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Synthesis of Dendritic Catalysts and Application in Asymmetric Transfer Hydrogenation

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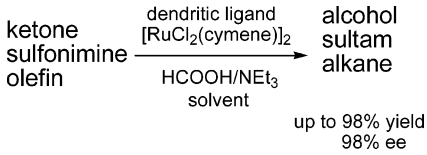

Fréchet-type core-functionalized chiral diamine-based dendritic ligands and hybrid dendritic ligands condensed from polyether wedge and Newkome-type poly(ether-amide) supported multiple ligands were designed and synthesized. The solubility of hybrid dendrimers was found to be finely controlled by the polyether dendron. The catalytic efficiency and recovery use of dendritic ruthenium complexes were compared in the transfer hydrogenation of acetophenone. The core-functionalized dendritic catalysts demonstrated much better recyclability, which verified the stabilizing effects of the bulky polyether wedge on the catalytically active complex. Moreover, the dendritic catalysts were applied in the asymmetric transfer hydrogenation of ketones, enones, imine, and activated olefin, and moderate to excellent enantioselectivitiy was achieved comparable to that of monomeric catalysts.

Introduction

Homogeneous asymmetric catalysis is one of the most important developments in chemistry. However, only a few examples have been applied in industrial processes due to the problems of separation and recycling of the expensive and sometimes toxic catalysts.[1] Recently significant advances in the development of supported homogeneous asymmetric catalysts have been achieved for the requirement of green chemistry. Some systems depending on the use of insoluble resin beads allow the facile recovery by filtration, but many of the potential active catalyst sites may be inaccessible if the resin is not compatible with the required solvent, and it may also be difficult to accurately assess the level of catalyst loading on resin beads.[2]

Dendrimers are well-defined macromolecules with controllable structures. Their applications in catalysis have triggered increasing attention since the dendritic catalysts have the advantages of total solubility and unhindered active sites and may be analyzed with routine spectroscopic techniques.[3] Moreover, the globular shapes of higher generation dendritic catalysts are suitable for membrane filtration[4] or selective precipitation under specific conditions.[5] The catalytic efficiency and recyclability of the dendritic system largely depend on the dendritic architecture that is used, and in general two

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(2) For reviews on recoverable catalysts, see the following special issue: *Chem. Rev*. **2002**, *102* (10).

(3) For recent reviews on dendritic catalysts, see: (a) Oosterom, G. E.; Reek, J. N. H.; Kamer, P. C. J.; van Leeuwen, P. W. N. M. *Angew. Chem., Int. Ed.* **2001**, *40*, 1828. (b) Astruc, D.; Chardac, F. *Chem. Rev*. **2001**, *101*, 2991. (c) Crooks, R. M.; Zhao, M.; Sun, L.; Chechik, V.; Yueng, L. K. *Acc. Chem. Res.* **2001**, *34*, 181. (d) Reek, J. N. H.; de Groot, D.; Oosterom, G. E.; Kamer, P. C. J.; van Leeuwen, P. W. N. M. *Rev. Mol. Biotechnol*. **2002**, *90*, 159. (e) Twyman, L. J.; King, A. S. H.; Martin, I. K. *Chem. Soc. Rev*. **2002**, *31*, 69. (f) van Heerbeek, R.; Kamer, P. C. J.; van Leeuwen, P. W. N. M.; Reek, J. N. H. *Chem. Rev*. **2002**, *102*, 3717. (g) Fan, Q.-H.; Li, Y.-M.; Chan, A. S. C. *Chem. Rev*. **2002**, *102*, 3385. (h) Caminade, A.-M.; Maraval, V.; Laurent, R.; Majoral, J.-P. *Curr. Org. Chem*. **2002**, *6*, 739.

(4) For an excellent review on the nanofiltration technique in dendritic catalyst recycling, see: Dijkstra, H. P.; van Klink, G. P. M.; van Koten, G. *Acc. Chem. Res.* **2002**, *35*, 798.

