroi, T.; Sayo, N.; Miura, T.; Kumobayashi, H. *Adv. Synth. Catal.* **2001**, *3*, 264.

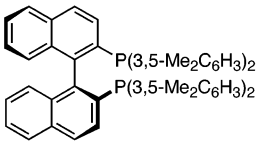
TABLE 3. Effects of Ligand on Chemical Yield and Enantioselectivity[a]



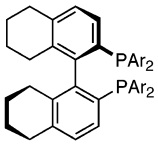
(*R*)-BINAP (Ar = Ph)

(*R*)-*p*-Tol-BINAP (Ar = 4-MeC_6H_4)

(*R*)-*p*-*t*BuC_6H_4-BINAP (Ar = 4-*t*Bu-C_6H_4)

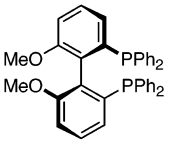


(*S*)-DM-BINAP

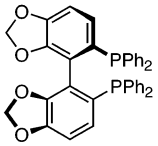


(*R*)-H_8-BINAP (Ar = Ph)

(*R*)-H_8-DM-BINAP (Ar = 3,5-$Me_2C_6H_3$)



(*R*)-MeO-BIPHEP



(*R*)-SEGPHOS

entry	ligand	yield[b] [%]	ee[c] [%]
1	(*R*)-BINAP	97	95
2	(*R*)-*p*-Tol-BINAP	49	96
3	(*R*)-*p*-*t*BuC_6H_4-BINAP	80	58
4	(*S*)-DM-BINAP	6	92
5	(*R*)-H_8-BINAP	>99	65
6	(*R*)-H_8-DM-BINAP	29	59
7	(*R*)-MeO-BIPHEP	80	81
8	(*R*)-SEGPHOS	52	81

[a] Unless otherwise specified, the reaction was carried out with allyltrimethoxysilane (2 equiv) and benzaldehyde (1 equiv) in the presence of a specified ligand (2 mol %), AgOTf (5 mol %), KF (5 mol %), and 18-crown-6 (5 mol %) at −20 °C for 4 h in THF. [b] Yield of isolated product. [c] Determined by HPLC analysis (Chiral OD-H, Daicel Chemical Industries, Ltd.).

TABLE 4. The Optimum Reaction Conditions of Asymmetric Allylation of Benzaldehyde: Concerning Temperature, Solvent, and Concentration[a]

entry	solvent (mL)	*T* [°C]	allylsilane [equiv]	yield[b] [%]	ee[c] [%]
1	THF (6)	−20	3	91	95
2	THF (6)	0	3	54	92
3	THF (6)	−40	3	4	95
4	toluene (6)	−20	3	<1	
5	DMF (6)	−20	3	67	71
6	CH_2Cl_2 (6)	−20	3	29	71
7	THF (3)	−20	2	97	95
8	THF (3)	−20	1	78	96

[a] Unless otherwise specified, the reaction was carried out with benzaldehyde (1.0 mmol), (*R*)-BINAP (2 mol %), AgOTf (5 mol %), KF (5 mol %), and 18-crown-6 (5 mol %) in a specified solvent for 4 h. [b] Yield of isolated product. [c] Determined by HPLC analysis (Chiral OD-H, Daicel Chemical Industries, Ltd.).

equimolar amount of the allylsilane gave 78% yield with 96% ee in the presence of 2 mol % of (*R*)-BINAP in THF (entries 7 and 8).

Optimized conditions were established for THF as solvent at −20 °C, and we employed these conditions in the addition of allyltrimethoxysilane to various aldehydes (Table 5). All reactions of aromatic and α,*β*-unsaturated aldehydes gave satisfactory yields and good ee values. When an α,*β*-unsaturated aldehyde was used, 1,2-addition took place exclusively (entry 2). In contrast, aliphatic aldehydes gave relatively low chemical yield with 2 mol % of (*R*)-BINAP and 5 mol % of other catalysts (condition A), while treatment of cyclohexanecarboxaldehyde with allyltrimethoxysilane and 6 mol % of (*R*)-BINAP and 15 mol % of the other catalysts (condition B) gave the allylated product in 62% yield with 93% ee (entry 8). Aliphatic aldehydes do not give any product in the presence of (*R*)-BINAP·AgF complex in MeOH.[8a]

TABLE 5. Asymmetric Allylation of Aldehydes Catalyzed by BINAP, AgOTf, KF, and 18-Crown-6[a]

entry	aldehyde	condition	yield[b] [%]	ee[c] [%]
1	PhCHO	A	91	95 (*R*)
2	(*E*)-PhCH=CHCHO	A	81	87 (*R*)
3[d]	2-furyl-CHO	A	57	95 (*R*)
4	1-naphthyl-CHO	A	95	92 (*R*)
5	4-$MeOC_6H_4CHO$	A	61	95 (*R*)
6[d]	4-BrC_6H_4CHO	A	95	96 (*R*)
7[e]	2-MeC_6H_4CHO	A	82	97 (*R*)
8	*c*-$C_6H_{11}CHO$	B	62	93[f] (*R*)
9	$PhCH_2CH_2CHO$	B	76	86 (*S*)

[a] Unless otherwise specified, the reaction was carried out wth condition A or B. Condition A: The reaction was carried out with allyltrimethoxysilane (3 equiv) and aldehyde (1 equiv) in the presence of chiral silver(I) catalyst prepared from (*R*)-BINAP (2 mol %), AgOTf (5 mol %), KF (5 mol %), and 18-crown-6 (5 mol %) in THF at −20 °C for 4 h. Condition B: The reaction was carried out with allyltrimethoxysilane (3 equiv) and aldehyde (1 equiv) in the presence of chiral silver(I) catalyst prepared from (*R*)-BINAP (6 mol %), AgOTf (15 mol %), KF (15 mol %), and 18-crown-6 (15 mol %) in THF at −20 °C for 24 h. [b] Isolated yield. [c] Determined by HPLC analysis (Chiralcel OD-H or OJ, Daicel Chemical Industries, Ltd.). [d] 2 mol % of (*R*)-BINAP and 2 equiv of allyltrimethoxysilane were used. [e] 3 mol % of (*R*)-*p*-Tol-BINAP was used. [f] Determined by HPLC analysis of the 3,5-dinitrobenzoate from the esterification (3,5-dinitrobenzoyl chloride, triethylamine/1,2-dichloromethane).

