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Chiral Schiff Bases as Highly Active and Enantioselective Catalysts in Catalytic Addition of Dialkylzinc to Aldehydes

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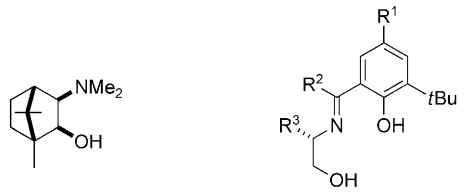
Dedicated to Professor Ryoji Noyori on the occasion of his 70th birthday

Abstract: We have developed chiral Schiff base catalysts based on the *ONO*-tridentate ligand for the catalytic enantioselective addition of dialkylzinc to aldehydes. Various aldehydes were smoothly converted into corresponding optically active secondary alcohols with high enantioselectivity (up to 98% *ee*) in high yield. Furthermore, we have succeeded in decreasing the catalyst loading minimum to 0.1 mol% in the chiral Schiff base-catalyzed enantioselective alkylation of aldehydes.

Keywords: aldehydes · alkylation · asymmetric catalysis · enantioselectivity · Schiff bases

Introduction

Dialkylzinc reagents are inert to carbonyl compounds because these molecules have linear structures and a C–Zn bond with low polarity. However, once the linearity is lost because of the coordination of zinc atom to a heteroatom, these reagents can react with aldehydes. After Oguni and Omi's first report,[1] a number of chiral amino alcohols have been developed for the catalytic asymmetric 1,2-addition of dialkylzinc to aldehydes, and one that achieves high enantioselectivity has been reported.[2] As a pioneering work, Noyori and Kitamura et al. developed (−)-DAIB ((−)-3-exo-(dimethylamino)isoborneol: **1**; see Figure 1) as a chiral β-amino alcohol and achieved highly enantioselective alkylation using dialkylzinc.[3] So far, most of the catalysts used for the asymmetric addition of dialkylzinc to aldehydes are chiral β-amino alcohol derivatives.[4] Furthermore, 2 or more mol% catalysts are often used for this asymmetric reaction. To our knowledge, there are only three studies that used *ONO*-tridentate ligands[5] and all of them afforded alkylated products in low enantiomeric excess compared with bidentate amino alcohols. For example, Corey and Hannon reported that the enantioselective ethylation of benzaldehyde catalyzed by 12 mol% tridentate ligand derived from (+)-pseudoephedrine gives a product in 86% *ee*.[5a]



(−)-DAIB (**1**)
β-amino alcohol (*ON*-bidentate ligand)

(*S*)-chiral Schiff base (**2**)
ONO-tridentate ligand

Figure 1. Chiral catalysts for enantioselective alkylation using dialkylzinc.

A variety of innovative studies have been reported in this exciting field. Examples include an asymmetric reaction system that uses a combination of dialkylzinc and titanium alkoxide,[6] asymmetric amplification,[4,7] and asymmetric autocatalysis.[8] Recently, Harada and Kanda reported that a titanium(IV) complex derived from 3-(3,5-diphenylphenyl)-binaphthol exhibits remarkably enhanced catalytic activity for the asymmetric addition of diethylzinc to aldehydes.[9] They achieved high enantioselectivity using less than 1 mol% unsymmetric 3-(3,5-diphenylphenyl)-binaphthol.

Following the report of enantioselective cyclopropanation of olefins using a chiral Schiff base-copper complex by Nozaki, Moriuchi, Takaya, and Noyori in 1966,[10] which is the first example of a homogeneous catalytic asymmetric reaction, catalytic asymmetric reactions in the presence of metal catalysts and chiral Schiff base as ligand have been ac-

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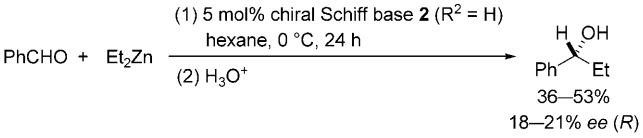
tively investigated. We prepared chiral Schiff base **2** from salicylaldehydes (or ketones), which possesses a bulky substituent at the ortho position on the phenolic hydroxyl group, and chiral amino alcohols for the enantioselective trimethylsilylcyanation of aldehydes in 1991.[11] Subsequent to our first report, a number of asymmetric reactions using this type of chiral Schiff base ligand have been reported.[12]

Herein, we describe the synthesis of a new chiral Schiff base as a new *ONO*-tridentate ligand and its application to the highly enantioselective alkylation of aldehydes using dialkylzinc reagents.[13]

Results and Discussion

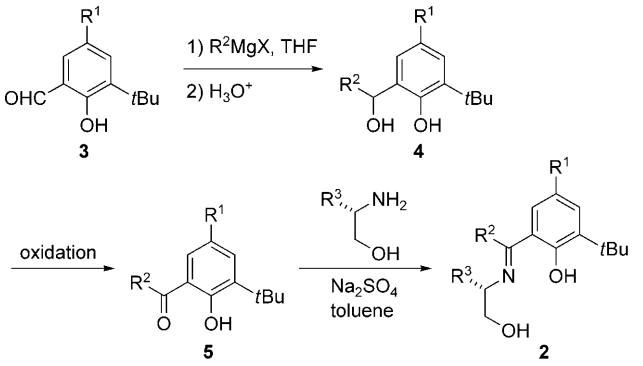
We first examined the asymmetric addition of diethylzinc to aldehydes with aldimine-type chiral Schiff bases **2** ($R^2=H$). Aldimine-type chiral Schiff bases **2** in Figure 1 were prepared easily from 3-*tert*-butyl-2-hydroxybenzaldehydes and chiral amino alcohols.[14] Unfortunately, we found that the desired alkylated product was obtained in moderate yield (36–53%) and poor enantioselectivity (18–21% *ee* (*R*); (Scheme 1)). Thus, we explored the utility of more effective



Scheme 1. Asymmetric addition of Et_2Zn using aldimine-type chiral Schiff base.

chiral Schiff bases as an *ONO*-tridentate ligand for asymmetric alkylation, and found that the use of ketoimine-type chiral Schiff bases **2** ($R^2 \neq H$) developed previously by our group[15] increased both the reactivity and enantioselectivity.

Ketoimine-type chiral Schiff bases **2** ($R^2 \neq H$) were prepared in three steps: the Grignard reaction of salicylaldehydes **3** with R^2MgX; oxidation of benzylic alcohols; and condensation with chiral amino alcohols (Scheme 2). Salicylaldehydes **3** were obtained following Casnati's method,[16] the Duff reaction,[17] or from a commercial source. The crucial step was the oxidation of benzylic alcohols **4** to ketones



Scheme 2. Synthesis of ketoimine-type chiral Schiff bases **2** ($R^2 \neq H$).