(5) For selected reports on dendritic catalyst recycling by precipitation, see: (a) Reetz, M. T.; Lohmer, G.; Schwickardi, R. *Angew. Chem., Int. Ed*. **1997**, *36*, 1526. (b) Petrucci-Samija, M.; Guillemette, V.; Dasgupta, M.; Kakkar, A. K. *J. Am. Chem. Soc*. **1999**, *121*, 1968. (c) Hu, Q.-S.; Pugh, V.; Sabat, M.; Pu, L. *J. Org. Chem*. **1999**, *64*, 7528. (d) Fan, Q.-H.; Chen, Y.-M.; Chen, X.-M.; Jiang, D.-Z.; Xi, F.; Chan, A. S. C. *Chem. Commun*. **2000**, 789. (e) Maraval, V.; Caminade, A.-M.; Majoral, J.-P. *Organometallics* **2000**, *19*, 4025.

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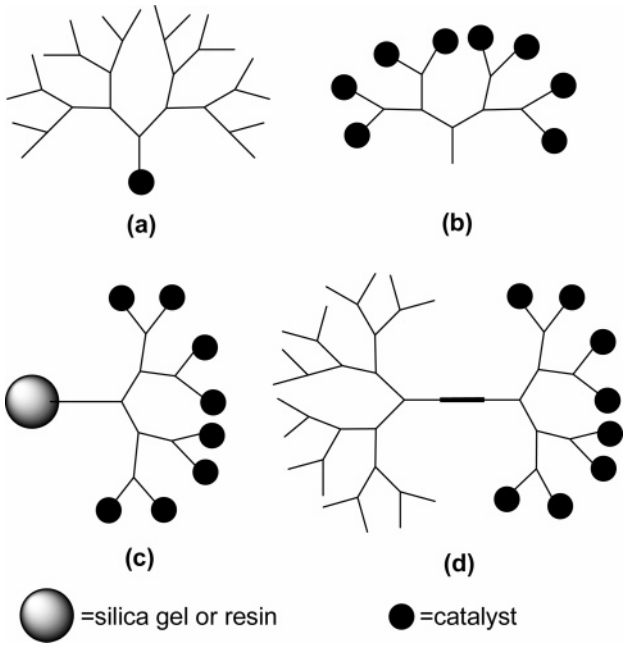
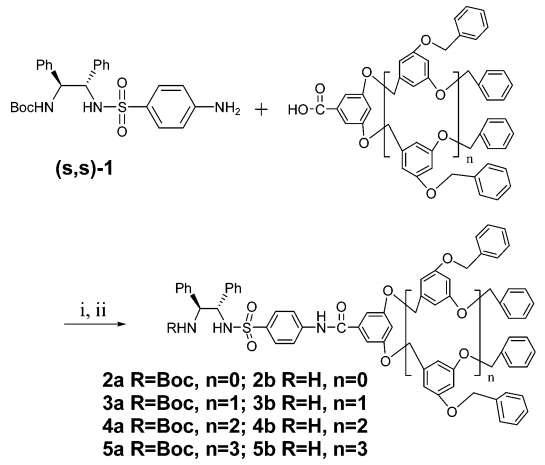


FIGURE 1. Different dendritic catalysts.

basic strategies evolved: one (or more) catalyst(s) in the core of dendrimer (Figure 1, type a), the other multiple active sites at the periphery of the dendrimer (type b). Recently, insoluble polymer supported periphery-functionalized dendritic catalysts were also developed (type c).[6]

Recently we reported the synthesis of core-functionalized dendritic ligands based on Noyori-Ikariya's TsDPEN ligand and the application of their Ru(II) complexes in the asymmetric transfer hydrogenation of acetophenone.[7a] High catalytic activity and completely maintained enantioselectivity were observed, and the higher generation catalysts could be recovered through solvent precipitation and reused several times without apparent loss of activity. Nevertheless, it still has the traditional disadvantages of core-functionalized dendritic catalysts: the efficiency of the dendritic wedge is very low. We also reported the synthesis of other types of dendrimers with up to 12 chiral diamine based ligands at the periphery of Newkome-type poly(ether amide).[7b] Their Ru(II) complexes demonstrated high catalytic activity and enantioselectivity in the asymmetric transfer hydrogenation of ketones and imines. However, we cannot easily realize their recycling use. To keep the advantages and get over disadvantages of these two types of catalysts, get to know more about the stabilizing effects of the bulky dendrons, we first synthesized the hybrid

