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# The synthesis of dendritic BINOL ligands and their applications in the asymmetric addition of diethylzinc to benzaldehyde

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**Abstract**—The synthesis of Fréchet-type dendritic BINOL ligands is described. These dendritic BINOL ligands were found to be effective in the enantioselective addition of diethylzinc to benzaldehyde both in the presence and absence of Ti(O-*i*-Pr)$_4$. In the latter case, the novel dendritic chiral BINOL ligands showed slightly higher enantioselectivities than their monomeric analogue.


## 1. Introduction

Dendrimers are highly branched macromolecules, which have precisely defined molecular structures with a nanoscale size. Since the pioneering work of van Koten et al. reported in 1994,[1] the use of dendrimer-based catalysts has been an interesting topic.[2] These structurally well-defined macromolecules could be used under homogeneous conditions and be readily recovered by simple precipitation or nanofiltration methods. We are interested in dendrimers with multiple catalytic centers on the periphery,[3] due to their potential applications in many asymmetric catalytic reactions.

Optically active binaphthyl-containing ligands have been extensively applied in various kinds of asymmetric catalytic reactions.[4] Therefore, we set up a study aimed at incorporating such ligands into dendritic structures. Herein, we report the synthesis of novel Fréchet-type dendritic ligands containing up to four BINOL units on the periphery (Scheme 1) and their application in the enantioselective addition of diethylzinc to benzaldehyde. Although dendritic ligands with several BINOL units were reported, their ligands were not employed in this reaction.[5] Other reported dendritic BINOL ligands contained only one BINOL unit.[6] It is possible to fine-tune the catalytic properties of the dendritic chiral catalysts through the adjustment of their structure, size, and shape. Thus, we have the opportunity to study the influence of the shape and architecture of the dendrimer skeleton with several BINOL units on the chiral microenvironment around the catalytic sites in the asymmetric reaction of benzaldehyde with diethylzinc. The experimental results showed high yields and good enantioselectivities. It was found that almost the same enantioselectivities were obtained with an increase of generation. These ligands could be quantitatively recovered almost without loss of yield or enantioselectivity. In addition, these novel dendritic ligands have shown slightly higher enantioselectivities than their monomeric analogue in this reaction in the absence of Ti(O-*i*-Pr)$_4$.

## 2. Results and discussion

### 2.1. Synthesis of dendritic BINOL ligands

A number of BINOL derivatives with substituents at the 3-position have been reported.[7] We provided a synthetic accessibility at the 3-position for attachments of the periphery of the dendrimer. The synthetic route is shown in Scheme 2. In the first step, the key BINOL derivative, MOM-protected 3-bromomethyl-binaphthol (*R*)-**5** was prepared under Shibasaki's conditions.[7d] The commercially available (*R*)-BINOL was chosen as the starting material. The hydroxyl group of (*R*)-**1** was protected with the methoxyl methyl (MOM) group, and the resulting MOM-protected BINOL (*R*)-**2** was lithiated with *n*-BuLi followed by carbonylation to give MOM-protected 3-formyl-binaphthol (*R*)-**3**. Reduction of (*R*)-**3** with $NaBH_4$ in

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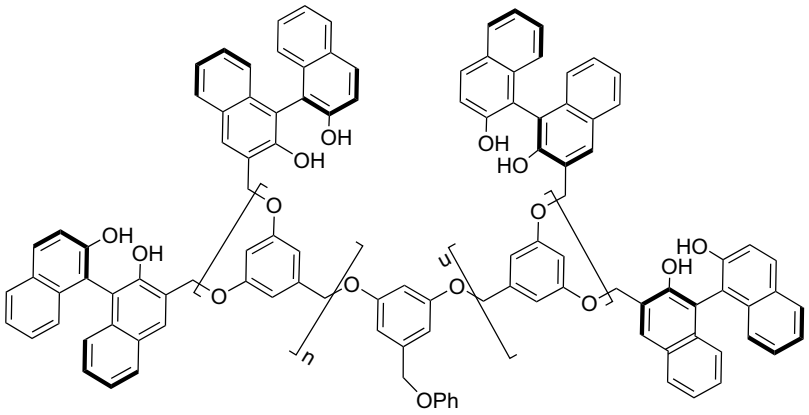