5. First, we tried the conventional method using chromium trioxide (CrO_3); however, it afforded ketones **5** in only up to 30% yield because of the oxidative decomposition of the phenolic moiety. Faced with the necessity to develop a new and efficient oxidation method for benzylic alcohols possessing a phenolic moiety, we succeeded in the oxidation of benzylic alcohols **4** using two new methods. The first method employs the Pd/C-ethylene system.[18] This oxidized the benzylic alcohol to the corresponding ketone based on hydrogen-transfer reaction. Utilizing 30 wt% of 10% Pd/C under ethylene atmosphere, ketone **5** was obtained in 83% yield ($R^1=H$, $R^2=Ph$). Very recently, we have developed a method for the aerobic oxidation of benzylic alcohols using activated carbon without a metal.[19] Using 50 wt% activated carbon under molecular oxygen atmosphere, ketone **5** was obtained in 77% yield ($R^1=t$Bu, $R^2=Ph$). This simple oxidation process is not only environmentally friendly but also economical and operationally simple. Chiral β-amino alcohols were prepared by the direct reduction of α-amino acid according to the methods developed by Abiko[20] and Meyers.[21] Thus, ketoimine-type chiral Schiff bases were prepared easily. Furthermore, it should be mentioned that ketoimine-type chiral Schiff bases are more stable in water and protic acid than their aldimine-type counterparts.

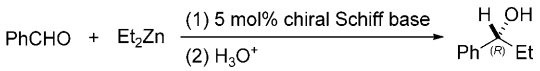
Using these ketoimine-type chiral Schiff bases, we examined the asymmetric addition of diethylzinc to benzaldehyde in hexane at 0°C (Table 1). In the case of the chiral Schiff bases derived from (*S*)-valinol ($R^3=i$Pr), the enantiomeric excess of the alkylated products was not so high (Table 1, entries 1–7). On the other hand, the use of the chiral Schiff base derived from (*S*)-*tert*-leucinol ($R^3=t$Bu) gave high enantioselectivities (Table 1, entries 8–12). Especially, chiral Schiff base **2i** afforded (*R*)-1-phenyl-1-propanol in 94% yield and 96% *ee* (Table 1, entry 9). Even if the amount of chiral Schiff base **2i** was decreased to 1 mol%, the same levels of chemical and optical yields were attained (Table 1, entry 10).

Table 2 lists various aldehydes examined with 1 mol% chiral Schiff base **2i** under optimized conditions. The reactions of aromatic aldehydes with Et_2Zn proceeded to give ethylated products in high yields and enantioselectivities (Table 2, entries 1–6). Hetero-aromatic aldehydes were also

Abstract in Japanese:

私たちが独自に開発したサリチルアルデヒド（もしくはケトン）と光学活性アミノアルコールとより容易に調製可能な光学活性シッフ塩基型配位子を有機亜鉛反応剤のアルデヒドへの不斉付加反応に適応した。反応は各種アルデヒドに対しても進行し、高い収率および最高98% *ee* と高エナンチオ選択性で様々な光学活性第二級アルコールが得られた。さらに、触媒量を0.1 mol%まで低減化しても、高いエナンチオ選択性にて生成物を与えることを見いだした。

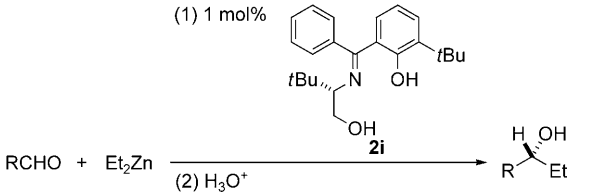
Table 1. Asymmetric addition of Et_2Zn to benzaldehyde using keto-imine-type chiral Schiff base **2**[a]



Entry	Chiral Schiff base **2**	R^1	R^2	R^3	Yield[b] [%]	*ee*[c,d] [%]
1	**2a**	H	Me	*i*Pr	84	88
2	**2b**	H	Ph	*i*Pr	95	90
3	**2c**	*t*Bu	Ph	*i*Pr	87	76
4	**2d**	H	4-*t*Bu−C_6H_4	*i*Pr	90	86
5	**2e**	*t*Bu	4-*t*Bu−C_6H_4	*i*Pr	81	63
6	**2f**	H	2-Np	*i*Pr	93	87
7	**2g**	*t*Bu	2-Np	*i*Pr	93	56
8	**2h**	H	Me	*t*Bu	90	94
9	**2i**	H	Ph	*t*Bu	94	96
10[e]	**2i**	H	Ph	*t*Bu	88	96
11[e]	**2j**	*t*Bu	Ph	*t*Bu	85	96
12[e]	**2k**	H	2-Np	*t*Bu	92	95

[a] All reactions were carried out in hexane at 0 °C for 24 h. [b] Determined by ^{1}H NMR analysis after silica-gel column chromatography. [c] Enantiomeric excess was determined by a chiral HPLC analysis (CHIRALCEL OD-H). [d] Absolute configuration was determined as *R* by comparison of optical rotation values with those in the literature.[22a] [e] 1 mol % chiral Schiff base was used.

Table 2. Asymmetric addition of Et_2Zn to various aldehydes.[a]



Entry	R	Yield[b] [%]	*ee*[c,d] [%]
1	Ph	88 (86)	96 (95) (*R*)
2	4-MeO−C_6H_4	96 (90)	80 (84) (*R*)
3	4-Cl−C_6H_4	92	90 (*R*)
4	2-F−C_6H_4	94	94 (*R*)
5	1-Np	98	65 (*R*)
6	2-Np	99	96 (*R*)
7	2-furyl	82	90 (*R*)[e]
8	2-thienyl	99	95 (*R*)[e]
9	PhC≡C	85	60 (*R*)
10	(*E*)-PhCH=CH	69 (55)	75 (76) (*R*)
11	$PhCH_2CH_2$	75 (81)	81 (83) (*R*)
12	*n*-C_5H_{11}	45	81 (*R*)[e]
13	*c*-C_6H_{11}	67	94 (*R*)[e]

[a] All reactions were carried out in hexane at 0 °C for 24 h. Values in parentheses are the yields obtained when toluene was used as solvent. [b] Isolated yield after Kugelrohr distillation. [c] Enantiomeric excess was determined by a chiral HPLC analysis (CHIRALCEL OD-H and OB). [d] All absolute configurations were determined as *R* by comparison of optical rotation values with those in the literature.[22a–d] [e] Determined by HPLC analysis of the corresponding benzoate using CHIRALPAK AD-H column.

ethylated effectively by a chiral Schiff base **2i**; noteworthy is 2-thiophenecarboxaldehyde, which gave a product in 99 % yield and 95 % *ee* (Table 2, entry 7 and 8). It should be noted that the present zinc Schiff base catalyst system is effective not only for aromatic aldehydes but also for aliphatic aldehydes. For example, the reaction of cyclohexanecarboxaldehyde with diethylzinc aided by 1 mol % chiral Schiff base **2i** gave an ethylated product in 94 % *ee* (Table 2, entry 13).

Next, we focused on catalytic activity for the asymmetric addition of diethylzinc to aldehydes. Novel chiral Schiff bases **2l–2o** possessing OMe or CF_3 groups were prepared according to the procedure shown in Scheme 2 (Figure 2). Using novel chiral Schiff bases **2m** and **2o**, the asymmetric addition of Et_2Zn to benzaldehyde was examined at very low catalyst load (Table 3). Even if the amount of chiral Schiff base **2m** and **2o** were decreased to 0.1 mol %, the same levels of chemical yield and enantiomeric excess (95 % *ee*) were obtained.

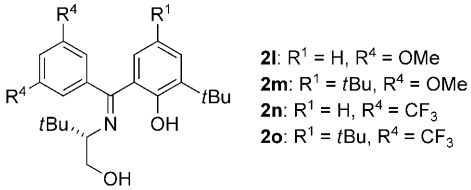


Figure 2. Novel chiral Schiff bases **2l–2o** possessing OMe or CF_3 groups.