SCHEME 1. Synthesis of Core-Functionlized Dendritic Ligands[a]



[a] Reagents: (i) $(PhO)_3P$, Py; (ii) TFA/DCM or HCl/EtOAc.

dendritic catalysts (Figure 1, type d) through the coupling of higher generation Fréchet's polyether dendrons[8] with Newkome-type poly(ether amide) supported multiple ligands.[7b] Thus the hybrid dendrimer[9] not only will be of the physical character of the Fréchet's polyether dendrons and reactivity of the periphery dendritic catalysts, but also can be easily synthesized and recovered through solvent precipitation. Moreover, the efficiency of polyether dendritic wedges can be improved.

Results and Discussion

Ligand Synthesis. The core-functionalized dendritic ligands were smoothly prepared by condensation of amino-derived chiral DPEN (*S*,*S*)-**1** with Fréchet's polyether dendrons[8] in pyridine, using $(PhO)_3P$[10] as the coupling reagent, and subsequent deprotection of the Boc-group (Scheme 1).[7a] The dendritic ligands were soluble in nonpolar solvents (DCM, chloroform, toluene, THF, etc.) but almost completely insoluble in alcoholic solvents.

Via a similar strategy, the previously reported periphery-functionalized dendron (*R*,*R*)-**6**[7b] was condensed with higher generation Fréchet's polyether dendritic wedges, and the following deprotection of the Boc-group readily gave the hybrid dendritic chiral ligands (*R*,*R*)-**7b** and (*R*,*R*)-**8b** (Scheme 2). Their physical character is the same as that of the polyether wedges, and the dendritic ligands are insoluble in methanol and isopropyl alcohol, but can be easily dissolved in THF or DCM.

In ^{1}H NMR of core dendrimers **2a**−**5a**, the resonance signal at δ 4.9−5.3 ppm from benzylic protons and the signal at δ 1.3−1.5 ppm of the Boc group indicated the coupling of dendron wedges with the ligand. However,

(6) (a) Bourque, S. C.; Maltais, F.; Xiao, W.-J.; Tardif, O.; Alper, H.; Arya, P.; Manzer, L. E. *J. Am. Chem. Soc.* **1999**, *121*, 3035. (b) Arya, P.; Rao, N. V.; Singkhonrat, J.; Alper, H.; Bourque, S. C.; Manzer, L. E. *J. Org. Chem*. **2000**, *65*, 1881. (c) Bourque, S. C.; Alper, H.; Manzer, L. E.; Arya, P. *J. Am. Chem. Soc*. **2000**, *122*, 956. (d) Arya, P.; Panda, G.; Rao, N. V.; Alper, H.; Bourque, S. C.; Manzer, L. E. *J. Am. Chem. Soc*. **2001**, *123*, 2889. (e) Antebi, S.; Arya, P.; Manzer, L. E.; Alper, H. *J. Org. Chem.* **2002**, *67*, 6623. (f) Dahan, A.; Portnoy, M. *Chem. Commun.* **2002**, 2700. (g) Dahan, A.; Portnoy, M. *Org. Lett.* **2003**, *5*, 1197. (h) Lu, S.-M.; Alper, H. *J. Am. Chem. Soc.* **2003**, *125*, 13126.