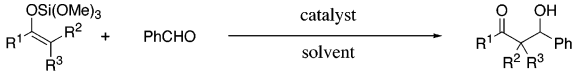
TABLE 6. Diastereo- and Enantioselective Addition of Crotyltrimethoxysilane to Benzaldehyde Catalyzed by BINAP, AgOTf, KF, and 18-Crown-6

E/*Z* ratio	yield [%]	anti (% ee):syn (% ee)
<1/99	91	85 (95):15 (75)
87/13	44	85 (95):15 (75)

Condensation of *γ*-substituted allylmetal reagents with carbonyl compounds is a challenging problem with regard to regioselectivity (α/*γ*) and stereoselectivity (*E*/*Z* or anti/syn).[1] The reaction of (*Z*)-crotyltrimethoxysilane (*E*/*Z* < 1/99) in the presence of (*R*)-BINAP, AgOTf, KF, and 18-crown-6 ether in THF at 0 °C for 24 h gave the *γ*-adduct almost exclusively with an anti/syn ratio of 85:15 (Table 6). The anti isomer had 95% ee and the 1*R*,2*R* configuration. (*E*)-enriched crotyltrimethoxysilane (*E*/*Z* = 87/13) gave the same selectivities and configuration. These results were quite similar to those given by the BINAP·AgOTf-catalyzed reaction with crotyltributyltin.

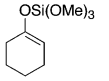
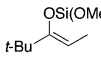
We have reported that trimethoxysilyl enol ethers gave aldol adducts in the condensation with aldehydes catalyzed by BINAP·AgF in MeOH.[8b,c] This reaction, however, caused undesired hydrolysis of the silyl enol ether by

TABLE 7. Diastereo- and Enantioselective Aldol Reaction of Trimethoxysilyl Enol Ethers Catalyzed by (*R*)-BINAP, AgOTf, KF, and 18-Crown-6[a]



condition A ; (*R*)-*p*-Tol-BINAP and AgF

condition B ; (*R*)-BINAP, AgOTf, KF and 18-crown-6

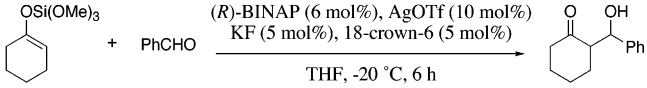
entry	silyl enol ether	condition	solvent	yield, %[b]	*syn/anti*[c]	% ee[d]
1		A	MeOH-Acetone	91	89/11	93
2		B	THF	78	9/91	93
3		A	MeOH	84	>99/1	97
4		B	THF	51	>99/1	90

[a] Unless otherwise specified, the reaction was carried out with condition A or B. Condition A: The reaction was carried out with trimethoxysilyl enol ether (1 equiv) and benzaldehyde (1 equiv) in the presence of (*R*)-*p*-Tol-BINAP·AgF (10 mol %) in MeOH−acetone at −78 °C for 5 h. Condition B: The reaction was carried out with trimethoxysilyl enol ether (1.0 equiv) and benzaldehyde (1.0 equiv) in the presence of (*R*)-BINAP (6 mol %), AgOTf (10 mol %), KF (10 mol %), and 18-crown-6 (10 mol %) in THF at −20 °C for 24 h. [b] Yield of isolated product. [c] Determined by ^{1}H NMR analysis. [d] Ee of the major diastereomer. Determined by HPLC analysis (Chiral OD-H, Daicel Chemical Industries, Ltd.).

MeOH and the yield and enantioselectivity were improved by using mixed solvents of MeOH with an aprotic solvent. Thus, the present BINAP/AgOTf/KF/18-crown-6 catalyst system was expected to be successfully applied to the Mukaiyama-type aldol reaction because the new mixed catalysts are also used in aprotic THF solvent. Furthermore, employment of substituted enol silanes for the present catalytic aldol reaction is quite attractive from the viewpoint of diastereoselectivity (anti/syn selectivity). In general, silyl enol ethers are known to react with aldehydes with syn selectivity irrespective of the double-bond geometry (*E* or *Z*) of the ether in the presence of a catalytic amount of chiral Lewis acids. In contrast, reagent-controlled diastereoselective aldol reaction of trichlorosilyl enol ethers catalyzed by chiral Lewis bases is known to be a useful method for obtaining both diastereomers of the aldol product selectively.[4a,b,13] BINAP·AgF catalyst showed similar diastereoselectivity to that of typical chiral Lewis acid catalysts and gave syn adducts from both (*E*) and (*Z*) enolates.[8b,c] Interestingly, the reaction of the trimethoxysilyl enol ether of cyclohexanone and benzaldehyde in the presence of a catalytic amount of (*R*)-BINAP, AgOTf, KF, and 18-crown-6 in THF preferentially gave an anti adduct (syn/anti = 9/91) with 93% ee (entry 2 in Table 7). In contrast, *tert*-butyl ethyl ketone-derived (*Z*)-silyl enol ether gave a syn product exclusively with 90% ee (entry 4 in Table 7). These results were quite similar to those given by the BINAP·AgOTf-catalyzed reaction with tin enolate.

Table 8 summarizes the results obtained for the reaction of aromatic, α,β-unsaturated, and primary aliphatic aldehydes with cyclohexanone-derived trimethoxysilyl enol ether under the influence of the catalyst. All the reactions resulted in remarkable anti- and enantioselectivities. In the reaction with cinnamaldehyde, only a 1,2-adduct was observed (entry 2). In the case of hydrocinnamaldehyde, a 2-fold amount of (*R*)-BINAP·AgOTf was necessary to obtain the desired product in a satisfactory yield (entry 6), which was not available in the BINAP·AgF-catalyzed aldol reaction.[8b,c]

TABLE 8. Diastereo- and Enantioselective Aldol Reaction of Trimethoxysilyl Enol Ethers with Aldehydes Catalyzed by (*R*)-BINAP, AgOTf, KF, and 18-Crown-6[a]



entry	aldehyde	yield[b] [%]	syn/anti[c]	ee[d] [%]
1	PhCHO	78	9/91	93
2	(*E*)-PhCH=CHCHO	68	27/73	89
3	1-naphthyl-CHO	70	5/95	90
4	4-MeOC$_6$H$_4$CHO	55	9/91	93
5	4-BrC$_6$H$_4$CHO	86	8/92	95
6[e]	PhCH$_2$CH$_2$CHO	41	21/79	83

[a] Unless otherwise specified, the reaction was carried out with trimethoxysilyl enol ether (1 equiv) and benzaldehyde (1 equiv) in the presence of (*R*)-BINAP (6 mol %), AgOTf (10 mol %), KF (10 mol %), and 18-crown-6 (10 mol %) in THF at −20 °C for 4 h. [b] Yield of isolated product. [c] Determined by ^{1}H NMR analysis. [d] Ee of the major diastereomer. Determined by HPLC analysis (Chiral OD-H, Daicel Chemical Industries, Ltd.). [e] (*R*)-BINAP (12 mol %) and AgOTf (20 mol %) were used.