(*R*)-**G$_0$** n = 0
(*R*)-**G$_1$** n = 1

**Scheme 1.**

MeOH/THF at 0 °C yielded MOM-protected 3-hydroxymethyl-binaphthol (*R*)-**4**, which after mesylation with MsCl/$Et_3N$ in toluene/ethyl acetate at 0 °C, filtration of $Et_3NH^+Cl^-$ and treatment with LiBr in DMF gave (*R*)-**5**. Compound (*R*)-**5** was then chosen as the starting material to synthesize Fréchet-type dendritic BINOL ligands based on 3,5-dihydroxybenzyl alcohol as the monomer unit according to the convergent strategy originally reported by Fréchet.[8] Reaction of (*R*)-**5** and 3,5-dihydroxybenzyl alcohol gave the first generation benzylic alcohol (*R*)-**6** with potassium carbonate in refluxing acetone under phase-transfer conditions for 72 h, which was isolated in 87% yield after purification by column chromatography on silica gel. It was essential to maintain efficient stirring throughout the reaction in order to maintain a high rate of conversion. After transformation of the benzylic alcohol functionality of (*R*)-**6** into the corresponding bromide (*R*)-**7**, compound (*R*)-**7** could be condensed with phenol followed by deprotection of the MOM group using TsOH. The first generation chiral BINOL dendrimers (*R*)-**G$_0$** were obtained in 72% yield. Using the intermediate (*R*)-**7**, the above procedure was performed repeatedly to afford the second generation chiral BINOL dendrimers (*R*)-**G$_1$** in 55% yield. For comparison, their monomeric analogue (*R*)-**13** was also synthesized through coupling of compound (*R*)-**5** with phenol followed by deprotection of the MOM group.

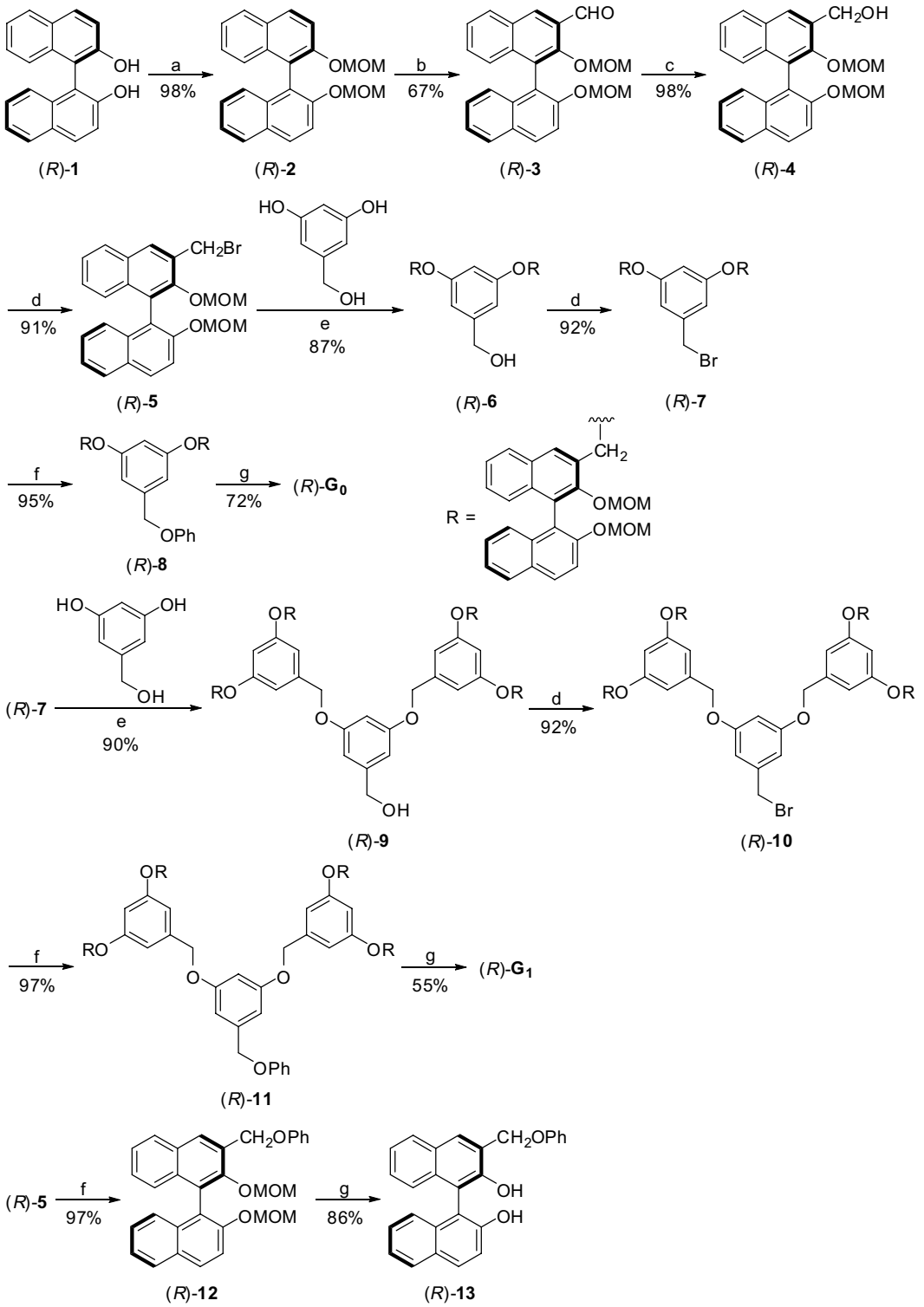
### 2.2. Asymmetric induction of dendritic BINOL ligands in the enantioselective addition of $Et_2Zn$ to benzaldehyde in the presence or absence of Ti(O-*i*-Pr)$_4$