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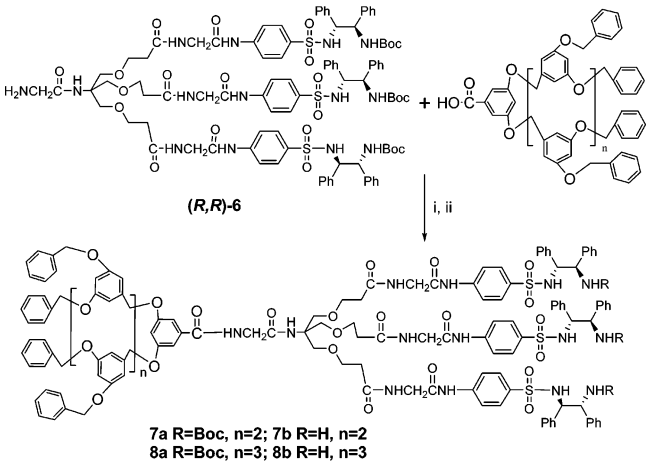
(10) Rabilloud, G.; Sillion, B. *J. Heterocycl. Chem*. **1980**, *17*, 1065.

SCHEME 2. Synthesis of Hybrid Dendritic Ligands[a]



[a] Reagents: (i) EDCI/HOBt, DIPEA; (ii) TFA, DCM, then NH_3.

TABLE 1. MS Data of Dendrimers

dendrimer	MW (calcd)	MW (found)
2a	806.2878	806.2828[a,e]
3a	1230	1230[b,e]
2b	684.2532	684.2429[a,d]
3b	1108.4207	1108.4179[a,d]
4b	1956.7556	1956.7929[a,d]
5b	3675.41	3676.03[c,e]
7b	3224.2	3224.7[c,e]
8b	4921	4926[c,e]

[a] ESI HRMS. [b] FAB MS. [c] MALDI-TOF MS. [d] (M + H). [e] (M + Na).

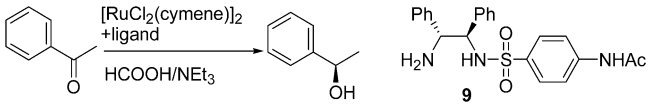
the usually poor ^{13}C NMR spectrum was observed due to the dominant ratio of dendron wedges in the core dendrimers, especially for higher generation ones. For the hybrid dendrimers **7** and **8**, the structures were similarly resolved and better ^{13}C NMR was obtained.

Indeed, the confirmation of the dendritic structures could be more smoothly obtained through MS techniques (ESI, FAB, or MALDI-TOF MS). All of the MS spectra displayed a very prominent peak corresponding to the dendrimers complexed with proton or sodium cation except for the Boc-protected higher generation dendrimers **4a**, **5a**, **7a**, and **8a**, whose elemental analyses were well obtained. MALDI-TOF MS was applied for the analysis of **5b** and hybrid dendritic ligands **7b** and **8b** (Table 1).

Asymmetric Transfer Hydrogenation Reaction. Having the core and hybrid dendritic ligands in hand, the catalytic activity and enantioselectivity of their Ru(II) complexes were studied via the transfer hydrogenation of acetophenone, and also compared with the monomeric Ru(II) complex of (*R,R*)-*N*-(4-acetylaminophenylsulfonyl)-1,2-diphenylethylenediamine (**9**).[7b] Initial experiments were conducted in homogeneous DCM solution with formic acid−triethylamine azeotrope as the hydrogen source. The average turnover frequency (TOFs, in relation to the per-Ru(II) complex) and enantioselectivity are summarized in Table 2.

It was found that the macromolecular catalysts showed only a slight difference as compared to monomeric catalyst **9**-Ru(II) in regard to catalytic activity, and good

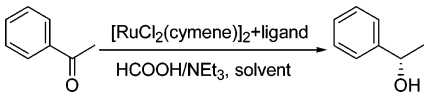
TABLE 2. Comparison of Dendritic and Monomeric Catalysts in Asymmetric Transfer Hydrogenation of Acetophenone[a]



entry	ligand	conv (%)[b]	TOF (h^{-1})[c]	ee (%)[d]
1[7b]	**9**	>99	13.2	97.1
2[7a]	**4b**	>99	11.0	96.5[e]
3	**7b**	96	9.7	96.2
4	**8b**	97	8.2	97.1

[a] Reactions were conducted in DCM solution at 28 °C for 20 h, S/C = 100. [b] Conversions were determined by GC. [c] The average TOFs were calculated over the 5 h reaction time. [d] Determined by GC with a Chrompack CP Chirasil-dex column (25 m × 0.25 mm). [e] (*S*)-Alcohol was obtained.