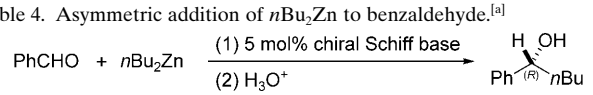
Table 3. Reduction of catalyst loading in asymmetric addition of Et_2Zn to benzaldehyde using chiral Schiff base.[a]

Entry	Catalyst	Catalyst loading [mol %]	Yield[b] [%]	*ee*[c] [%]
1	**2i**	1.0	88	96
2	**2i**	0.5	88	96
3	**2i**	0.1	71	90
4	**2m**	1.0	93	96
5	**2m**	0.5	92	96
6	**2m**	0.1	99	95
7	**2o**	1.0	91	96
8	**2o**	0.5	93	96
9	**2o**	0.1	74	95

[a] All reactions were carried out on the 1.8 mmol scale in hexane at 0 °C for 24 h. [b] Isolated yield after Kugelrohr distillation. [c] Enantiomeric excess was determined by a chiral HPLC analysis (CHIRALCEL OD-H).

The asymmetric *n*-butylation of aldehydes using di-*n*-butylzinc reagent (nBu_2Zn) was also examined.[23] As shown in Table 4, the reaction of nBu_2Zn with benzaldehyde proceeded smoothly in the presence of 5 mol % chiral Schiff bases **2i–2o** to give (*R*)-1-phenyl-1-pentanol in high enantiomeric purity. It should be noted that the reduction of benzaldehyde occurred in the case of nBu_2Zn.[24] Five mol % chiral Schiff base was required in the asymmetric addition of nBu_2Zn to benzaldehyde to obtain the desired product in a satisfactory yield. We disclosed that chiral Schiff base **2m** was the most effective catalyst for the asymmetric *n*-butylation at 20 °C (Table 4, entry 4). Then, we examined the reactions at lower temperatures using chiral Schiff base **2m** (Table 4, entries 5 and 6). Chiral Schiff base **2m** afforded an *n*-butylated product in 83 % yield and 98 % *ee* at 0 °C, and

Table 4. Asymmetric addition of nBu$_2$Zn to benzaldehyde.[a]



Entry	Schiff base	Temperature [°C]	Yield [%][b,c]	*ee* [%][d,e]
1[f]	**2i**	20	73 (17)	95
2	**2j**	20	80 (13)	97
3	**2l**	20	81 (14)	97
4	**2m**	20	82 (10)	97
5	**2m**	10	79 (9)	98
6[f]	**2m**	0	83 (6)	98
7	**2n**	20	77 (19)	96
8	**2o**	20	73 (13)	96

[a] All reactions were carried out in hexane/heptane (1:7) for 6 h, unless otherwise noted. [b] Isolated yield after Kugelrohr distillation. [c] Values in parentheses indicate yield of benzyl alcohol as a reduced product. [d] Enantiomeric excess was determined by a chiral HPLC analysis (CHIRALCEL OB). [e] Absolute configuration was determined as *R* by comparison of optical rotation values with those in the literature.[22e] [f] Reaction time was 24 h.

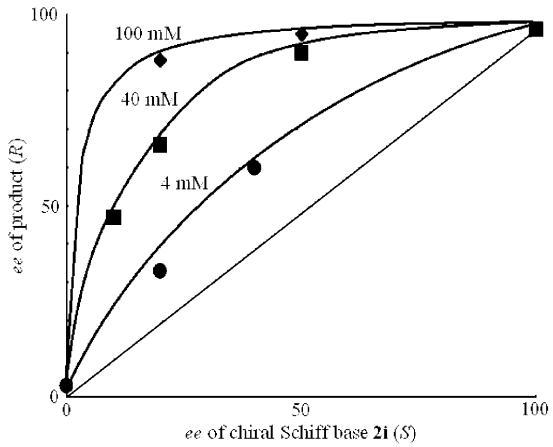
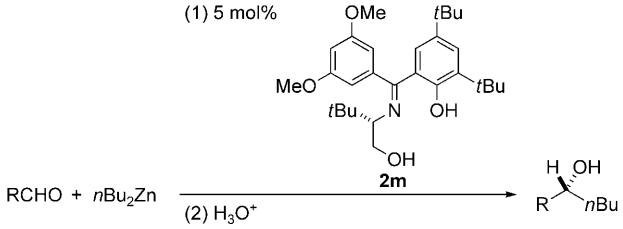


Figure 3. Correlation between *ee* of alkylated product and *ee* of chiral Schiff base **2i**; reaction using 0.8 M Et$_2$Zn, 0.4 M PhCHO, and chiral Schiff base **2i** (●: 4 mM, ■: 40 mM, ◆: 100 mM) in hexane at 0 °C for 24 h.

suppressed the formation of the side reduction product to only 6%.

Table 5 shows the asymmetric addition of nBu$_2$Zn to various aldehydes using the chiral Schiff base **2m**. Most aromatic and hetero-aromatic aldehydes were *n*-butylated in high yield and enantiomeric excess (Table 5, entries 1–8, 82–98% *ee*).

Table 5. Asymmetric addition of nBu$_2$Zn to various aldehydes.[a]



Entry	R	Yield[b] [%]	*ee*[c,d] [%]
1	Ph	83	98 (*R*)
2	4-Me−C$_6$H$_4$	82	97 (*R*)
3	4-MeO−C$_6$H$_4$	81	85 (*R*)[e]
4	3-Cl−C$_6$H$_4$	79	97 (*R*)[e]
5	4-Cl−C$_6$H$_4$	74	98 (*R*)
6	2-furyl	73	93 (*R*)[f]
7	2-thienyl	82	98 (*R*)[f]
8	(*E*)-PhCH=CH	73	82 (*R*)

[a] All reactions were carried out in heptane/hexane (7:1) at 0 °C for 24 h. [b] Isolated yield after Kugelrohr distillation. [c] Enantiomeric excess was determined by a chiral HPLC analysis (CHIRALCEL OB and OD-H). [d] Absolute configurations were determined as *R* by comparison of optical rotation values with those in the literature.[22e–i] [e] Absolute configurations were determined as *R* by comparison with the retention time in HPLC analyses. [f] Determined by HPLC analysis of the corresponding benzoate using CHIRALPAK AD-H column.

The non-linear effect, which is the relationship between the enantiomeric excess of the alkylated product and chiral Schiff base **2i**, was studied in the asymmetric addition of Et$_2$Zn to benzaldehyde (Figure 3). Noyori and Kitamura et al. investigated the mechanism of the positive non-linear effect (namely, asymmetric amplification) by conducting ^{1}H NMR analysis, X-ray analysis, and calculations using (−)-DAIB as a catalyst, and concluded that the difference in reactivity between heterodimer and homodimer is the origin of the asymmetric amplification.[4,7,25] We disclosed that the degrees of amplification were strongly related to the concentration of the chiral Schiff base. In the case of 100 mM catalyst (◆), a strong positive non-linear effect was observed. These experimental results indicate that the aggregation of zinc species participates in the catalytic cycles.