From these results, BINAP·AgOTf and 18-crown-6·KF complexes are believed to act separately as catalysts and not to generate AgF because it is insoluble in THF. To confirm this working hypothesis, we performed ^{19}F NMR experiments: (*R*)-BINAP·AgOTf complex was treated with a 1:1 mixture of 18-crown-6·KF in THF-d_8 at room temperature; however, no peaks assignable to AgF or related fluoride species appeared, and only peaks of TfO^- species were observed. Two probable reaction mechanisms for the catalytic asymmetric allylation are shown in Figure 4. Judging from the fact that crotyltrimethoxysilane reacted with benzaldehyde anti-selectively regardless of the *E*/*Z* stereochemistry in the presence of BINAP·AgOTf/KF/18-crown-6 as catalysts, the Lewis acid mechanism via an acyclic antiperiplanar transition state structure seems more preferable (path a).[14] However, the transmetalation pathway b cannot be denied completely because the anti product can be obtained from both *E*- and *Z*-crotylsilanes when rapid *E*/*Z* isomerization of a crotyl silver compound occurs. At present, we have no further experimental evidence for the mechanism.

In marked contrast to the case of allylation, the diastereoselectivity of the aldol reaction depends on the geometry of trimethoxysilyl enol ether. In the reaction, BINAP·AgOTf plays an important role in accomplishing the diastereoselectivity. For example, when the aldol reaction of cyclohexane-derived trimethoxysilyl enol ether with benzaldehyde was performed with KF (1 eq) and 18-crown-6 (1 eq) without BINAP·AgOTf, the opposite syn-selectivity was obtained (eq 5).

(13) (a) Denmark, S. E.; Winter, S. B. D.; Su, X.; Wong, K.-T. *J. Am. Chem. Soc.* **1996**, *118*, 7404. (b) Denmark, S. E.; Wong, K.-T.; Stavenger, R. A. *J. Am. Chem. Soc.* **1997**, *119*, 2333. (c) Denmark, S. E.; Stavenger, R. A.; Wong, K.-T.; Su, X. *J. Am. Chem. Soc.* **1999**, *121*, 4982.

(14) (a) Yamamoto, Y.; Yatagai, H.; Naruta, Y.; Maruyama, K. *J. Am. Chem. Soc.* **1980**, *102*, 7107. (b) Yamamoto, Y.; Yatagai, H.; Ishihara, Y.; Maeda, N.; Maruyama, K. *Tetrahedron* **1984**, *40*, 2239.

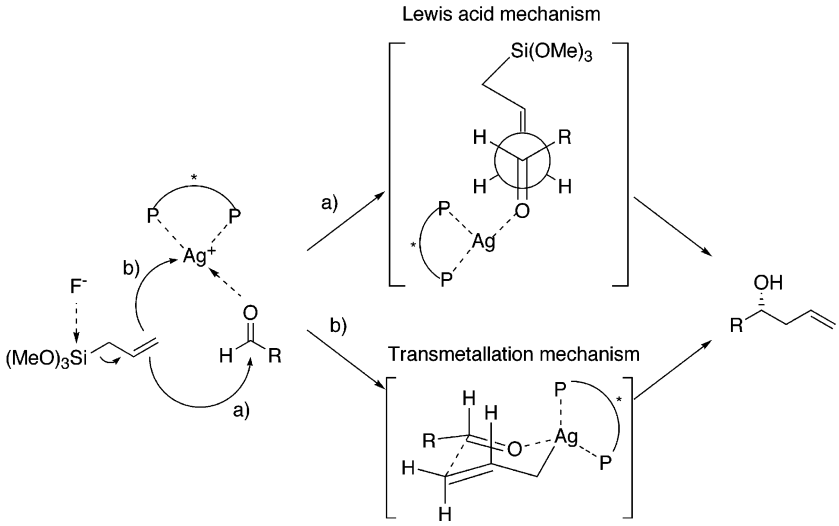


FIGURE 4. Probable reaction mechanisms of the catalytic asymmetric allylation.

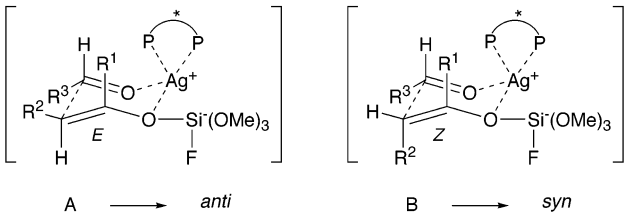
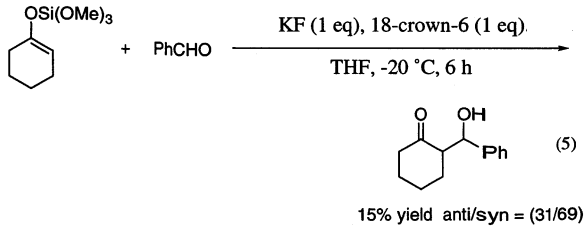


FIGURE 5. Probable cyclic transition-state structure in the aldol reaction.



These results unambiguously indicate that cyclic transition state structures (A and B, Figure 5) are probable models. In these assemblies, the BINAP·Ag(I) complex coordinates as a chiral Lewis acid to both an aldehyde and a silyl enol ether to form a six-membered cyclic structure, in which fluoride ion activates the silyl enol ether to form a pentacoordinated silicate. Thus, from the *E*-enolate, the anti aldol product can be obtained via a cyclic transition state model A, and another model B connects the *Z*-enolate to the syn product. Similar cyclic models containing a BINAP-coordinated silver atom instead of a fluorinated trimethoxysilyl group are also possible alternatives when the transmetalation to silver enolate occurs rapidly.

Conclusion

We have described here novel methods for highly enantioselective allylation and aldol reaction of aldehydes with trimethoxysilyl compounds using a catalytic amount of BINAP, AgOTf, KF, and 18-crown-6 ether in THF. The main features of these processes are as follows: (1) the mixed catalysts behave as bifunctional chiral catalysts for these asymmetric reactions in which both an aldehyde and a trimethoxysilyl compound are activated separately; (2) a negative nonlinear effect is observed when a 1:1 mixture of BINAP and AgOTf is used; (3) not only aromatic and α,β-unsaturated aldehydes but aliphatic aldehydes also give the coupling products in satisfactory yields in both allylation and aldol reaction; (4) remarkable γ and anti-selectivities are observed for the reaction with crotyltrimethoxysilanes, irrespective of the configuration at the double bond; (5) (*E*)-trimethoxysilyl enol ether gives anti-products, while (*Z*)-trimethoxysilyl enol ether gives the syn-adduct with high selectivity; and (6) these processes are environmentally friendlier because less toxic trimethoxysilyl compounds are used instead of tin compounds. Further work is now in progress on the catalytic allylation and aldol reaction and the detailed reaction mechanism.