Recently, the catalytic enantioselective addition of diethylzinc to aldehydes has attracted much attention because of its potential in the preparation of a variety of high value, non-racemic, chiral alcohols.[9] Most recently, titanium complexes of BINOL and its derivatives were reported to be effective catalysts for the asymmetric addition of diethylzinc to aldehydes.[7a,b,10] Using the dendritic BINOL ligands, we examined their asymmetric induction in the Lewis acid catalyzed enantioselective addition of diethylzinc to benzaldehyde.

Firstly, the monomeric analogue (*R*)-**13** was used to optimize the reaction conditions. According to the literature,[10a] an excess of Ti(O-*i*-Pr)$_4$ was needed to obtain the efficient catalytic activity. Using dichloromethane as solvent, the effect of molar ratio of (*R*)-**13**/Ti(O-*i*-Pr)$_4$ on the enantioselectivity and yield was investigated. The experimental results were summarized in Table 1. It was found that the molar ratio of (*R*)-**13**/Ti(O-*i*-Pr)$_4$ had an evident influence on the yield (entries 1–4). The yield increased with the decrease of the molar ratio of (*R*)-**13**/Ti(O-*i*-Pr)$_4$. In addition, the molar ratio of (*R*)-**13**/Ti(O-*i*-Pr)$_4$ hardly influenced the enantioselectivity. Obviously, when the molar ratio of (*R*)-**13**/Ti(O-*i*-Pr)$_4$ was 1:10, high yield (up to 95.2%) and good enantioselectivity (up to 89.3% ee) were obtained. Yet, a larger excess of Ti(O-*i*-Pr)$_4$ hardly affected the yield and enantioselectivity. So, the appropriate molar ratio of (*R*)-**13**/Ti(O-*i*-Pr)$_4$ was 1:10.

As shown in Table 1, the reaction solvent also played an important role on the yield and enantioselectivity. Much lower enantioselectivity and yield were obtained when using diethyl ether or THF as solvent (entries 5 and 6). The use of dichloromethane or toluene as a solvent gave better enantioselectivity and yield (entries 3 and 7). It was noteworthy that the best enantioselectivity and yield were achieved when dichloromethane served as a solvent. Therefore, dichloromethane was chosen to be the preferred solvent for the rest of the study.

Based on the optimal reaction conditions obtained above (the molar ratio of BINOL in dendritic ligands to Ti(O-*i*-Pr)$_4$ was 1:10), we next examined the asymmetric induction of the dendritic BINOL ligands in the same reaction. As shown in Table 2, using the catalysts derived from these dendritic BINOL ligands, high yields and good enantioselectivities were achieved for benzaldehyde. It was found that almost the same enantioselectivity was obtained with the increase of generation (entries 3 and 4). Moreover, these dendritic BINOL ligands could be easily recovered due to their different solubilities in various organic solvents. For example, (*R*)-**G$_1$** was used to carry out the recycling experiment. Upon completion of the reaction, (*R*)-**G$_1$**

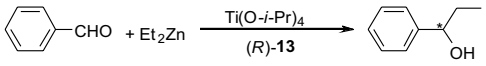



**Scheme 2.** Synthesis of dendritic BINOL ligands. Reagents and conditions: (a) NaH, MOMCl, THF, 0 °C; (b) (i) *n*-BuLi, TMEDA, THF, −78 to 0 °C; (ii) DMF, −78 to 0 °C; (c) $NaBH_4$, THF/MeOH = 1:1 (v/v), 0 °C; (d) (i) MsCl, toluene/AcOEt = 1:1 (v/v), 0 °C; (ii) LiBr, DMF, rt; (e) $K_2CO_3$, 3,5-dihydroxybenzyl alcohol, 18-crown-6, acetone, reflux; (f) $K_2CO_3$, phenol, 18-crown-6, acetone, reflux; (g) $TsOH{\cdot}H_2O$, $CH_2Cl_2$/MeOH = 1:1 (v/v), 40 °C.

was quantitatively precipitated by the addition of methanol and recovered via filtration. The recovered ligand was reused in the asymmetric addition of diethylzinc to benzaldehyde without almost any loss in the yield or enantioselectivity (entries 5 and 6).