TABLE 3. Solvent Effects on Dendritic Catalysts in Asymmetric Transfer Hydrogenation of Acetophenone[a]



entry	ligand	solvent	conv (%)[b]	TOF (h^{-1})[c]	ee (%)[d]
1	**4b**	DCM	>99	11.0	96.5
2	**4b**	THF	98	8.0	95.1
3	**4b**	Toluene	96	7.4	95.8
4	**4b**	DMF	70	7.2	93.4
5	**4b**	CH_3CN	68	6.2	94.7
6	**4b**	–[e]	98	6.2	96.0
7	**7b**	–[e]	97	6.0	96.7[f]
8	**8b**	–[e]	94	3.8	96.7[f]
9	**7b**	THF	99	15.0	98.2[f]
10	**8b**	THF	98	10.4	97.8[f]

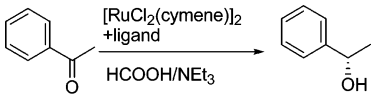
[a] Reactions were conducted at 28 °C for 20 h, S/C = 100. [b] Conversions were determined by GC. [c] The average TOFs were calculated over the 5 h reaction time. [d] Determined by GC with a Chrompack CP Chirasil-dex column (25 m × 0.25 mm). [e] In neat HCOOH−NEt_3 azeotrope for 28 h. [f] (*R*)-Alcohol was obtained.

retention of high enantioselectivity was observed in all dendritic catalysts (only **4b** was selected as an example for core dendritic ligands).[7a]

On the other hand, the solubility of crowded dendritic catalysts in solvents may affect the conformation of dendrimers in solution,[11] so the accessibility of substrate to the active site may also be different. We investigated the transfer hydrogenation of core dendritic ligand **4b** and hybrid ligands **7b** and **8b** in various solvents. The results were summarized in Table 3. For core dendritic catalyst **4b**-Ru(II), DCM demonstrated the best solvent effect, and comparable results could be obtained when THF was used (Table 3, entry 2). However, poor conversion was observed in polar DMF or acetonitrile solution although the enantioselectivity was still high (entries 4 and 5). Interestingly, it was found that the highly hydrophobic catalyst **4b**-Ru(II) could be well dissolved in neat HCOOH−NEt_3 azeotrope. Good conversion and enantioselectivity were obtained in the transfer hydrogenation of acetophenone, while its TOF value was less than what was obtained in nonpolar solvent (entry 6). Hybrid dendrimers showed similar catalytic activity

(11) De Backer, S.; Prinzie, Y.; Verheijen, W.; Smet, M.; Desmedt, K.; Dehaen, W.; De Schryver, F. C. *J. Phys. Chem. A* **1998**, *102*, 5451.

TABLE 4. Recycling Use of Dendritic Catalysts in Asymmetric Transfer Hydrogenation of Acetophenone[a]



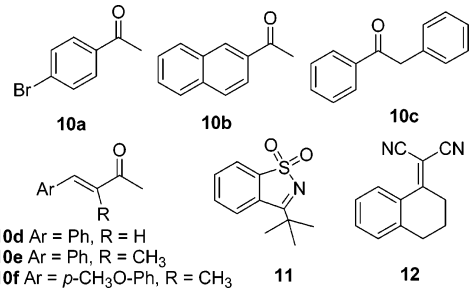
entry	ligand	*t* (h)	conv (%)[b]	ee (%)[c]
1[7a]	**5b** (first)	20	98	96.5
2[7a]	**5b** (second)	20	92	96.6
3[7a]	**5b** (third)	25	87	96.8
4[7a]	**5b** (fourth)	30	85	96.7
5[7a]	**5b** (fifth)	40	73	96.3
6[7a]	**5b** (sixth)	40	52	87.0
7	**7b** (first)	20	96	96.2[d]
8	**7b** (second)	24	70	97.6[d]
9	**7b** (third)	25	31	97.4[d]
10	**8b** (first)	20	97	97.1[d]
11	**8b** (second)	24	72	97.2[d]