Experimental Section

General. Analytical TLC was done on precoated (0.25 mm) silica gel plates. Column chromatography was conducted with 230−400 mesh silica gel. Infrared (IR) spectra were recorded on a FTIR spectrometer. ^{1}H NMR spectra were measured on a 300-MHz spectrometer. Chemical shifts of ^{1}H NMR spectra were reported relative to tetramethylsilane (δ 0) or chloroform (δ 7.26). Splitting patterns are indicated as s, singlet; d, doublet; t, triplet; q, quartet; m, multiplet; and br, broad. ^{13}C NMR spectra were measured on a 75-MHz spectrometer. Chemical shifts of ^{13}C NMR spectra were reported relative to $CDCl_3$ (δ 77.0). Analytical high-performance liquid chromatography (HPLC) was done with a chiral column (4.6 mm × 25 cm, CHIRALCEL OB-H, OD-H, OJ, or CHIRALPAK AD). Optical rotation was measured on a polarimeter. Microanalyses were accomplished at the Faculty of Agriculture, Nagoya University.

All experiments were carried out under an atmosphere of standard grade argon gas (oxygen <10 ppm) and exclusion of direct light. Tetahydrofuran (THF) was distilled from sodium-bezophenone ketyl prior to use. Allyltrimethoxysilane and aldehydes were purified by distillation before use. (*R*)-*p*-*t*BuC_6H_4-BINAP was prepared according to the reported

procedure.[15] (*E*)-enriched crotyltrimethoxysilane (*E*/*Z* = 83/17) was prepared by treatment of crotylmagnesium chloride with tetramethoxysilane in dry ether and purified by distillation before use. (*Z*)-Crotyltrimethoxysilane (*E*/*Z* < 1/99) was prepared by reaction of (*Z*)-crotyltrichlorosilane with MeOH in the presence of triethylamine and purified by distillation before use. The (*Z*)-crotylsilane was synthesized from trichlorosilane, 1,3-butadiene, and $Pd(PPh_3)_4$ according to Iseki's procedure.[2h] Trimethoxysilyl enol ethers of cyclohexanone were prepared by 1,4-hydrosilylation of 2-cyclohexen-1-one with $(MeO)_3SiH$ catalyzed by $(Ph_3P)_3RhCl$ or $(Ph_3P)_4RhH$.[16] Trimethoxysilyl enol ethers of *tert*-butyl ethyl ketone were prepared by treating the ketone with LDA in ether followed by silylation with $(MeO)_3SiCl$.[17] Other chemicals were used as purchased.

Typical Experimental Procedure for Asymmetric Allylation of Aldehydes with Allylic Trimethoxysilane Reagents Catalyzed by BINAP·AgOTf and KF·18-Crown-6: Synthesis of (*R*)-1-Phenyl-3-buten-1-ol (Entry 4 in Table 2, Entry 1 in Table 4, and Entry 1 in Table 5).[18] A mixture of AgOTf (12.8 mg, 0.0498 mmol), (*R*)-BINAP (12.5 mg, 0.0201 mmol), KF (2.9 mg, 0.0499 mmol), and 18-crown-6 (200 μL, 0.25 M in THF) was dissolved in dry THF (6 mL) under argon atmosphere and with direct light excluded, and stirred at 20 °C for 20 min. To the resulting solution was added dropwise benzaldehyde (102 mg, 1.00 mmol) and allyltrimethoxysilane (505 μL, 3.00 mmol) successively at −20 °C. The mixture was stirred for 4 h at this temperature and treated with 1 M (=1 mol dm^{-3}) HCl (5 mL) at ambient temperature for 30 min. The resulting suspension was filtered off by a glass filter funnel filled with Celite and silica gel and concentrated in vacuo. The residual crude product was purified by column chromatography on silica gel (1:10 ethyl acetate/hexane as the eluant) to afford the homoallylic alcohol (135 mg, 91% yield) as a colorless oil. The enantioselectivity was determined to be 95% ee by HPLC analysis, using a chiral column (Chiralcel OD-H, hexane/*i*-PrOH = 40/1, flow rate = 1.0 mL/min): t_{major} = 12.7 min (*R*), t_{minor} = 14.3 min (*S*). The absolute configuration was determined to be *R* by comparison of the $[\alpha]_D$ value with reported data: (*R*)-enriched alcohol (90% ee), $[\alpha]_D$ +43.7° (*c* 6.7, benzene).[19] The observed $[\alpha]_D$ value of the product with 95% ee: $[\alpha]^{22}_D$ +56.5° (*c* 1.0, benzene). Elemental Anal. Calcd for $C_{10}H_{12}O$: C 81.04, H 8.16. Found: C 81.06, H 8.16. Spectral data of the product: TLC R_f 0.34 (1:3 ethyl acetate/hexane); IR (neat) 3700−3120, 3077, 3031, 2907, 1642, 1603, 1493, 1455, 1316, 1198, 1115, 1076, 1048, 916, 870, 758, 700 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 2.01 (d, 1 H, *J* = 2.5 Hz), 2.52 (m, 2 H), 4.75 (dt, 1 H, *J* = 6.9, 2.5 Hz), 5.14−5.20 (m, 2 H), 5.82 (m, 1 H), 7.25−7.37 (m, 5 H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 43.5, 73.2, 117.8, 125.7 (2 C), 127.2, 128.1 (2 C), 134.3, 143.8.

(*R*),(*E*)-1-Phenyl-1,5-hexadien-3-ol (Entry 2 in Table 5).[18] TLC R_f 0.28 (1:3 ethyl acetate/hexane); IR (neat) 3670−3120, 3079, 3026, 2979, 1642, 1599, 1579, 1493, 1449, 1130, 1071, 1030, 967, 916, 749, 693 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 1.78 (br, 1 H), 2.39 (m, 2 H), 4.37 (dd, 1 H, *J* = 12.3, 6.1 Hz), 5.16−5.22 (m, 2 H), 5.87 (m, 1 H), 6.25 (dd, 1 H, *J* = 15.9, 6.3 Hz), 6.62 (d, 1 H, *J* = 15.7 Hz), 7.22−7.40 (m, 5 H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 41.9, 71.7, 118.4, 126.4 (2 C), 127.6, 128.5 (2 C), 130.3, 131.5, 134.0, 136.6; $[\alpha]^{26}_D$ −12.3° (*c* 1.0, Et_2O). The enantioselectivity was determined to be 87% ee by HPLC analysis, using a chiral column (Chiralcel OD-H, hexane/*i*-PrOH = 20/1, flow rate = 1.0 mL/min): t_{major} = 14.0 min (*R*), t_{minor} = 25.5 min (*S*). Elemental Anal. Calcd for $C_{12}H_{14}O$: C 82.72, H 8.10. Found: C 82.73, H 8.10.