Herein, we also studied the enantioselective addition of diethylzinc to benzaldehyde in the absence of Ti(O-*i*-Pr)$_4$ (entries 7–10). Moderate enantioselectivities were obtained, but it was found that the chiral dendritic ligands (*R*)-$\mathbf{G}_0$ and (*R*)-$\mathbf{G}_1$ showed much higher catalytic activity and

**Table 1.** Asymmetric addition of diethylzinc to benzaldehyde catalyzed by titanium complex of (*R*)-**13**[a]




| Entry | Solvent | (*R*)-**13**/Ti(O-*i*-Pr)$_4$ (M/M) | Yield[b] (%) | ee[c] (%) | Configuration[d] |
|---|---|---|---|---|---|
| 1 | $CH_2Cl_2$ | 1:7 | 80.3 | 87.9 | (*R*) |
| 2 | $CH_2Cl_2$ | 1:8 | 85.4 | 87.4 | (*R*) |
| 3 | $CH_2Cl_2$ | 1:10 | 95.2 | 89.3 | (*R*) |
| 4 | $CH_2Cl_2$ | 1:14 | 94.6 | 89.3 | (*R*) |
| 5 | Ether | 1:10 | 46.0 | 73.5 | (*R*) |
| 6 | THF | 1:10 | 42.3 | 35.2 | (*R*) |
| 7 | Toluene | 1:10 | 93.5 | 83.6 | (*R*) |

[a] Benzaldehyde/(*R*)-**13**/$Et_2Zn$ = 1.0:0.2:3 (molar ratio); reaction temperature = 0 °C; reaction time = 7 h.
[b] Isolated yield.
[c] Determined by HPLC with a Chiralcel OD column.
[d] Determined by the sign of the specific rotation.

**Table 2.** Asymmetric addition of diethylzinc to benzaldehyde catalyzed by (*R*)-BINOL and dendritic BINOL ligands in the presence of Ti(O-*i*-Pr)$_4$[a]

| Entry | Ligand | Yield[b] (%) | ee[c] (%) | Configuration[d] |
|---|---|---|---|---|
| 1 | (*R*)-BINOL | 95.7 | 84.2 | (*R*) |
| 2 | (*R*)-**13** | 95.2 | 89.3 | (*R*) |
| 3 | (*R*)-**G**$_0$ | 95.7 | 87.3 | (*R*) |
| 4 | (*R*)-**G**$_1$ | 95.2 | 87.1 | (*R*) |
| 5[e] | (*R*)-**G**$_1$ | 94.3 | 88.5 | (*R*) |
| 6[f] | (*R*)-**G**$_1$ | 96.7 | 89.2 | (*R*) |
| 7[g] | (*R*)-BINOL | 17.3 | 5.2 | (*R*) |
| 8[g] | (*R*)-**13** | 83.1 | 35.6 | (*R*) |
| 9[g] | (*R*)-**G**$_0$ | 75.0 | 39.0 | (*R*) |
| 10[g] | (*R*)-**G**$_1$ | 77.8 | 40.7 | (*R*) |

[a] Benzaldehyde/(*R*)-**13**/Ti(O-*i*-Pr)$_4$/$Et_2Zn$ = 1.0:0.2:2.0:3 (molar ratio); benzaldehyde/(*R*)-**G**$_0$/Ti(O-*i*-Pr)$_4$/$Et_2Zn$ = 1.0:0.1:2.0:3 (molar ratio); benzaldehyde/(*R*)-**G**$_1$/Ti(O-*i*-Pr)$_4$/$Et_2Zn$ = 1.0:0.05:2.0:3 (molar ratio); solvent = dichloromethane; reaction temperature = 0 °C; reaction time = 7 h.
[b] Isolated yield.
[c] Determined by HPLC with a Chiralcel OD column.
[d] Determined by the sign of the specific rotation.
[e] Recovered (*R*)-**G**$_1$ was used for the second run.
[f] Recovered (*R*)-**G**$_1$ was used for the third run.
[g] Reactions were carried out in the absence of Ti(O-*i*-Pr)$_4$.

enantioselectivity than BINOL. Pu et al. also observed a similar enhancement of catalytic activity and enantioselectivity when they used the BINOL derivative 3,3′-(2″,5″-dihexyloxyphenyl)-1,1′-binaphthol as a chiral ligand in the addition reaction of diethylzinc to aldehydes in the absence of Ti(O-*i*-Pr)$_4$.[11] It is noteworthy that our novel dendritic ligands showed slightly higher enantioselectivities than their monomeric analogue (*R*)-**13** in this reaction in the absence of Ti(O-*i*-Pr)$_4$. This is probably due to the presence of multiple catalytic centers in close vicinity maybe resulting in positive cooperativity with enhanced enantioselectivity. The reaction of BINOL with diethylzinc provides the zinc phenoxide and aggregates through intermolecular Zn–O–Zn bonds. When using BINOL as the ligand, it was considered to be catalytically inactive because the zinc ions are coordinatively saturated.[12] As a result of the steric effect, these BINOL units on the periphery of dendrimers may hinder the formation of aggregates of zinc species in comparison to BINOL. In addition, the oxygen on the linkage of the dendritic BINOL ligands may possibly coordinate to or interact with the zinc species, which may generate more active catalytic centers.[6b] These catalytic centers at the periphery of the dendrimer might work cooperatively to enhance the enantioselectivity.