In this catalytic system, the chiral Schiff base as an *ONO* ligand initially reacted with dialkylzinc reagent to form the chiral Schiff base–zinc complex with the generation of two equivalents of ethane. Analyzing the resultant complex by ^{1}H NMR spectroscopy, we confirmed that two hydroxyl protons in the chiral Schiff base disappeared. In the presence of aldehyde, the chiral Schiff base–zinc complex coordinated as a chiral Lewis acid to the aldehyde. The stereochemical outcome of this asymmetric addition of dialkylzinc could be reasonably explained by the proposed transition state shown in Figure 4. When an *S*-chiral Schiff base is used as a chiral source, the alkyl nucleophile attacks the *Re* face of the activated aldehyde, forming an *R*-configuration alkylated product. This is because the phenolic-oxygen atom would be blocked by the *tert*-butyl substituent in the chiral Schiff base. On the other hand, when a chiral Schiff base without a *tert*-butyl group at the *ortho* position (R^1=H, R^2=Ph, R^3=

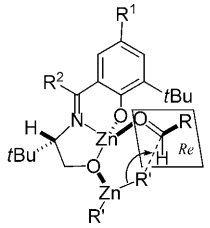


Figure 4. Proposed transition state for the asymmetric addition of dialkylzinc.

*t*Bu) is employed for the reaction, the alkyl nucleophile attacks the *Si* face of the aldehyde to produce the *S*-configuration product in 57% *ee* (*S*).

Conclusions

The new ketoimine-type chiral Schiff base is used as a catalyst for the asymmetric 1,2-addition of dialkylzinc reagents to aldehydes. This system exhibits high catalytic activity and enantioselectivity.

Experimental Section

General

All reactions were carried out in oven-dried glassware with magnetic stirring. All melting points were measured on a Yanaco MP-500D melting point apparatus and uncorrected. ^{1}H and ^{13}C NMR spectra (400 and 100.6 MHz, respectively) were recorded on a JEOL JNM-LA 400 spectrometer using Me_4Si as the internal standard (0 ppm). IR spectra were measured with a Perkin–Elmer FTIR Spectrometer Spectrum-1000. Elemental analyses were performed with a Yanaco CHN Corder MT-5 elemental analyzer. Mass spectra were measured on a Thermo Quest LCQ DECA Plus spectrometer. Optical rotations were measured on a HORIBA SEPA-300 polarimeter for solution in a 1 dm cuvette. Preparative column chromatography was carried out on a Fuji Silysia BW-820MH or YMC*Gel Silica (6 nm I-40–63 um). Thin-layer chromatography (TLC) was carried out on Merck-25 TLC aluminium sheets Silica gel 60 F254. HPLC was performed on a Shimadzu LC-VP series or a HITACHI L-2000 series instrument equipped with a diode-array detector. Chiral column used for HPLC analyses was DAICEL CHIRALCEL OD-H, CHIRALCEL OB, or CHIRALPAK AD-H (0.46×25 cm).

Syntheses

General procedure for the synthesis of ketoimine-type chiral Schiff base: A mixture of toluene (10 mL), L-valinol or L-*tert*-leucinol (8.5 mmol), salicylketone (7.5 mmol), and anhydrous Na_2SO_4 (3 g) was refluxed at 115 °C for 24 h. The mixture was filtered through a glass filter and the filtrate was evaporated. The residue was subjected to column chromatography on silica gel using hexane/ethyl acetate (15:1) as eluent to afford the corresponding chiral Schiff base **2** ($R^2 \neq$ H).

2i: 92%; yellow solid; R_f=0.30 (hexane/ethyl acetate, 5:1); m.p.: 143–144 °C; $[\alpha]_D^{29}=-44.2$ (c=1.00, $CHCl_3$); IR (KBr): ν_{max}=3476, 2960, 1593, 1442, 1324, 1288, 1254, 1214, 1141, 919, 752, 706 cm^{-1}; ^{1}H NMR (400 MHz, $CDCl_3$): δ=0.93 (s, 9H), 1.36 (t, J=6.4 Hz, 1H), 1.48 (s, 9H), 3.25 (dd, J=9.6, 4.8 Hz, 1H), 3.79–3.87 (m, 2H), 6.56 (t, J=7.8 Hz, 1H), 6.63 (dd, J=7.8, 1.8 Hz, 1H), 7.16 (m, 1H), 7.30 (dd, J=7.6, 2.0 Hz, 1H), 7.37 (m, 1H), 7.45 (m, 3H), 16.25 ppm (s, 1H); ^{13}C NMR (100.6 MHz, $CDCl_3$): δ=27.1, 29.5, 33.9, 35.0, 63.5, 70.9, 116.2, 119.7, 128.0, 128.2, 128.3, 128.6, 129.0, 129.4, 130.3, 134.5, 137.9, 163.0, 175.9 ppm; MS (ESI): m/z 354 $[M+H]^+$; elemental analysis: calcd (%) for $C_{23}H_{31}NO_2$: C 78.15, H 8.84, N 3.96; found: C 78.21, H 8.97, N 4.02.

2j: 65%; yellow solid; R_f=0.33 (hexane/ethyl acetate, 5:1); m.p.: 180–181 °C; $[\alpha]_D^{25}=-25.9$ (c=1.00, $CHCl_3$); IR (KBr): ν_{max}=3427, 2964, 2907, 2871, 1609, 1583, 1477, 1363, 1252, 887, 774, 704 cm^{-1}; ^{1}H NMR (400 MHz, $CDCl_3$): δ=0.92 (s, 9H), 1.09 (s, 9H), 1.49 (s, 9H), 1.55 (s, 1H), 3.27 (dd, J=8.0, 4.4 Hz, 1H), 3.79–3.87 (m, 2H), 6.62 (s, 1H), 7.18 (m, 1H), 7.38 (m, 2H), 7.45 (m, 3H), 15.98 ppm (s, 1H); ^{13}C NMR (100.6 MHz, $CDCl_3$): δ=27.1, 29.5, 31.2, 33.9, 33.4, 35.2, 63.5, 70.9, 118.8, 126.5, 127.0, 127.8, 128.5, 129.0, 134.6, 137.1, 138.1, 160.6, 176.1 ppm; MS (ESI): m/z 410 $[M+H]^+$; elemental analysis: calcd (%) for $C_{25}H_{35}NO_4$: C 79.17, H 9.60, N 3.42; found: C 79.02, H 9.70, N 3.42.

2l: 60%; yellow solid; R_f=0.22 (hexane/ethyl acetate, 5:1); m.p.: 68–69 °C; $[\alpha]_D^{29}=-31.6$ (c=1.00, $CHCl_3$); IR (KBr): ν_{max}=3438, 2959, 2908, 2874, 1593, 1457, 1424, 1356, 1206, 1157, 1065, 846, 753 cm^{-1}; ^{1}H NMR (400 MHz, $CDCl_3$): δ=0.95 (s, 9H), 1.39 (s, 1H), 1.48 (s, 9H), 3.29 (dd, J=8.8, 3.6 Hz, 1H), 3.78 (s, 6H), 3.73–3.87 (m, 2H), 6.31 (s, 1H), 6.51 (t, J=1.8 Hz, 1H), 6.55 (s, 1H), 6.59 (t, J=7.8 Hz, 1H), 6.76 (dd, J=7.8, 1.8 Hz, 1H), 7.30 (dd, J=7.8, 1.8 Hz, 1H), 16.15 ppm (s, 1H); ^{13}C NMR (100.6 MHz, $CDCl_3$): δ=27.2, 29.4, 33.8, 35.0, 55.4, 55.4, 63.4, 71.0, 100.7, 106.2, 107.0, 116.2, 119.2, 129.4, 130.2, 136.2, 137.8, 160.4, 160.6, 162.9, 175.2 ppm; MS (ESI): m/z 414 $[M+H]^+$; elemental analysis: calcd (%) for $C_{25}H_{35}NO_4$: C 72.61, H 8.53, N 3.39; found: C 72.48, H 8.72, N 3.47.