(*R*)-1-(2-Furyl)-3-buten-1-ol (Entry 3 in Table 5).[20] TLC R_f 0.30 (1:3 ethyl acetate/hexane); IR (neat) 3750−3040, 3079, 2980, 1644, 1505, 1436, 1341, 1229, 1150, 1057, 1011, 922, 885, 864, 812, 739 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 2.00 (br, 1 H), 2.61−2.66 (m, 2 H), 4.76 (m, 1 H), 5.14−5.23 (m, 2 H), 5.82 (m, 1 H), 6.26 (d, 1 H, *J* = 3.2 Hz), 6.34 (dd, 1 H, *J* = 3.1, 1.6 Hz), 7.39 (d, 1 H, *J* = 1.8 Hz); ^{13}C NMR (75 MHz, $CDCl_3$) δ 40.0, 66.8, 106.0, 110.0, 118.4, 133.6, 141.9, 155.9; $[\alpha]^{26}_D$ +29.9° (*c* 1.0, Et_2O). The enantioselectivity was determined to be 95% ee by HPLC analysis, using a chiral column (Chiralcel OJ, Ltd., hexane/*i*-PrOH = 40/1, flow rate = 1.0 mL/min): t_{minor} = 15.4 min (*S*), t_{major} = 16.6 min (*R*). Elemental Anal. Calcd for $C_8H_{10}O_2$: C 69.54, H 7.30. Found: C 69.60, H 7.25.

(*R*)-1-(1-Naphthyl)-3-buten-1-ol (Entry 4 in Table 5).[19,21] TLC R_f 0.36 (1:3 ethyl acetate/hexane); IR (neat) 3650−3120, 3071, 2979, 2940, 2908, 1640, 1597, 1510, 1433, 1395, 1167, 1055, 916, 801, 777 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 2.16 (d, 1 H, *J* = 2.8 Hz), 2.57−2.72 (m, 1 H), 2.72−2.85 (m, 1 H), 5.17−5.27 (m, 2 H), 5.54 (m, 1 H), 5.94 (m, 1 H), 7.46−7.55 (m, 3 H), 7.67 (d, 1 H, *J* = 7.1 Hz), 7.79 (d, 1 H, *J* = 8.2 Hz), 7.87−7.90 (m, 1 H), 8.08 (d, 1 H, *J* = 7.8 Hz); ^{13}C NMR (75 MHz, $CDCl_3$) δ 42.7, 69.8, 118.0, 122.7, 122.9, 125.3 (2 C), 125.9, 127.8, 128.8, 130.1, 133.6, 134.7, 139.4; $[\alpha]^{23}_D$ +97.3° (*c* 1.0, benzene). The enantioselectivity was determined to be 92% ee by HPLC analysis, using a chiral column (Chiralcel OD-H, hexane/*i*-PrOH = 9/1, flow rate = 1.0 mL/min): t_{minor} = 8.6 min (*S*), t_{major} = 14.8 min (*R*). Elemental Anal. Calcd for $C_{12}H_{14}O$: C 84.81, H 7.12. Found: C 84.83, H 7.10.

(*R*)-1-(*p*-Methoxyphenyl)-3-buten-1-ol (Entry 5 in Table 5).[18b,21,22] TLC R_f 0.27 (1:3 ethyl acetate/hexane); IR (neat) 3700−3120, 3075, 3002, 2936, 2900, 2838, 1642, 1613, 1586, 1514, 1464, 1443, 1302, 1248, 1175, 1036, 1003, 918, 872, 833, 812, 770 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 1.94 (d, 1 H, *J* = 0.9 Hz), 2.50 (d, 2 H, *J* = 6.6 Hz), 3.81 (s, 3 H), 4.69 (t, 1 H, *J* = 6.3 Hz), 5.11−5.18 (m, 2 H), 5.80 (m, 1 H), 6.89 (d, 2 H, *J* = 8.8 Hz), 7.29 (d, 2 H, *J* = 8.8 Hz); ^{13}C NMR (75 MHz, $CDCl_3$) δ 43.7, 55.2, 72.9, 113.7 (2 C), 118.1, 127.0 (2 C), 134.6, 136.0, 158.9; $[\alpha]^{23}_D$ +30.5° (*c* 1.0, benzene). The enantioselectivity was determined to be 95% ee by HPLC analysis, using a chiral column (Chiralcel OD-H, hexane/*i*-PrOH = 20/1, flow rate = 0.5 mL/min): t_{major} = 10.4 min (*R*), t_{minor} = 12.3 min (*S*). Elemental Anal. Calcd for $C_{11}H_{14}O$: C 74.13, H 7.92. Found: C 74.14, H 7.92.

(*R*)-1-(*p*-Bromophenyl)-3-buten-1-ol (Entry 6 in Table 5).[18b,22−24] TLC R_f 0.39 (1:3 ethyl acetate/hexane); IR (neat) 3680−3120, 3079, 2979, 2934, 2905, 1642, 1593, 1489, 1431, 1406, 1297, 1194, 1071, 1011, 918, 870, 826, 777, 739, 718 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 2.03 (d, 1 H, *J* = 3.0 Hz), 2.48 (m, 2 H), 4.71 (m, 1 H), 5.14−5.20 (m, 2 H), 5.80 (m, 1 H), 7.24 (d, 2 H, *J* = 8.3 Hz), 7.48 (d, 2 H, *J* = 8.3 Hz); ^{13}C NMR (75 MHz, $CDCl_3$) δ 43.6, 72.5, 118.6, 121.1, 127.5 (2 C), 131.3 (2 C), 133.9, 142.7; $[\alpha]^{24}_D$ +23.2° (*c* 1.0, benzene). The enantioselectivity was determined to be 96% ee by HPLC analysis, using a chiral column (Chiralcel OJ, hexane/*i*-PrOH

(15) Takaya, H.; Mashima, K.; Koyano, K.; Yagi, M.; Kumobayashi, H.; Taketomi, T.; Akutagawa, S.; Noyori, R. *J. Org. Chem.* **1986**, *51*, 629.

(16) (a) Ojima I.; Kogure, T. *Organometallics* **1982**, *1*, 1390. (b) Zheng G. Z.; Chan, T. H. *Organometallics* **1995,** *14*, 70.

(17) (a) Peppard, D. F.; Brown, W. G.; Johnson, W. C. *J. Am. Chem. Soc.* **1946**, *68*, 70. (b) Moedritzer, K.; Van Wazer, J. R. *Inorg. Chem.* **1964**, *3*, 268.

(18) (a) Hoffmann, R. W.; Herold, T. *Chem. Ber.* **1981**, *114*, 375. (b) Denmark, S. E.; Coe, D. M.; Pratt, N. E.; Griedel, B. D. *J. Org. Chem.* **1994**, *59*, 6161.

(19) Riediker, M.; Duthaler, R. O. Angew. *Chem., Int. Ed. Engl.* **1989**, *28*, 494.

(20) (a) Kusakabe, M.; Kitano, Y.; Kobayashi, Y.; Sato, F. *J. Org. Chem.* **1989**, *54*, 2085. (b) Racherla, U. S.; Liao, Y.; Brown, H. C. *J. Org. Chem.* **1992**, *57*, 6614.

(21) Sugimoto, K.; Aoyagi, S.; Chibayashi, C. *J. Org. Chem.* **1997**, *62*, 2322.