## 3. Conclusion

In conclusion, new recyclable chiral dendrimers based on BINOL have been successfully synthesized. Excellent yields and enantioselectivities were achieved in the asymmetric addition of diethylzinc to benzaldehyde. It was found that almost the same enantioselectivity were obtained with an increase of generation. Furthermore, the dendritic chiral BINOL ligands showed slightly higher enantioselectivities than their monomeric analogue in the asymmetric addition of diethylzinc to benzaldehyde in the absence of Ti(O-*i*-Pr)$_4$.

## 4. Experimental

### 4.1. General

Oxygen- and moisture-sensitive reactions were carried out under an argon atmosphere. Solvents were purified and dried by standard methods prior to use. All commercially available reagents were used without further purification unless otherwise noted. Column chromatography was performed on silica gel (200–300 mesh). Melting points were measured on a Kofler apparatus and are uncorrected. Optical rotations were measured on a Perkin–Elmer model 341 polarimeter. Infrared spectra were recorded on a Nicolet NEXUS 670 FT-IR spectrometer. $^1$H NMR and $^{13}$C NMR spectra were recorded on a Varian Mercury-400 (400 MHz) spectrometer in $CDCl_3$ with TMS as an internal standard.

### 4.2. General procedure for the synthesis of dendritic benzyl alcohols

A mixture of the appropriate MOM-protected 3-bromomethyl-binaphthol (*R*)-**5** or dendritic benzyl bromide

(2.2 equiv), 3,5-dihydroxybenzyl alcohol (1.0 equiv), dried potassium carbonate (2.5 equiv) and 18-crown-6 (0.2 equiv) in dry acetone was heated at reflux and stirred vigorously under argon for 72 h. The mixture was allowed to cool and evaporated to dryness under reduced pressure. The residue was partitioned between water and $CH_2Cl_2$, and the aqueous layer extracted with $CH_2Cl_2$ several times. The combined organic layers were then washed with brine, and dried over anhydrous $Na_2SO_4$. Evaporation of the solvent gave the crude product. The crude product was purified as outlined in the following text.

**4.2.1. Compound (*R*)-6.** (*R*)-**6** was prepared from MOM-protected 3-bromomethyl-binaphthol (*R*)-**5** and purified by column chromatography on silica gel (hexane/ethyl acetate = 3:1) to give (*R*)-**6** as a white foam: yield 87%; mp 62–63 °C; $[\alpha]_D^{20} = +103$ (*c* 1.0, $CH_2Cl_2$); IR (KBr) 3436, 1594, 1505, 1448, 1358, 1154, 1076 $cm^{-1}$; $^1H$ NMR (400 MHz, $CDCl_3$) $\delta$ 2.91 (s, 6H), 3.14 (s, 6H), 4.57 (d, $J = 6.0$ Hz, 2H), 4.66 (s, 2H), 4.68 (d, $J = 6.0$ Hz, 2H), 5.03 (d, $J = 6.8$ Hz, 2H), 5.11 (d, $J = 6.8$ Hz, 2H), 5.44 (s, 4H), 6.75–6.76 (m, 3H), 7.18–7.60 (m, 14H), 7.86–7.98 (m, 6H), 8.12 (s, 2H); $^{13}C$ NMR (100 MHz, $CDCl_3$) $\delta$ 55.9, 56.7, 66.0, 94.8, 99.4, 105.6, 116.4, 120.4, 124.2, 125.1, 125.4, 125.7, 126.2, 126.8, 127.9, 128.1, 128.5, 129.6, 129.9, 130.3, 130.8, 133.6, 133.9, 151.7, 152.8, 160.1; MALDI-TOF-MS *m/z* 935.28 $[M+Na]^+$; Anal. Calcd for $C_{57}H_{52}O_{11}$: C, 74.98; H, 5.74. Found: C, 75.10; H, 5.85.