2m: 70%; yellow solid; R_f=0.19 (hexane/ethyl acetate, 5:1); m.p.: 203–204 °C; $[\alpha]_D^{29}=-21.4$ (c=1.00, $CHCl_3$); IR (KBr): ν_{max}=3469, 2962, 1596, 1454, 1364, 1293, 1206, 1062, 837, 715 cm^{-1}; ^{1}H NMR (400 MHz, $CDCl_3$): δ=0.94 (s, 9H), 1.14 (s, 9H), 1.26 (s, 1H), 1.49 (s, 9H), 3.31 (dd, J=8.4, 4.0 Hz, 1H), 3.77 (s, 3H), 3.79 (s, 3H), 3.79–3.89 (m, 2H), 6.34 (s, 1H), 6.52 (t, J=2.4 Hz, 1H), 6.57 (s, 1H), 6.78 (d, J=2.4 Hz, 1H), 7.38 (d, J=2.4 Hz, 1H), 15.93 ppm (s, 1H); ^{13}C NMR (100.6 MHz, $CDCl_3$): δ=27.2, 29.5, 31.3, 33.8, 34.0, 35.2, 55.5, 63.5, 70.9, 101.0, 106.1, 107.1, 118.3, 126.3, 127.1, 136.3, 137.1, 138.1, 160.5, 175.5 ppm; MS (ESI): m/z 470 $[M+H]^+$; elemental analysis: calcd (%) for $C_{29}H_{43}NO_4$: C 74.16, H 9.23, N 2.98; found: C 74.08, H 9.34, N 3.09.

2n: 64%; yellow solid; R_f=0.28 (hexane/ethyl acetate, 10:1); m.p.: 62–63 °C; $[\alpha]_D^{25}=-14.5$ (c=1.00, $CHCl_3$); IR (KBr): ν_{max}=3440, 2965, 2910, 1595, 1439, 1383, 1316, 1280, 1175, 1140, 904, 752, 681 cm^{-1}; ^{1}H NMR (400 MHz, $CDCl_3$): δ=0.93 (s, 9H), 1.48 (s, 9H), 1.51 (s, 1H), 3.01 (dd, J=9.2, 3.2 Hz, 1H), 3.82 (t, J=9.2 Hz, 1H), 3.89 (d, J=9.2 Hz, 1H), 6.43 (dd, J=7.8, 1.6 Hz, 1H), 6.63 (t, J=7.8 Hz, 1H), 7.34 (dd, J=7.8, 1.6 Hz, 1H), 7.63 (s, 1H), 7.98 (s, 1H), 15.65 ppm (s, 1H); ^{13}C NMR (100.6 MHz, $CDCl_3$): δ=27.0, 29.4, 33.8, 35.1, 63.0, 71.8, 116.9, 118.9, 122.5 (m, $^3J_{C\text{-}F}$=4.1 Hz), 124.6 (q, $^1J_{C\text{-}F}$=272.6 Hz) , 124.6 (q, $^1J_{C\text{-}F}$=272.6 Hz), 128.3, 129.4, 130.0, 130.3, 131.5 (q, $^2J_{C\text{-}F}$=33.9 Hz), 131.7 (q, $^2J_{C\text{-}F}$=33.9 Hz), 136.7, 138.4, 162.5, 171.8 ppm; MS (ESI): m/z 490 $[M+H]^+$; elemental analysis: calcd (%) for $C_{25}H_{29}F_6NO_2$: C 61.34, H 5.97, N 2.86; found: C 61.43, H 5.99, N 2.78.

2o: 66%; yellow solid; R_f=0.39 (hexane/ethyl acetate, 5:1); m.p.: 149–150 °C; $[\alpha]_D^{29}=-7.6$ (c 1.00, $CHCl_3$); IR (KBr): ν_{max}=3628, 2966, 1580, 1477, 1385, 1280, 1141, 1039, 905 cm^{-1}; ^{1}H NMR (400 MHz, $CDCl_3$): δ=0.93 (s, 9H), 1.09 (s, 9H), 1.41 (s, 1H), 1.49 (s, 9H), 3.07 (dd, J=9.4, 3.4 Hz, 1H), 3.83 (t, J=9.4 Hz, 1H), 3.90 (dd, J=9.4, 3.4 Hz, 1H), 6.38 (d, J=2.6 Hz, 1H), 7.42 (d, J=2.6 Hz, 1H), 7.67 (s, 1H), 8.00 (s, 1H), 8.03 (s, 1H), 15.44 ppm (s, 1H); ^{13}C NMR (100.6 MHz, $CDCl_3$): δ=26.5, 29,5, 31.1, 33.9, 34.0, 35.3, 60.1, 71.8, 118.0, 122.3 (m, $^3J_{C\text{-}F}$=3.7 Hz), 123.1 (q, $^1J_{C\text{-}F}$=272.6 Hz), 123.1 (q, $^1J_{C\text{-}F}$=272.6 Hz), 125.6, 127.6, 128.3, 128.6, 130.4, 131.4 (q, $^2J_{C\text{-}F}$=33.8 Hz) , 131.7 (q, $^2J_{C\text{-}F}$=33.8 Hz), 136.9, 137.7, 138.9, 160.2, 171.9 ppm; MS (ESI): m/z 546 $[M+H]^+$; elemental analysis: calcd (%) for $C_{29}H_{37}F_6NO_2$: C 63.84, H 6.84, N 2.57; found: C 63.04, H 7.03, N 2.57.

General procedure for asymmetric ethylation (Table 2): To a solution of chiral Schiff base (0.018 mmol) in solvent (4 mL) at −40 °C was added diethylzinc (0.37 mL, 3.6 mmol). The solution was warmed to 0 °C, stirred for 30 min, and then cooled to −40 °C again, after which an aldehyde (1.8 mmol) was added. The reaction mixture was stirred for 24 h at 0 °C and then quenched by adding an aqueous solution of HCl (20 mL, 1 N). After extraction with diethyl ether (20 mL x 3), silica-gel column chromatography [eluent: hexane/ethyl acetate, 10:1], and Kugelrohr distillation, the product was obtained. Enantiomeric excess was determined by HPLC analysis using a chiral column.

(*R*)-1-Phenyl-1-propanol: 88%, 96% *ee* (t_R of *R*-isomer: 11.07 min; t_R of *S*-isomer: 13.36 min [column: CHIRALCEL OD-H (DAICEL); eluent: hexane-2-propanol (97.5:2.5), 1.0 mL min^{-1}]); $[\alpha]_D^{29}=+41.9$ (c=1.00, $CHCl_3$) (lit. [22a]: $[\alpha]_D^{20}=+42.9$ (c=3.58, $CHCl_3$, 87.5% *ee* (*R*))).