(22) Motoyama, Y.; Okano, M.; Narusawa, H.; Makihara, N.; Aoki, K.; Nishiyama, H. *Organometallics* **2001**, *20*, 1580.

(23) For another method of preparation of the racemic compound, see: (a) Chen, C.; Shen, Y.; Huang, Y.-Z. *Tetrahedron Lett.* **1988**, *29*, 1395. For a method of analytical resolution of the racemic compound, see: (b) Halterman, R. L.; Roush, W. R.; Hoong, L. K. *J. Org. Chem.* **1987**, *52*, 1152.

(24) Yamada, K.; Tozawa, T.; Nishida, M.; Mukaiyama, T. *Bull. Chem. Soc. Jpn.* **1997**, *70*, 2301.

= 9/1, flow rate = 0.5 mL/min): t_{minor} = 15.1 min (*S*), t_{major} = 16.2 min (*R*). Elemental Anal. Calcd for $C_{10}H_{11}BrO$: C 52.89, H 4.88. Found: C 52.88, H 4.88.

(*R*)-1-(*o*-Tolyl)-3-buten-1-ol (Entry 7 in Table 5).[2h,18b,22] TLC R_f 0.40 (1:3 ethyl acetate/hexane); IR (neat) 3650−3125, 3075, 3025, 2979, 1640, 1489, 1462, 1051, 916, 870, 756, 725 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 1.94 (d, 1 H, J = 2.5 Hz), 2.36 (s, 3 H), 2.47 (m, 2 H), 4.99 (m, 1 H), 5.16−5.23 (m, 2 H), 5.88 (m, 1 H), 7.13−7.27 (m, 3 H), 7.50 (d, 1 H, J = 7.4 Hz); $[\alpha]^{24}_D$ +75.5° (*c* 1.0, benzene). The enantioselectivity was determined to be 97% ee by HPLC analysis, using a chiral column (Chiralcel AD, hexane/*i*-PrOH = 20/1, flow rate = 0.5 mL/min): t_{major} = 15.7 min (*R*), t_{minor} = 18.2 min (*S*). Elemental Anal. Calcd for $C_{11}H_{14}O$: C 81.44, H 8.70. Found: C 81.44, H 8.69.

(*R*)-1-Cyclohexyl-3-buten-1-ol (Entry 8 in Table 5).[2k] TLC R_f 0.25 (1:5 ethyl acetate/hexane); IR (neat) 3700−3120, 1641, 1451, 1036, 986, 911, cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 0.8−1.4 (m, 5 H), 1.54 (d, 1 H, J = 6.9 Hz), 1.60−1.92 (m, 6 H), 2.07−2.18 (m, 1 H), 2.29−2.38 (m, 1 H), 3.40 (m, 1 H), 5.15 (m, 2 H), 5.87 (m, 1 H); $[\alpha]^{25}_D$ +13.7° (*c* 1.0, ethanol). The enantioselectivity was determined to be 93% ee by HPLC analysis of the 3,5-dinitrobenzoate of the product prepared by esterification (3,5-dinitrobenzoyl chloride, triethylamine/1,2-dichloroethane), using a chiral column (Chiralcel OD-H, hexane/EtOH = 50/1, flow rate = 1.0 mL/min): t_{major} = 12.1 min (*R*), t_{minor} = 13.1 min (*S*). Elemental Anal. Calcd for $C_{10}H_{17}O$: C 77.87, H 11.76. Found: C 77.87, H 11.76.

(*S*)-1-Phenyl-5-hexen-3-ol (Entry 9 in Table 5).[2k,21,22,24,25] TLC R_f 0.33 (1:3 ethyl acetate/hexane); IR (neat) 3700−3120, 3027, 2930, 2863, 1642, 1603, 1497, 1455, 1075, 1049, 1040, 995, 916, 747, 700 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 1.60 (d, 1 H, J = 1.9 Hz), 1.80 (m, 2 H), 2.16−2.23 (m, 1 H), 2.29−2.36 (m, 1 H), 2.64−2.84 (m, 2 H), 3.68 (m, 1 H), 5.15 (d, 2 H, J = 11.8 Hz), 5.75−5.86 (s, 1 H), 7.16−7.31 (m, 5 H); $[\alpha]^{24}_D$ −26.4° (*c* 1.0, benzene). The enantioselectivity was determined to be 86% ee by HPLC analysis, using a chiral column (Chiralcel OD-H, hexane/*i*-PrOH = 20/1, flow rate = 0.5 mL/min): t_{major} = 19.6 min (*S*), t_{minor} = 30.2 min (*R*). Elemental Anal. Calcd for $C_{12}H_{16}O$: C 81.77, H 9.15. Found: C 81.77, H 9.16.

(1*R*,2*R*)-2-Methy-1-phenyl-3-buten-1-ol (Table 6).[26] The α/γ and anti/syn ratios were determined to be <1/99 and 85/15, respectively, by ^1H NMR analysis. The enantioselectivities of the anti and syn isomers were determined to be 95% ee and 75% ee, respectively, by HPLC analysis, using a chiral column (Chiralcel OD-H, hexane/*i*-PrOH = 40/1, flow rate = 0.5 mL/min): $t_{anti-minor}$ = 15.0 min (1*S*,2*S*), $t_{syn-minor}$ = 15.5 min (1*S*,2*R*), $t_{anti-major+syn-major}$ = 17.8 min (1*R*,2*R* + 1*R*,2*S*). The absolute configuration of the major anti isomer was determined to be 1*R*,2*R* by comparison of the $[\alpha]_D$ value with reported data. (1*S*,2*S*)-enriched alcohol (66% ee): $[\alpha]^{25}_D$ −73.4 (*c* 2.0, $CHCl_3$).[26] (1*S*,2*R*)-Isomer (55% ee): $[\alpha]^{25}_D$ −15.0 (*c* 0.93, $CHCl_3$).[26] Observed $[\alpha]_D$ value of the product: $[\alpha]^{25}_D$ +112.4 (*c* 1.0, $CHCl_3$; data obtained on a 85:15 mixture of anti and syn isomers). The absolute configuration of the major syn isomer was determined to be 1*R*,2*S* by HPLC analysis.[22] Elemental Anal. Calcd for $C_{11}H_{14}O$: C 81.44, H 8.70. Found: C 81.44, H 8.70. Spectral data obtained on a 85:15 mixture of anti and syn isomers: TLC R_f 0.38 (1:5 ethyl acetate/hexane); IR (neat) 3630−3130, 3081, 3065, 3031, 2977, 2932, 2872, 1640, 1603, 1495, 1455, 1374, 1196, 1117, 1076, 1021, 914, 762, 702 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$, anti isomer) δ 0.87 (d, 3 H, J = 6.9 Hz), 2.16 (d, 1 H, J = 2.7 Hz), 2.48 (m, 1 H), 4.36 (dd, 1 H, J = 8.1, 2.4 Hz), 5.17−5.24 (m, 2 H), 5.75−5.87 (m, 1 H), 7.26−7.36 (m, 5 H); ^{13}C NMR (75 MHz, $CDCl_3$, anti isomer) δ 16.5, 46.3, 77.8, 116.9, 126.8 (2 C), 127.6, 128.2 (2 C), 140.6, 142.4.