**4.2.2. Compound (*R*)-9.** (*R*)-**9** was prepared from (*R*)-**7** and purified by column chromatography on silica gel (hexane/ethyl acetate = 4:3) to give (*R*)-**9** as a white foam: yield 90%; mp 107–108 °C; $[\alpha]_D^{20} = +88$ (*c* 1.0, $CH_2Cl_2$); IR (KBr) 3469, 1594, 1505, 1447, 1358, 1239, 1153 $cm^{-1}$; $^1H$ NMR (400 MHz, $CDCl_3$) $\delta$ 2.87 (s, 12H), 3.08 (s, 12H), 4.53 (s, 2H), 4.56 (d, $J = 5.6$ Hz, 4H), 4.67 (d, $J = 5.6$ Hz, 4H), 5.00–5.02 (m, 8H), 5.1 (d, $J = 7.2$ Hz, 4H), 5.43 (s, 8H), 6.55–6.59 (m, 3H), 6.80 (s, 6H), 7.17–7.95 (m, 40H), 8.12 (s, 4H); $^{13}C$ NMR (100 MHz, $CDCl_3$) $\delta$ 55.9, 56.7, 66.2, 66.9, 94.8, 99.4, 101.6, 105.7, 106.4, 116.4, 120.5, 124.1, 125.1, 125.5, 125.7, 126.2, 126.8, 127.9, 128.1, 128.5, 129.6, 129.9, 130.3, 130.9, 133.6, 133.9, 139.4, 151.8, 152.9, 160.1, 160.2; MALDI-TOF-MS *m/z* 1951.75 $[M+Na]^+$; Anal. Calcd for $C_{121}H_{108}O_{23}$: C, 75.29; H, 5.64. Found: C, 75.11; H, 5.50.

### 4.3. General procedure for the synthesis of dendritic benzyl bromides

To an ice-cooled solution of dendritic benzyl alcohol (1.0 equiv) in toluene/ethyl acetate (v/v = 1:1) were added successively $Et_3N$ (5.0 equiv) and MsCl (3.0 equiv). The mixture was stirred at 0 °C for 90 min. The resultant suspension was filtered to remove solid $Et_3NH^+Cl^-$ and the solid was washed with ethyl acetate. The combined filtrate and washings were cooled to 0 °C and then LiBr (10.0 equiv) and DMF were added. The mixture was stirred at room temperature for 20 min. It was then diluted with diethyl ether and washed with water, 1.0 M aq HCl, saturated aq $NaHCO_3$ and brine. It was dried over anhydrous $Na_2SO_4$ and evaporated in vacuo to give dendritic benzyl bromide, which was pure enough to be used in next step without further purification.

### 4.4. General procedure for the synthesis of MOM-protected dendritic BINOL ligands

A mixture of the appropriate MOM-protected 3-bromomethyl-binaphthol (*R*)-**5** or dendritic benzyl bromide (1.0 equiv), phenol (1.2 equiv), dried potassium carbonate (1.5 equiv) and 18-crown-6 (0.2 equiv) in dry acetone was heated at reflux and stirred vigorously under argon for 72 h. The mixture was allowed to cool and evaporated to dryness under reduced pressure. The residue was partitioned between water and $CH_2Cl_2$, and the aqueous layer extracted with $CH_2Cl_2$ several times. The combined organic layers were then washed with brine, and dried over anhydrous $Na_2SO_4$. Evaporation of the solvent gave the crude product. The crude product was purified as outlined in the following text.

**4.4.1. Compound (*R*)-8.** Compound (*R*)-**8** was prepared from (*R*)-**7** and purified by column chromatography on silica gel (hexane/ethyl acetate = 4:1) to give (*R*)-**8** as a white foam: yield 95%; mp 73–74 °C; $[\alpha]_D^{20} = +90$ (*c* 1.0, $CH_2Cl_2$); IR (KBr) 1595, 1501, 1467, 1358, 1239, 1154, 1011 $cm^{-1}$; $^1H$ NMR (400 MHz, $CDCl_3$) $\delta$ 2.93 (s, 6H), 3.15 (s, 6H), 4.57 (d, $J = 8.0$ Hz, 2H), 4.68 (d, $J = 8.0$ Hz, 2H), 5.03 (d, $J = 9.6$ Hz, 2H), 5.06 (s, 2H), 5.12 (d, $J = 9.6$ Hz, 2H), 5.44 (s, 4H), 6.80–7.60 (m, 22H), 7.86–7.99 (m, 6H), 8.13 (s, 2H); $^{13}C$ NMR (100 MHz, $CDCl_3$) $\delta$ 55.9, 56.7, 66.2, 69.8, 94.8, 99.4, 101.5, 106.3, 109.7, 114.9, 116.4, 120.4, 120.9, 124.2, 125.1, 125.5, 125.7, 126.3, 126.8, 127.9, 128.1, 128.5, 129.4, 129.6, 129.9, 130.3, 130.9, 133.6, 133.9, 139.7, 151.8, 152.8, 158.6, 160.2; MALDI-TOF-MS *m/z* 1011.33 $[M+Na]^+$; Anal. Calcd for $C_{63}H_{56}O_{11}$: C, 76.50; H, 5.71. Found: C, 76.82; H, 5.83.