[a] Reactions were conducted at 28 °C in DCM solution, S/C = 100. [b] Conversions were determined by GC. [c] Determined by GC with a Chrompack CP Chirasil-dex column (25 m × 0.25 mm). [d] (*R*)-Alcohol was obtained.

under the same conditions (entries 7 and 8). However, the best results (especially in regard to the TOF value) were gained when THF was used as solvent, which indicated the importance of the solubility of the dendrimers in the solution for high catalytic efficiency (Table 2, entries 9 and 10 vs entries 7 and 8).

A significant advantage of dendritic catalysts is that they can be easily separated from substrates and products through membrane filtration or precipitation owing to the globular macromolecular structures. Therefore the recyclability of these large dendritic catalysts was tested by the precipitation method. After a specific reaction time, DCM was removed under reduced pressure and dry methanol was added to precipitate the dendritic catalyst. Then the solution was removed and the next reaction could be conducted. Table 4 shows the results with **5b**-Ru(II), **7b**-Ru(II), and **8b**-Ru(II) as the catalysts, respectively. It was noted that the higher generation core dendritic catalyst **5b**-Ru(II) completely maintained the enantioselectivity in successive use. 1-Phenethanol was provided after 30 h for the fourth use with 85% conversion and 96.7% ee (entry 4), and high enantioseletivity (96.3%ee) remained even for the fifth use (entry 5).[7a] However, further addition of $[RuCl_2(cymene)]_2$ into **5b**-Ru(II) catalysis could not regain the reactivity and even poorer selectivity was observed (entry 6). Nevertheless, for hybrid dendrimers **7b** and **8b**, whose active sites are far from the bulky polyether dendrons, much poorer recycling results were obtained, and the activity has been mostly lost after three uses though without a decrease in enantioselectivity (entries 7−11). It was noteworthy that a similar observation had been reported for the heterogeneous polymer immobilized TsDPEN catalysts.[12,13] Therefore, the "dendritic effect" from large polyether dendron was quite important to stabilize the catalytically active complex. Such site-isolation effect had also been observed in bis(μ-oxo)dicopper species toward oxidative self-decomposition.[14]

TABLE 5. Asymmetric Transfer Hydrogenation of Unsaturated Compounds[a]



entry	substrate	ligand	*t* (h)	yield[b] (%)	ee[c] (%)
1	**10a**	**4b**	24	90	90.1
2	**10a**	**7b**	24	85	91.4[d]
3	**10a**	**8b**	24	83	92.7[d]
4	**10b**	**2b**	24	85	95.1
5	**10b**	**4b**	24	80	94.1
6	**10b**	**7b**	24	86	92.8[d]
7	**10c**	**7b**	24	75	93.9[e]
8	**10d**	**13**	28	87	39.0[e]
9	**10d**	**4b**	28	85	37.3[e]
10	**10e**	**13**	45	86	76.4[e]
11	**10e**	**4b**	45	91	74.9[e]
12	**10f**	**13**	72	61	68.9[e]
13	**10f**	**4b**	72	54	67.5[e]
14	**11**	**4b**	10	90	95.5[e]
15[f]	**12**	**13**	2	94	60.6[e]
16[f]	**12**	**4b**	5	98	55.7[e]

[a] Reactions were conducted at 28 °C in DCM solution, S/C = 100. [b] Isolated yield. [c] Determined by GC with a Chrompack CP Chirasil-dex column (25 m × 0.25 mm). [d] (*R*)-Alcohol was obtained. [e] Determined by HPLC on a chiral column. [f] Reaction was carried out in 0.5 M THF solutions at 30 °C.