Typical Experimental Procedure for Asymmetric Aldol Reaction of Trimethoxysilyl Enol Ethers with Aldehydes Catalyzed by (*R*)-BINAP·AgOTf and KF·18-Crown-6 Complexes: Synthesis of 2-(Hydroxyphenylmethyl)cyclohexanone (Entry 2 in Table 7, Entry 1 in Table 8).[13,27] A mixture of AgOTf (51.4 mg, 0.200 mmol), (*R*)-BINAP (74.7 mg, 0.120 mmol), KF (5.8 mg, 0.1 mmol), and 18-crown-6 (400 μL, 0.25 M in THF) was dissolved in anhydrous THF (12 mL) under argon atmosphere and with direct light excluded and stirred at 20 °C for 30 min. To the resulting solution was added dropwise benzaldehyde (203.3 μL, 2.00 mmol) and (1-cyclohexenyloxy)trimethoxysilane (414.7 μL, 2.00 mmol) successively at −20 °C. The mixture was stirred for 6 h at this temperature and then treated with brine (6 mL) and solid KF (ca. 1 g) at ambient temperature for 30 min. The resulting precipitate was filtered off by a glass filter funnel filled with Celite and silica gel. The filtrate was dried over Na_2SO_4 and concentrated in vacuo after filtration. The residual crude product was purified by column chromatography on silica gel (1:10 ethyl acetate/hexane as the eluant) to afford a mixture of the aldol adducts (317.2 mg, 78% yield) as white solids. The anti (*R**,*S**)/syn (*R**,*R**) ratio was determined to be 91/9 by ^1H NMR analysis. The enantioselectivities of the anti and syn isomers were determined to be 93% ee and 22% ee, respectively, by HPLC analysis, using a chiral column (Chiralcel OD-H, hexane/*i*-PrOH = 20/1, flow rate = 0.5 mL/min): $t_{syn-minor}$ = 18.3 min (2*S*,1′*S*), $t_{syn-major}$ = 20.4 min (2*R*,1′*R*), $t_{anti-major}$ = 24.4 min (2*S*,1′*R*), $t_{anti-minor}$ = 39.4 min (2*R*,1′*S*). The absolute configurations of all stereoisomers were unambiguously established by Denmark and co-workers.[13c] Specific rotation of the anti isomer (93% ee): $[\alpha]^{29}_D$ +20.1° (*c* 1.0, $CHCl_3$). Elemental Anal. Calcd for $C_{13}H_{16}O_2$: C 76.44, H 7.90. Found: C 76.35, H 7.96. Specific rotation of the syn isomer (22% ee): $[\alpha]^{28}_D$ +37.1° (*c* 1.0, $CHCl_3$). Elemental Anal. Calcd for $C_{13}H_{16}O_2$: C 76.44, H 7.90. Found: C 76.10, H 8.23. Other spectral data (TLC, IR, ^1H NMR, and ^{13}C NMR) of the anti and syn isomers indicated good agreement with reported data.[8c,13,27]

1-Hydroxy-2,4,4-trimethyl-1-phenyl-3-pentanone (Entry 4 in Table 7).[5c,8c,28] The anti/syn ratio was determined to be <1/99 by ^1H NMR analysis. The enantioselectivity of the syn isomer was determined to be 90% ee by HPLC analysis, using a chiral column (Chiralcel OD-H, hexane/*i*-PrOH = 40/1, flow rate = 0.5 mL/min): $t_{syn-minor}$ = 17.8 min, $t_{syn-major}$ = 19.0 min. Specific rotation of the syn isomer (90% ee): $[\alpha]^{29}_D$ −75.3° (*c* 1.0, $CHCl_3$). Other spectral data (IR and ^1H NMR) of the syn isomer indicated good agreement with reported data.[5c,8c,28]

2-[(*E*)-1-Hydroxy-3-phenyl-2-propenyl]cyclohexanone (Entry 2 in Table 8).[5d,8c,13,27] The anti (*R**,*S**)/syn (*R**,*R**) ratio was determined to be 73/27 by ^1H NMR analysis. The enantioselectivities of the anti and syn isomers were determined to be 89% ee and 33% ee, respectively, by HPLC analysis, using a chiral column (Chiralpak AD, hexane/*i*-PrOH = 40/1, flow rate = 0.5 mL/min): $t_{syn-minor}$ = 77.2 min, $t_{syn-major}$ = 98.2 min, $t_{anti-major}$ = 106.3 min (2*S*,1′*R*), $t_{anti-minor}$ = 121.9 min (2*R*,1′*S*). The absolute configurations of the anti isomers were assigned by Denmark and co-workers.[13] Specific rotation of the anti isomer (89% ee): $[\alpha]^{29}_D$ −18.3° (*c* 1.0, $CHCl_3$). Elemental Anal. Calcd for $C_{15}H_{18}O_2$: C 78.23, H 7.88. Found: C 78.22, H 8.14. Specific rotation of the syn isomer (33% ee): $[\alpha]^{30}_D$ −6.6° (*c* 1.0, $CHCl_3$). Elemental Anal. Calcd for $C_{15}H_{18}O_2$: C 78.23, H 7.88. Found: C 78.12, H 8.12. Other spectral data (TLC, IR, ^1H NMR, and ^{13}C NMR) of the anti and syn isomers indicated good agreement with reported data.[5d,8c,13a−c]

2-[(1-Naphthyl)hydroxymethyl]cyclohexanone (Entry 3 in Table 8).[13b,c] The anti (*R**,*S**)/syn (*R**,*R**) ratio was determined to be 95/5 by ^1H NMR analysis. The enantioselec-

(25) (a) Seebach, D.; Imwinkelried, R.; Stucky, G. *Helv. Chim. Acta* **1987**, *70*, 448. (b) Minowa, N.; Mukaiyama, T. *Bull. Chem. Soc. Jpn.* **1987**, *60*, 3697.

(26) Roush, W. R.; Ando, K.; Powers, D. B.; Palkowitz, A. D.; Halterman, R. L. *J. Am. Chem. Soc.* **1990**, *112*, 6339.