(*R*)-1-(4-Methoxyphenyl)-1-propanol: 96%, 80% *ee* (t_R of *R*-isomer: 19.57 min; t_R of *S*-isomer: 23.09 min [column: CHIRALCEL OD-H (DAICEL); eluent: hexane/2-propanol (95:5), 0.5 mL min^{-1}]); $[\alpha]_D^{29}=+24.1$ (c=1.00, benzene) (lit. [22a]: $[\alpha]_D^{20}=+31.3$ (c=4.48, benzene, 96.9% *ee* (*R*))).

(*R*)-1-(4-Chlorophenyl)-1-propanol: 92%, 90% *ee* (t_R of *S*-isomer: 13.96 min; t_R of *R*-isomer: 15.10 min [column: CHIRALCEL OD-H (DAICEL); eluent: hexane/2-propanol (95:5), 0.5 mL min^{-1}]); $[\alpha]_D^{29}=$

+24.1 (c=1.00, benzene) (lit. [22a]: $[\alpha]_D^{20}$=+26.4 (c=5.27, benzene, 96.9% *ee* (*R*))).

(*R*)-1-(2-Fluorophenyl)-1-propanol: 94%, 94% *ee* (t_R of *S*-isomer: 10.05 min; t_R of *R*-isomer: 12.19 min [column: CHIRALCEL OB (DAICEL); eluent: hexane/2-propanol (96:4), 0.5 mL min^{-1}]); $[\alpha]_D^{29}$=+31.5 (c=1.00, $CHCl_3$) (lit. [22b]: $[\alpha]_D^{25}$=−20.1 (c=1.77, $CHCl_3$, 62% *ee* (*S*))).

(*R*)-1-(1′-Naphthyl)-1-propanol: 98%, 65% *ee* (t_R of *S*-isomer: 9.41 min; t_R of *R*-isomer: 12.69 min [column: CHIRALCEL OD-H (DAICEL); eluent: hexane/2-propanol (90:10), 1.0 mL min^{-1}]); $[\alpha]_D^{30}$=+50.1 (c=1.00, $CHCl_3$) (lit. [22a]: $[\alpha]_D^{20}$=+52.6 (c=2.55, $CHCl_3$, 93.5% *ee* (*R*))).

(*R*)-1-(2′-Naphthyl)-1-propanol: 99%, 96% *ee* (t_R of *S*-isomer: 8.33 min; t_R of *R*-isomer: 9.35 min [column: CHIRALCEL OD-H (DAICEL); eluent: hexane/2-propanol (90:10), 1.0 mL min^{-1}]); $[\alpha]_D^{29}$=+36.8 (c=1.00, $CHCl_3$) (lit. [22a]: $[\alpha]_D^{20}$=+27.5 (c=3.80, benzene, 96.1% *ee* (*R*))).

(*R*)-1-(2-Furyl)-1-propanol: 82%, 90% *ee* (Analysis of its benzoate, t_R of *R*-isomer: 11.07 min; t_R of *S*-isomer: 12.60 min [column: CHIRALCEL AD-H (DAICEL); eluent: hexane/2-propanol (98:2), 0.5 mL min^{-1}]); $[\alpha]_D^{29}$=+25.9 (c=2.10, $CHCl_3$) (lit. [22a]: $[\alpha]_D^{20}$=+14.3 (c=2.20, $CHCl_3$, 78% *ee* (*R*))).

(*R*)-1-(2-Thienyl)-1-propanol: 99%, 95% *ee* (Analysis of its benzoate, t_R of *R*-isomer: 6.81 min; t_R of *S*-isomer: 8.91 min [column: CHIRALCEL AD-H (DAICEL); eluent: hexane/2-propanol (98:2), 0.5 mL min^{-1}]); $[\alpha]_D^{28}$=+26.4 (c=2.20, $CHCl_3$) (lit. [22a]: $[\alpha]_D^{20}$=+23.3 (c=2.24, $CHCl_3$, 94.9% *ee* (*R*))).

(*R*)-1-Phenylpent-1-yn-3-ol: 85%, 60% *ee* (t_R of *R*-isomer: 8.54 min; t_R of *S*-isomer: 21.55 min [column: CHIRALCEL OD-H (DAICEL); eluent: hexane/2-propanol (95:5), 1.0 mL min^{-1}]); $[\alpha]_D^{28}$=+12.5 (c=1.00, Et_2O) (lit. [22c]: $[\alpha]_D^{20}$=+7.8 (c=2.12, Et_2O, 38% *ee* (*R*))).

(*R*)-(*E*)-1-Phenylpent-1-en-3-ol: 69%, 75% *ee* (t_R of *R*-isomer: 12.23 min; t_R of *S*-isomer: 20.79 min [column: CHIRALCEL OD-H (DAICEL); eluent: hexane/2-propanol (95:5), 1.0 mL min^{-1}]); $[\alpha]_D^{28}$=+6.1 (c=1.01, $CHCl_3$) (lit. [22a]: $[\alpha]_D^{20}$=+5.2 (c=1.91, $CHCl_3$, 81.3% *ee* (*R*))).

(*R*)-1-Phenyl-3-pentanol: 75%, 81% *ee* (t_R of *R*-isomer: 9.51 min; t_R of *S*-isomer: 13.60 min [column: CHIRALCEL OD-H (DAICEL); eluent: hexane/2-propanol (95:5), 1.0 mL min^{-1}]); $[\alpha]_D^{28}$=−23.4 (c=1.00, EtOH) (lit. [23c]: $[\alpha]_D^{19}$=−21.2 (c=7.72, EtOH, 94% *ee* (*S*))).

(*R*)-3-Octanol: 45%, 81% *ee* (Analysis of its benzoate, t_R of *S*-isomer: 13.76 min; t_R of *R*-isomer: 14.17 min [column: CHIRALCEL OD-H (DAICEL); eluent: hexane/2-propanol (99.94:0.06), 0.5 mL min^{-1}]); $[\alpha]_D^{28}$=−7.4 (c=1.00, $CHCl_3$) (lit. [22d]: $[\alpha]_D^{20}$=+12.5 (c=1.29, $CHCl_3$, 56% *ee* (*S*))).

(*R*)-1-Cyclohexyl-1-propanol: 67%, 94% *ee* (Analysis of its benzoate, t_R of *R*-isomer: 9.48 min; t_R of *S*-isomer: 11.50 min [column: CHIRALCEL AD-H (DAICEL); eluent: hexane/2-propanol (99.9:0.1), 1.0 mL min^{-1}]); $[\alpha]_D^{28}$=+4.5 (c=1.00, $CHCl_3$) (lit. [22a]: $[\alpha]_D^{20}$=+6.35 (c=3.00, $CHCl_3$, 94.8% *ee* (*R*))).