**4.4.2. Compound (*R*)-11.** Compound (*R*)-**11** was prepared from (*R*)-**10** and purified by column chromatography on silica gel (hexane/ethyl acetate = 2:1) to give (*R*)-**11** as a white foam: yield 97%; mp 98–99 °C; $[\alpha]_D^{20} = +76$ (*c* 1.0, $CH_2Cl_2$); IR (KBr) 1594, 1503, 1448, 1359, 1239, 1155, 1011 $cm^{-1}$; $^1H$ NMR (400 MHz, $CDCl_3$) $\delta$ 2.90 (s, 12H), 3.12 (s, 12H), 4.56 (d, $J = 5.2$ Hz, 4H), 4.68 (d, $J = 5.2$ Hz, 4H), 4.98 (d, $J = 6.8$ Hz, 4H), 5.01 (s, 6H), 5.08 (d, $J = 6.8$ Hz, 4H), 5.44 (s, 8H), 6.60–7.94 (m, 54H), 8.13 (s, 4H); $^{13}C$ NMR (100 MHz, $CDCl_3$) $\delta$ 55.9, 56.6, 66.2, 69.7, 70.0, 94.8, 99.4, 101.6, 106.3, 114.8, 116.4, 120.4, 120.9, 124.1, 125.0, 125.4, 125.6, 126.2, 126.7, 127.8, 128.1, 128.5, 129.4, 129.6, 129.9, 130.3, 130.9, 133.6, 133.9, 139.3, 139.5, 151.8, 152.8, 158.6, 160.1, 160.2; MALDI-TOF-MS *m/z* 2027.77 $[M+Na]^+$; Anal. Calcd for $C_{127}H_{112}O_{23}$: C, 76.03; H, 5.63. Found: C, 75.90; H, 5.65.

**4.4.3. Compound (*R*)-12.** Compound (*R*)-**12** was prepared from (*R*)-**5** and purified by column chromatography on silica gel (hexane/ethyl acetate = 5:1) to give (*R*)-**12** as a colorless oil: yield 97%; $[\alpha]_D^{20} = +28$ (*c* 1.0, $CH_2Cl_2$); IR (KBr) 1712, 1595, 1497, 1358, 1239, 1154, 1062 $cm^{-1}$; $^1H$ NMR (400 MHz, $CDCl_3$) $\delta$ 3.13 (s, 3H), 3.32 (s, 3H), 4.83 (d, $J = 6.0$ Hz, 1H), 4.95, (d, $J = 6.0$ Hz, 1H), 5.20 (d,

$J = 6.8$ Hz, 1H), 5.28 (d, $J = 6.8$ Hz, 1H), 5.66 (s, 2H), 7.11–8.13 (m, 15H), 8.36 (s, 1H); $^{13}$C NMR (100 MHz, $CDCl_3$) $\delta$ 55.6, 56.4, 65.8, 94.5, 99.3, 114.6, 116.1, 120.2, 120.7, 124.0, 124.9, 125.3, 125.4, 125.5, 126.1, 126.6, 127.7, 127.9, 128.4, 129.3, 129.7, 130.4, 130.7, 133.4, 133.8, 151.7, 152.7, 158.6; MS (EI) $m/z$ 481 (0.42) $[M+1]^+$, 480 (1.06) $[M]^+$, 404 (0.49), 355 (0.11), 343 (0.64); Anal. Calcd for $C_{31}H_{28}O_5$: C, 77.48; H, 5.87. Found: C, 78.52; H, 5.81.

### 4.5. General procedure for the synthesis of dendritic BINOL ligands

Typical procedure: To a stirred solution of (*R*)-**12** or MOM-protected dendritic BINOL ligands in $CH_2Cl_2$/MeOH (v/v = 1:1) was added TsOH. The solution was stirred at 40 °C for 40 h. It was then diluted with $CH_2Cl_2$, washed with saturated $NaHCO_3$ and brine and dried over anhydrous $Na_2SO_4$. Evaporation of solvent gave the crude product. The crude product was purified as outlined in the following text.

**4.5.1. Compound (*R*)-13.** Compound (*R*)-**13** was prepared from (*R*)-**12** and purified by column chromatography on silica gel (hexane/ethyl acetate = 4:1) to give (*R*)-**13** as a white foam: yield 86%; mp 61–62 °C; $[\alpha]_D^{20} = +53$ (*c* 1.0, $CH_2Cl_2$); IR (KBr) 3510, 1596, 1501, 1388, 1249, 1174, 1140 cm$^{-1}$; $^1$H NMR (400 MHz, $CDCl_3$) $\delta$ 5.05 (s, 1H), 5.40 (s, 2H), 5.52 (s, 1H), 7.02–7.38 (m, 12H), 7.91–7.98 (m, 3H), 8.16 (s, 1H); $^{13}$C NMR (100 MHz, $CDCl_3$) $\delta$ 65.9, 106.8, 110.9, 111.5, 114.9, 117.7, 120.9, 123.9, 124.1, 124.2, 125.4, 127.3, 127.4, 128.2, 128.3, 128.4, 129.1, 129.3, 129.5, 131.3, 133.0, 133.4, 150.5, 152.6, 159.9; MS (EI) $m/z$ 392 (10.59) $[M]^+$, 343 (3.78), 334 (1.44), 312 (2.61); Anal. Calcd for $C_{27}H_{20}O_3$: C, 82.63; H, 5.14. Found: C, 82.75; H, 5.17.