For exploring the scope and limitations of the reaction catalyzed by dendritic catalysts, various prochiral ketones **10a**−**f**, imine **11**, and activated olefin **12** were applied in the asymmetric transfer hydrogenation reaction with HCOOH−NEt_3 as the hydrogen source (Table 5). In general, excellent enantioselectivity (>90% ee) was achieved for aromatic ketones with good isolated yields for both types of dendritic catalysts (entries 1−7). α,β-Unsaturated ketones **10d**−**f** were selectively reduced to allylic alcohol with low to moderate enantioselectivity.[15] A methyl substituent in the α-position could increase the enantioselectivity dramatically, but slightly lower enantioselectivitiy was obtained when bulky dendritic ligand **4b** was used compared with (*S*,*S*)-TsDPEN **13** (entries 8−13). Imine **11** was transfer hydrogenated to useful Sultam with excellent enantiomeric purity and yield by using **4b** as the ligand (entry 14).[16] In addition, the prochiral α,α-dicyanoolefin **12** could be reduced with almost quantitative yield, but the bulky dendron exhibits no beneficial effect on the enantioselectivity (entries 15 vs 16).[17]

(12) (a) ter Halle, R.; Schulz, E.; Lemaire, M. *Synlett* **1997**, 1257. (b) Bayston, D. J.; Travers, C. B.; Polywka, M. E. C. *Tetrahedron*: *Asymmetry* **1998**, *9*, 2015.

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In conclusion, Fréchet-type core dendritic DPEN ligands and hybrid dendritic ligands based on Fréchet's polyether dendron and Newkome's poly(ether-amide) were designed and synthesized. High catalytic activity and enantioselectivity, comparable to the monomeric catalyst, were achieved in transfer hydrogenation of various unsaturated compounds. Much better recyclability for higher generation core-functionalized dendritic catalyst was observed compared with that of the hybrid dendritic catalysts. This finding supplied strong support for the stabilizing effect of the bulky polyether dendron on the catalytically active complex. In particular, to the best of our knowledge, hybrid dendritic ligands and catalysts have not been synthesized and used in asymmetric synthesis.[3,9] Future work to develop more efficient recyclable dendritic catalysts is in progress.

Experimental Section

General Methods. Melting points were determined in open capillaries and were uncorrected. NMR spectra were recorded with tetramethylsilane as the internal standard. Chiral 1,2-diphenylethylene-diamine was produced in our laboratory according to Corey's procedure,[18] $[\alpha]^{20}_D$ +106.7 (*c* 1.0, methanol, *R,R*-isomer). All other reagents were used without purification as commercially available.

General Procedure for Condensation of Fréchet-Type Acid with (*S,S*)-1. (*S,S*)-*N*-Boc-*N*′-(4-aminophenylsulfonyl)-1,2-dipheylethylenediamine (**1**) (467 mg, 1.0 mmol),[7] Dendritic acid (1.05 equiv), and triphenyl phosphite (370 mg, 1.1 mmol) were stirred in Pyridine (2 mL) at 95 °C for 24 h. The solution was poured into water (30 mL) and extracted with EtOAc (40 mL). The organic phase was washed successively with 0.5 M citric acid, sodium bicarbonate, and brine dried. Flash chromatography on silica gel gave the Boc-protected dendrimers **2a**−**5a**.

***(S,S)*-5a:** 51% yield; mp 83−86 °C; $[\alpha]^{20}_D$ −2.57 (*c* 0.43, acetone); ^{1}H NMR ($CDCl_3$, 300 MHz) δ 1.49 (s, 9H), 4.92, 4.98 (br s × 2, 60H), 6.55, 6.65 (br s × 2, 45H), 7.28−7.37 (m, 94H) ppm, the two NCHs of DPEN are too small to be detected; IR (KBr) 3415, 3031, 1687, 1449, 1373, 1157, 1051 cm^{-1}; Anal. Calcd for $C_{242}H_{213}N_3O_{35}S$: C, 77.40; H, 5.72; N, 1.12; S, 0.85. Found: C, 77.80; H, 5.77; N, 1.12; S, 0.75.