General procedure for asymmetric butylation (Table 5): To a solution of chiral Schiff base (0.018 mmol) in hexane (0.5 mL) at −40 °C was added di-*n*-butylzinc (~1 M in heptane, 3.6 mL, ~3.6 mmol). The solution was warmed to 0 °C, stirred for 30 min, and then cooled to −40 °C again, after which an aldehyde (1.8 mmol) was added. The reaction mixture was stirred for 24 h at 0 °C and then quenched by adding an aqueous solution of HCl (20 mL, 1 N). After extraction with diethyl ether (20 mL x 3), silica-gel column chromatography [eluent: hexane/ethyl acetate, 10:1], and Kugelrohr distillation, the product was obtained. Enantiomeric excess was determined by HPLC analysis using a chiral column.

(*R*)-1-Phenyl-1-pentanol: 83%, 98% *ee* (t_R of *S*-isomer: 10.56 min; t_R of *R*-isomer: 11.91 min [column: CHIRALCEL OB (DAICEL); eluent: hexane/2-propanol (99:1), 1.0 mL min^{-1}]); $[\alpha]_D^{29}$=+40.0 (c=1.00, $CHCl_3$) (lit. [22e]: $[\alpha]_D^{27}$=−15.9 (c=1.20, $CHCl_3$, 59% *ee* (*S*))).

(*R*)-1-(4-Methylphenyl)-1-pentanol: 82%, 97% *ee* (t_R of *R*-isomer: 53.20 min; t_R of *S*-isomer: 59.80 min [column: CHIRALCEL OD-H (DAICEL); eluent: hexane/2-propanol (99.9:0.1), 1.0 mL min^{-1}]); $[\alpha]_D^{29}$=+37.1 (c=1.00, benzene) (lit. [22f]: $[\alpha]_D^{25}$=+28.5 (c=1.10, benzene, 76% *ee* (*R*))).

(*R*)-1-(4-Methoxyphenyl)-1-pentanol: 81%, 85% *ee* (t_R of *R*-isomer: 16.81 min; t_R of *S*-isomer: 18.22 min [column: CHIRALCEL OD-H (DAICEL); eluent: hexane/2-propanol (95:5), 0.5 mL min^{-1}] Absolute configuration was determined as *R* by comparison with the retention time in HPLC analysis.); $[\alpha]_D^{31}$=+29.0 (c=1.00, benzene)).

(*R*)-1-(3-Chlorophenyl)-1-pentanol: 79%, 97% *ee* (t_R of *S*-isomer: 20.01 min; t_R of *R*-isomer: 22.35 min [column: CHIRALCEL OD-H (DAICEL); eluent: hexane/2-propanol (98:2), 0.5 mL min^{-1}] Absolute configuration was determined as *R* by comparison with the retention time in HPLC analysis.); $[\alpha]_D^{31}$=+24.3 (c=1.00, benzene))).

(*R*)-1-(4-Chlorophenyl)-1-pentanol: 74%, 98% *ee* (t_R of *S*-isomer: 17.17 min; t_R of *R*-isomer: 18.45 min [column: CHIRALCEL OD-H (DAICEL); eluent: hexane/2-propanol (98:2), 0.5 mL min^{-1}]); $[\alpha]_D^{30}$=+35.3 (c=1.00, benzene) (lit. [22f]: $[\alpha]_D^{25}$=+14.8 (c=0.87, benzene, 66% *ee* (*R*))).

(*R*)-1-(2-Furyl)-1-pentanol: 73%, 93% *ee* (Analysis of its benzoate, t_R of *R*-isomer: 10.51 min; t_R of *S*-isomer: 11.27 min [column: CHIRALCEL AD-H (DAICEL); eluent: hexane/2-propanol (98:2), 0.5 mL min^{-1}]); $[\alpha]_D^{32}$=+16.8 (c 1.00, $CHCl_3$) (lit. [22g]: $[\alpha]_D^{25}$=+9.2 (c 1.07, $CHCl_3$, 94% *ee* (*R*))).

(*R*)-1-(2-Thienyl)-1-pentanol: 82%, 98% *ee* (Analysis of its benzoate, t_R of *R*-isomer: 11.90 min; t_R of *S*-isomer: 13.02 min [column: CHIRALCEL AD-H (DAICEL); eluent: hexane/2-propanol (98:2), 0.5 mL min^{-1}]); $[\alpha]_D^{32}$=+19.5 (c=1.00, $CHCl_3$) (lit. [22h]: $[\alpha]_D^{25}$=+20.7 (c=1.11, $CHCl_3$, > 95% *ee* (*R*))).

(*R*)-(*E*)-1-Phenylhept-1-en-3-ol: 72%, 83% *ee* (t_R of *R*-isomer: 8.65 min; t_R of *S*-isomer: 11.88 min [column: CHIRALCEL OD-H (DAICEL); eluent: hexane/2-propanol (80:20), 0.6 mL min^{-1}]); $[\alpha]_D^{30}$=−3.0 (c=1.00, benzene) (lit. [22i]: $[\alpha]_D^{25}$=−2.7 (c=0.47, benzene, 66% *ee* (*R*))).

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[1] N. Oguni, T. Omi, *Tetrahedron Lett.* **1984**, *25*, 2823–2824.
[2] a) R. Noyori, M. Kitamura, *Angew. Chem.* **1991**, *103*, 34–55; *Angew. Chem. Int. Ed. Engl.* **1991**, *30*, 49–69; b) K. Soai, S. Niwa, *Chem. Rev.* **1992**, *92*, 833–856; c) L. Pu, H.-B. Yu, *Chem. Rev.* **2001**, *101*, 757–824.
[3] a) M. Kitamura, S. Suga, K. Kawai, R. Noyori, *J. Am. Chem. Soc.* **1986**, *108*, 6071–6072; b) M. Kitamura, S. Okada, S. Suga, R. Noyori, *J. Am. Chem. Soc.* **1989**, *111*, 4028–4036; c) R. Noyori, S. Suga, K. Kawai, S. Okada, M. Kitamura, N. Oguni, M. Hayashi, T. Kaneko, Y. Matsuda, *J. Organomet. Chem.* **1990**, *382*, 19–37.
[4] R. Noyori, *Asymmetric Catalysis in Organic Synthesis*, Wiley, New York, **1994**, chap. 5, p. 255.
[5] a) E. J. Corey, F. J. Hannon, *Tetrahedron Lett.* **1987**, *28*, 5237–5240; b) Y.-J. Cherng, J.-M. Fang, T.-J. Lu, *J. Org. Chem.* **1999**, *64*, 3207–3212; c) T. I. Danilova, V. I. Rozenberg, E. V. Sergeeva, Z. A. Starikova, S. Bräse, *Tetrahedron: Asymmetry* **2003**, *14*, 2013–2019.
[6] a) M. Yoshioka, T. Kawakita, M. Ohno, *Tetrahedron Lett.* **1989**, *30*, 1657–1660; b) H. Takahashi, T. Kawakita, M. Yoshioka, S. Kobayashi, M. Ohno, *Tetrahedron Lett.* **1989**, *30*, 7095–7098; c) H. Takahashi, T. Kawakita, M. Ohno, M. Yoshioka, S. Kobayashi, *Tetrahedron* **1992**, *48*, 5691–5700; d) B. Schmidt, D. Seebach, *Angew. Chem.* **1991**, *103*, 100–101; *Angew. Chem. Int. Ed. Engl.* **1991**, *30*, 99–101.
[7] H. B. Kagan, *Adv. Synth. Catal.* **2001**, *343*, 227–233.