**4.5.2. Dendritic BINOL ligand (*R*)-G$_0$.** Compound (*R*)-**G$_0$** was prepared from (*R*)-**8** and purified by column chromatography on silica gel (hexane/ethyl acetate = 2:1) and recrystallization from toluene to give (*R*)-**G$_0$** as a white foam: yield 72%; mp 126–127 °C; $[\alpha]_D^{20} = +46$ (*c* 1.0, $CH_2Cl_2$); IR (KBr) 3498, 1596, 1448, 1383, 1213, 1148, 1050 cm$^{-1}$; $^1$H NMR (400 MHz, $CDCl_3$) $\delta$ 5.04 (s, 2H), 5.14 (s, 2H), 5.34 (s, 4H), 5.44 (s, 2H), 6.86–7.39 (m, 22H), 7.88–7.93 (m, 6H), 8.13 (s, 2H); $^{13}$C NMR (100 MHz, $CDCl_3$) $\delta$ 65.8, 69.8, 106.8, 110.9, 111.4, 114.8, 117.7, 121.0, 124.0, 124.1, 124.2, 124.3, 125.4, 127.4, 128.3, 128.5, 129.1, 129.3, 129.4, 131.3, 133.0, 133.4, 150.5, 152.6, 160.0; MALDI-TOF-MS $m/z$ 835.35 $[M+Na]^+$; Anal. Calcd for $C_{55}H_{40}O_7$: C, 81.26; H, 4.96. Found: C, 81.53; H, 4.89.

**4.5.3. Dendritic BINOL ligand (*R*)-G$_1$.** Compound (*R*)-**G$_1$** was prepared from (*R*)-**11** and purified by column chromatography on silica gel (hexane/ethyl acetate = 1:1) and recrystallization from toluene to give (*R*)-**G$_1$** as a white foam: yield 55%; mp 158–159 °C; $[\alpha]_D^{20} = +49$ (*c* 1.0, $CH_2Cl_2$); IR (KBr) 3435, 1597, 1445, 1381, 1210, 1149, 1034 cm$^{-1}$; $^1$H NMR (400 MHz, $CDCl_3$) $\delta$ 5.08 (s, 4H), 5.41 (s, 14H), 5.55 (s, 4H), 7.02–7.42 (m, 42H), 7.92–7.99 (m, 12H), 8.17 (s, 4H); $^{13}$C NMR (100 MHz, $CDCl_3$) $\delta$ 66.0, 111.1, 111.5, 115.1, 117.7, 121.3, 124.0, 124.1, 124.2, 124.3, 125.7, 127.4, 127.5, 128.4, 128.5, 129.2, 129.3, 129.5, 129.6, 131.3, 133.0, 133.4, 150.7, 152.7, 158.6; MALDI-TOF-MS $m/z$ 1675.67 $[M+Na]^+$; Anal. Calcd for $C_{111}H_{80}O_{15}$: C, 80.61; H, 4.88. Found: C, 80.75; H, 4.82.

### 4.6. General procedure for asymmetric addition of diethylzinc to benzaldehyde

Typical procedure: Under argon, Ti(O-*i*-Pr)$_4$ (85 μL, 0.25 mmol) was added to a solution of (*R*)-**13** (9.8 mg, 0.025 mmol) in 1 mL of dichloromethane at room temperature and the mixture was stirred at ambient temperature for 15 min followed by the addition of diethylzinc (1.0 M in hexane, 0.375 mL) with continued stirring for 15 min. The solution was cooled to 0 °C and benzaldehyde (13 μL, 0.125 mmol) was added with a microsyringe. The reaction mixture was allowed to stir at 0 °C for 7 h. The reaction mixture was quenched with 2.0 mL of 1.0 M hydrochloric acid solution, the mixture was extracted with ethyl acetate several times. The combined organic layers were then washed with saturated $NaHCO_3$ and brine, and dried over anhydrous $Na_2SO_4$. The residue was purified by column chromatography on silica gel (hexane/ethyl acetate = 8:1) to afford 1-phenyl-1-propanol as a colorless liquid. The enantiomeric excess was determined by HPLC over a chiral column (Daicel Chiralcel OD).

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