(27) Juaristi, E.; Beck, A. K.; Hansen, J.; Matt, T.; Mukhopadhyay, T.; Simson, M.; Seebach, D. *Synthesis* **1993**, 1271.

tivities of the anti and syn isomers were determined to be 90% ee and 48% ee, respectively, by HPLC analysis, using a chiral column (Chiralcel OD-H, hexane/*i*-PrOH = 40/1, flow rate = 0.5 mL/min): $t_{syn-major}$ = 34.3 min, $t_{syn-minor}$ = 47.8 min, $t_{anti-minor}$ = 92.4 min (2*R*,1′*S*), $t_{anti-major}$ = 98.6 min (2*S*,1′*R*). The absolute configurations of the anti isomers were assigned by Denmark and co-workers.[13b,c] Specific rotation of the anti isomer (90% ee): $[\alpha]^{28}_D$ +7.1° (*c* 1.0, $CHCl_3$). Elemental Anal. Calcd for $C_{17}H_{18}O_2$: C 80.28, H 7.13. Found: C 80.29, H 7.31. Specific rotation of the syn isomer (48% ee): $[\alpha]^{29}_D$ +40.1° (*c* 1.0, $CHCl_3$). Elemental Anal. Calcd for $C_{17}H_{18}O_2$: C 80.28, H 7.13. Found: C 80.27, H 7.27. Other spectral data (TLC, IR, ^{1}H NMR, and ^{13}C NMR) of the anti and syn isomers indicated good agreement with reported data.[13b,c]

2-[Hydroxy(4-methoxyphenyl)methyl]cyclohexanone (Entry 4 in Table 8).[29] The anti (*R**,*S**)/syn (*R**,*R**) ratio was determined to be 91/9 by ^{1}H NMR analysis. The enantioselectivities of the anti and syn isomers were determined to be 93% ee and 19% ee, respectively, by HPLC analysis, using a chiral column (Chiralcel OD-H, hexane/*i*-PrOH = 20/1, flow rate = 0.25 mL/min): $t_{syn-major}$ = 53.0 min, $t_{syn-minor}$ = 55.8 min, $t_{anti-major}$ = 70.2 min, $t_{anti-minor}$ = 99.8 min. Specific rotation of the anti isomer (93% ee): $[\alpha]^{29}_D$ +19.2° (*c* 1.0, $CHCl_3$). Elemental Anal. Calcd for $C_{14}H_{18}O_3$: C 71.77, H 7.74. Found: C 71.70, H 7.86. Specific rotation of the syn isomer (19% ee): $[\alpha]^{27}_D$ +9.8° (*c* 1.0, $CHCl_3$). Elemental Anal. Calcd for $C_{14}H_{18}O_3$: C 71.77, H 7.74. Found: C 71.61, H 7.78. Other spectral data (TLC, IR, ^{1}H NMR, and ^{13}C NMR) of the anti and syn isomers indicated good agreement with reported data.[29]

2-[(4-Bromophenyl)hydroxymethyl]cyclohexanone (Entry 5 in Table 8).[8c,29c,30] The anti (*R**,*S**)/syn (*R**,*R**) ratio was determined to be 92/8 by ^{1}H NMR analysis. Specific rotation of the anti isomer (white solids, 95% ee): $[\alpha]^{29}_D$ +17.4° (*c* 1.0, $CHCl_3$). Elemental Anal. Calcd for $C_{13}H_{15}O_2Br$: C 55.14, H 5.34. Found: C 55.07, H 5.41. The enantioselectivity was determined to be 95% ee by HPLC analysis, using a chiral column (Chiralcel OB-H, hexane/*i*-PrOH = 40/1, flow rate = 0.5 mL/min): t_{major} = 43.3 min, t_{minor} = 52.9 min. Specific rotation of the syn isomer (white solids, 37% ee): $[\alpha]^{29}_D$ +49.5 (*c* 1.0, $CHCl_3$). Elemental Anal. Calcd for $C_{13}H_{15}O_2Br$: C 55.14, H 5.34. Found: C 55.04, H 5.39. The enantioselectivity was determined to be 37% ee by HPLC analysis, using a chiral column (Chiralcel OD-H, Daicel Chemical Industries, Ltd., hexane/*i*-PrOH = 40/1, flow rate = 0.5 mL/min): t_{major} = 45.8 min, t_{minor} = 58.9 min. Spectral data (TLC, IR, ^{1}H NMR, and ^{13}C NMR) of the anti and syn isomers indicated good agreement with reported data.[8c,29c,30]

2-(1-Hydroxy-3-phenylpropyl)cyclohexanone (Entry 6 in Table 8).[13b,c] The anti (*R**,*R**)/syn (*R**,*S**) ratio was determined to be 79/21 by ^{1}H NMR analysis. The enantioselectivities of the anti and syn isomers were determined to be 83% ee and 57% ee, respectively, by HPLC analysis, using a chiral column (Chiralcel OD-H and AD, hexane/*i*-PrOH = 20/1, flow rate = 0.5 mL/min): $t_{anti-major}$ = 45.0 min, $t_{syn-minor}$ = 47.1 min, $t_{anti-minor}$ = 51.2 min, $t_{syn-major}$ = 56.8 min. Observed $[\alpha]_D$ value of the product: $[\alpha]^{26}_D$ −11.8 (*c* 1.0, $CHCl_3$; data obtained on a 79:21 mixture of anti and syn isomers). Elemental Anal. Calcd for $C_{14}H_{18}O_3$: C 77.55, H 8.68. Found: C 77.35, H 8,84. Other spectral data (TLC, IR, ^{1}H NMR, and ^{13}C NMR) of the anti and syn isomers indicated good agreement with reported data.[13b,c]

Note Added after ASAP Posting. There was an error in the *E*/*Z* ratio of the first entry in Table 6, an erroneous graphic in Table 6, an error in the spelling of trimethoxysilyl enol ether in Condition B of Table 7, and other minor typographical errors in the version posted June 19, 2003; the corrected version was posted June 20, 2003.

Acknowledgment. We thank Takasago International Corporation for its generous gift of (*R*)-SEGPHOS, (*S*)-DM-BINAP, (*R*)-H_8-BINAP, and (*R*)-H_8-DM-BINAP.

JO020691C

(28) (a) Ando, A.; Shioiri, T. *Tetrahedron* **1989**, *45*, 4969. (b) Ando, A.; Tatematsu, T.; Shioiri, T. *Chem. Pharm. Bull.* **1991**, *39*, 1967. (c) Heathcock, C. H.; Buse, C. T.; Kleschick, W. A.; Prirung, M. C.; Sohn, J. E.; Lampe, J. *J. Org. Chem.* **1980**, *45*, 1066.

(29) (a) Nakamura, E.; Shimizu, M.; Kuwajima, I.; Sakata, J.; Yokoyama, K.; Noyori, R. *J. Org. Chem.* **1983**, *48*, 932. (b) Kobayashi, S.; Hachiya, I. *J. Org. Chem.* **1994**, *59*, 3590. (c) Yanagisawa, A.; Asakawa, K.; Yamamoto, H. *Chirality* **2000**, *12*, 421.

(30) Huang, Y.-Z.; Chen, C.; Shen, Y. *J. Chem. Soc., Perkin Trans. 1* **1988**, 2855.