[8] a) K. Soai, T. Shibata, H. Morioka, K. Choji, *Nature* **1995**, *378*, 767–768; b) K. Soai, T. Shibata, I. Sato, *Bull. Chem. Soc. Jpn.* **2004**, *77*, 1063–1073.
[9] T. Harada, K. Kanda, *Org. Lett.* **2006**, *8*, 3817–3819.
[10] a) H. Nozaki, S. Moriuti, H. Takaya, R. Noyori, *Tetrahedron Lett.* **1966**, *7*, 5239–5244; b) H. Nozaki, H. Takaya, S. Moriuti, R. Noyori, *Tetrahedron* **1968**, *24*, 3655–3669.
[11] a) M. Hayashi, Y. Miyamoto, T. Inoue, N. Oguni, *J. Chem. Soc. Chem. Commun.* **1991**, 1752–1753; b) M. Hayashi, Y. Miyamoto, T. Inoue, N. Oguni, *J. Org. Chem.* **1993**, *58*, 1515–1522; c) M. Hayashi, T. Inoue, Y. Miyamoto, N. Oguni, *Tetrahedron* **1994**, *50*, 4385–4398.
[12] For selected examples of asymmetric reactions using a chiral Schiff base, see: a) E. M. Carreira, R. A. Singer, W. Lee, *J. Am. Chem. Soc.* **1994**, *116*, 8837–8838; b) C. Bolm, F. Bienewald, *Angew. Chem.* **1995**, *107*, 2883–2885; *Angew. Chem. Int. Ed. Engl.* **1995**, *34*, 2640–2642; c) D. A. Cogan, G. Liu, K. Kim, B. J. Backes, J. A. Ellman, *J. Am. Chem. Soc.* **1998**, *120*, 8011–8019; d) A. T. Radosevich, C. Musich, F. D. Toste, *J. Am. Chem. Soc.* **2005**, *127*, 1090–1091; e) C. Ohta, H. Shimizu, A. Kondo, T. Katsuki, *Synlett* **2002**, 161–163; f) C. Bolm, *Coord. Chem. Rev.* **2003**, *237*, 245–256; g) J. Legros, C. Bolm, *Chem. Eur. J.* **2005**, *11*, 1086–1092; h) A. G. Dossetter, T. F. Jamison, E. N. Jacobsen, *Angew. Chem.* **1999**, *111*, 2549–2552; *Angew. Chem. Int. Ed.* **1999**, *38*, 2398–2400; i) M. Braun, W. Kotter, *Angew. Chem.* **2004**, *116*, 520–523; *Angew. Chem. Int. Ed.* **2004**, *43*, 514–517; j) Q. Fan, L. Lin, J. Liu, Y. Huang, X. Feng, G. Zhang, *Org. Lett.* **2004**, *6*, 2185–2188; k) W. Wang, S. Gou, X. Liu, X. Feng, *Synlett* **2007**, 2875–2878; l) X. Zhou, X. Liu, X. Yang, D. Shang, J. Xin, X. Feng, *Angew. Chem.* **2008**, *120*, 398–400; *Angew. Chem. Int. Ed.* **2008**, *47*, 392–394.
[13] T. Tanaka, Y. Yasuda, M. Hayashi, *J. Org. Chem.* **2006**, *71*, 7091–7093.
[14] M. Hayashi, T. Inoue, N. Oguni, *J. Chem. Soc. Chem. Commun.* **1994**, 341–342.
[15] a) M. Hayashi, K. Tanaka, N. Oguni, *Tetrahedron: Asymmetry* **1995**, *6*, 1833–1836; b) M. Hayashi, K. Yoshimoto, N. Hirata, K. Tanaka, N. Oguni, K. Harada, A. Matsushita, Y. Kawachi, H. Sasaki, *Isr. J. Chem.* **2001**, *41*, 241–246.
[16] a) G. Casiraghi, G. Casnati, M. Cornia, A. Pochini, G. Sartori, R. Ungaro, *J. Chem. Soc. Perkin Trans. 1* **1978**, 322–325; b) G. Casnati, G. Casiraghi, G. Puglia, G. Sartori, G. Terenghi, *Jpn. Kokai Tokkyo Koho* JP 53-34737.
[17] a) J. F. Larrow, E. N. Jacobsen, Y. Gao, Y. Hong, X. Nie, C. M. Zepp, *J. Org. Chem.* **1994**, *59*, 1939–1942; b) J. C. Duff, E. J. Bills, *J. Chem. Soc.* **1934**, 1305–1308.
[18] a) M. Hayashi, K. Yamada, S. Nakayama, *Synthesis* **1999**, 1869–1871; b) M. Hayashi, K. Yamada, S. Nakayama, H. Hayashi, S. Yamazaki, *Green Chem.* **2000**, *2*, 257–260.
[19] Y. Sano, T. Tanaka, M. Hayashi, *Chem. Lett.* **2007**, *36*, 1414–1415.
[20] A. Abiko, S. Masamune, *Tetrahedron Lett.* **1992**, *33*, 5517–5518.
[21] a) M. J. McKennon, A. I. Meyers, K. Drauz, M. Schwarm, *J. Org. Chem.* **1993**, *58*, 3568–3571; b) G. S. Poindexter, A. I. Meyers, *Tetrahedron Lett.* **1977**, *18*, 3527–3528.
[22] a) W.-M. Dai, H.-J. Zhu, X.-J. Hao, *Tetrahedron: Asymmetry* **2000**, *11*, 2315–2337; b) D. Seebach, A. K. Beck, B. Schmidt, Y.-M. Wang, *Tetrahedron* **1994**, *50*, 4363–4384; c) N. Arroyo, U. Haslinger, K. Mereiter, M. Widhalm, *Tetrahedron: Asymmetry* **2000**, *11*, 4207–4219; d) O. Prieto, D. J. Ramón, M. Yus, *Tetrahedron: Asymmetry* **2000**, *11*, 1629–1644; e) T. Utsukihara, O. Misumi, N. Kato, T. Kuroiwa, C. A. Horiuchi, *Tetrahedron: Asymmetry* **2006**, *17*, 1179–1185; f) K. H. Yong, N. J. Taylor, J. M. Chong, *Org. Lett.* **2002**, *4*, 3553–3556; g) T. Kametani, M. Tsubuki, Y. Tatsuzaki, T. Honda, *J. Chem. Soc. Perkin Trans. 1* **1990**, 639–646; h) Y. Kitano, M. Kusakabe, Y. Kobayashi, F. Sato, *J. Org. Chem.* **1989**, *54*, 994–996; i) Z. Chai, X.-Y. Liu, J.-K. Zhang, G. Zhao, *Tetrahedron: Asymmetry* **2007**, *18*, 724–728.
[23] a) M. Hatano, T. Miyamoto, K. Ishihara, *Adv. Synth. Catal.* **2005**, *347*, 1561–1568; b) M. Hatano, T. Miyamoto, K. Ishihara, *Synlett* **2006**, 1762–1764; c) M. Hatano, T. Miyamoto, K. Ishihara, *J. Org. Chem.* **2006**, *71*, 6474–6484.
[24] G. E. Coates, D. Ridley, *J. Chem. Soc. A* **1966**, 1064–1069.
[25] R. Noyori, S. Suga, H. Oka, M. Kitamura, *Chem. Rec.* **2001**, *1*, 85–100.

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