General Procedure for the Synthesis of Boc-Protected Hybrid Dendrimers. Branched ligand (*R*,*R*)-**6** (192 mg, 0.1 mmol),[7b] Fréchet-type acid (1.05 equiv), EDCI (25 mg, 0.13 mmol), and HOBt (14 mg, 0.1 mmol) were stirred in DCM (5 mL) and cooled in ice water. NEt_3 (18 μL, 0.13 mmol) was added and the solution was stirred overnight. The solution was washed successively with 0.5 M citric acid, saturated sodium bicarbonate, and brine and dried. Flash chromatography on silica gel gave the Boc-protected hybrid dendrimers.

***(R,R)*-7a:** 81% yield; $[\alpha]^{20}_D$ +21.5 (*c* 0.45, THF); ^{1}H NMR (CD_3COCD_3, 400 MHz) δ 1.32 (s, 27H), 2.47 (br s, 6H), 3.58−3.78 (m, 12H), 4.12 (br s, 8H), 4.70−4.72 (m, 3H), 4.93−5.00 (m, 31H), 6.58−6.72 (m, 21H), 6.97−7.53 (m, 82H), 7.92 (br s, 3H), 9.72 (br s, 3H) ppm; partial ^{13}C NMR (CD_3COCD_3, 50 MHz) δ 28.6, 37.0, 44.6, 60.7, 63.9, 68.2, 69.9, 70.5, 79.5, 102.1, 102.3, 107.3, 107.4, 119.6, 127.9, 128.2, 128.4, 128.6, 128.8, 129.2, 136.8, 138.1, 139.8, 140.3, 140.6, 140.7, 142.6, 142.7, 156.5, 160.7, 160.9, 161.0, 169.2, 173.2 ppm; IR (KBr) 3295, 1687, 1595, 1534, 1452, 1370 cm^{-1}. Anal. Calcd for $C_{201}H_{204}N_{14}O_{37}S_3$: C, 68.90; H, 5.87; N, 5.60; S, 2.75. Found: C, 68.40; H, 5.81; N, 5.54; S, 2.50.

General Procedure for Deprotection of the Boc Group. Boc-protected dendrimer (0.2 mmol) was dissolved in DCM (1 mL) and the solution was cooled with ice water. TFA (1 mL) was added and the solution was stirred for 1 h. The solvent was removed under vacuum and water (10 mL) was added. The mixture was neutralized with ammonia and stirred at room temperature for 2 h. The solid was collected, washed with water, and dried under vacuum.

***(S,S)*-2b:** 91% yield; $[\alpha]^{20}_D$ +3.5 (*c* 0.15, CH_2Cl_2); ^{1}H NMR ($CDCl_3$, 300 MHz) δ 4.39−4.41 (m, 1H) 4.60−4.61 (m, 1H), 5.08 (s, 4H), 6.79 (s, 1H), 7.48−7.03 (m, 22H), 7.61 (d, J = 8.1 Hz, 2H), 7.67 (d, J = 8.7 Hz, 2H) ppm; IR (KBr) 3430, 3195, 1676, 1591, 1323, 1158, 1056 cm^{-1}; ESI HRMS calcd for $C_{41}H_{37}N_3O_5S$ + H 684.2532, obsd 684.2429.

Asymmetric Transfer Hydrogenation Reaction: General Procedure for Asymmetric Transfer Hydrogenation of Unsaturated Compounds. $[RuCl_2(cymene)]_2$ (1.3 mg, 0.002 mmol), Dendritic ligand (1.1 equiv of Ru), and NEt_3 (1.2 μL, 0.008 mmol) were stirred in DCM at room temperature for 2 h. Then unsaturated compound (0.4 mmol) and formic acid/triethylamine azeotrope (0.2 mL) were added in turn. The solution was stirred at 28 °C and monitored by TLC. After completion, the solution was diluted with 5 mL of ethyl acetate, washed with brine, and dried (Na_2SO_4). Flash chromatography gave the pure reduced product.

For transfer hydrogenation of activated olefin **12**, THF was used as the solvent.

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Supporting Information Available: Characterization data for compounds **2a**−**4a**, **8a**, **3b**−**5b**, **7b**, and **8b**; NMR and GC or HPLC data for the reduction products; spectra of dendritic ligands. This material is available free of charge via the Internet at http://pubs.acs.org.

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