Structurally Rigid and Optically Active Dendrimers

Qiao-Sheng Hu, Vincent Pugh, Michal Sabat, and Lin Pu*

Department of Chemistry, University of Virginia, Charlottesville, Virginia 22901

Received May 25, 1999

Novel rigid and optically active dendrimers containing cross-conjugated units are synthesized from the coupling of phenylacetylene-based dendrons with an optically pure diacetate of 4,4′,6,6′-tetrabromo-1,1′-bi-2-naphthol. The UV and fluorescence spectroscopic studies demonstrate that there is a very efficient energy migration from the cross-conjugated dendrons to the center core, leading to greatly enhanced fluorescences at higher generations. This is the first example of an efficient energy migration conducted in an optically pure dendritic system, which is potentially useful in developing an enantioselective fluorescence sensor. The generation 2 dendrimer has been used to catalyze the asymmetric reaction of diethylzinc with aldehydes and has shown high enantioselectivity in the presence of Ti(O-i-Pr)$_4$.

Introduction

Dendrimers have become a subject of intense research in recent years due to their unique structures and properties.[1] Rigid dendritic molecules with well-defined structures and shapes are potentially useful in fabricating nanoscale optical and electronic devices for nanotechnology.[2,3] Optically active dendrimers can be used to carry out asymmetric processes. They respond differently toward the left and right circularly polarized lights and are potentially useful as chiral sensors to recognize the enantiomers of chiral molecules. During the past decade, chiral dendrimers of various structures have been prepared.[4] For example, Seebach et al. have used tris(hydroxylmethyl)methane-based chiral triols to construct the core, branch, and peripheral units of dendrimers to make so-called “fully chiral” dendritic materials.[4a] They have also observed that the titanium complexes of dendrimers containing a chiral α,α,α′,α′-tetraaryl-1,3-dioxolane-4,5-dimethanol (TADDOL) core can catalyze the diethylzinc addition to benzaldehyde with high enantioselectivity.[4a] Meijer et al. have studied the effect of the dendritic packing on the chiral optical properties of chiral amino acid-derived end groups.[4b] Other chiral dendrimers have also been obtained by using either naturally occurring chiral units such as carbohydrates[4c] and amino acids[4d] or synthetic chiral units.[4f−h]

Optically active 1,1′-bi-2-naphthol and its derivatives have found broad applications in asymmetric catalysis, chiral recognition, and materials sciences.[5,6] We envisage that incorporation of the chiral 1,1′-binaphthyl units into a rigid dendritic system will not only lead to a new type of dendrimers for applications as chiral sensors and chiral catalysts, but will also provide a unique opportunity to study the influence of the shape and architecture of the dendrimers on the chirality of binaphthyls. As an integrated part of our program to design and synthesize chiral conjugated macromolecules,[6] we have used 1,1′-binaphthyl molecules to construct novel rigid and cross-conjugated optically active dendrimers.[7] Optically active dendrimers made of only conjugated units have not been prepared before. Herein, our synthesis and characterization of the chiral binaphthyl-based rigid dendrimers, the optical spectroscopic properties of these materials and a preliminary study of their application as asymmetric catalysts are reported.

---

(1) For recent reviews, see: (a) Fischer, M.; Vögtle, F. *Angew. Chem., Int. Ed. Engl.* **1999**, *38*, 884. (b) Tomalia, D. A.; Durst, H. D. *Top. Curr. Chem.* **1993**, *165*, 193. (c) Fréchet, J. M. J. *Science* **1994**, *263*, 1710. (d) Zeng, F.; Zimmerman, S. C. *Chem. Rev.* **1997**, *97*, 1681. (e) Smith, D. K.; Diederich, F. *Chem. Eur. J.* **1998**, *4*, 1353. (f) Newkome, G. R.; Moorefield, C. N.; Vögtle, F. *Dendritic Macromolecules: Concepts, Syntheses, Perspectives*; VCH: Weinheim, Germany, 1996. (g) Gorman, C. *Adv. Mater.* **1998**, *10*, 295.

(2) (a) Moore, J. S. *Acc. Chem. Rev.* **1997**, *30*, 402. (b) Xu, Z.; Kahr, M.; Walker, K. L.; Wilkins, C. L.; Moore, J. S. *J. Am. Chem. Soc.* **1994**, *116*, 4537. (c) Xu, Z.; Moore, J. S. *Angew. Chem., Int. Ed. Engl.* **1993**, *32*, 1354. (d) Devadoss, C.; Bharathi, P.; Moore, J. S. *Macromolecules* **1998**, *31*, 8091. (e) Devadoss, C.; Bharathi, P.; Moore, J. S. *J. Am. Chem. Soc.* **1996**, *118*, 9635. (f) Xu, Z.; Moore, J. S. *Acta Polym.* **1994**, *45*, 83.

(3) For reviews on nanostructured materials, see: (a) *Chem. Mater.* **1996**, *8*. (b) *Chem. Rev.* **1999**, 99.

(4) (a) Seebach, D.; Rheiner, P. B.; Greiveldinger, G.; Butz, T.; Sellner, H. *Top. Curr. Chem.* **1998**, *197*, 125. (b) Peerlings, H. W. I.; Meijer, E. W. *Chem. Eur. J.* **1997**, *3*, 1563. (c) Aoi, K.; Itoh, K.; Okada, M. *Macromolecules* **1995**, *28*, 5391. (d) Shao, J.; Tam, J. P. *J. Am. Chem. Soc.* **1995**, *117*, 3894. (e) Chow, H.-F.; Mak, C.-C. *J. Chem. Soc., Perkin Trans. 1* **1994**, 2223. (f) Chang, H.-T.; Chen, C.-T.; Kondo, T.; Siuzdak, G.; Sharpless, K. B. *Angew. Chem., Int. Ed. Engl.* **1996**, *35*, 182. (g) McElhanon, J. R.; McGrath, D. V. *J. Am. Chem. Soc.* **1998**, *120*, 1647. (h) Issberner, J.; Böhme, M.; Grimme, S.; Nieger, M.; Paulus, W.; Vögtle, F. *Tetrahedron: Asymmetry* **1996**, *7*, 2223.

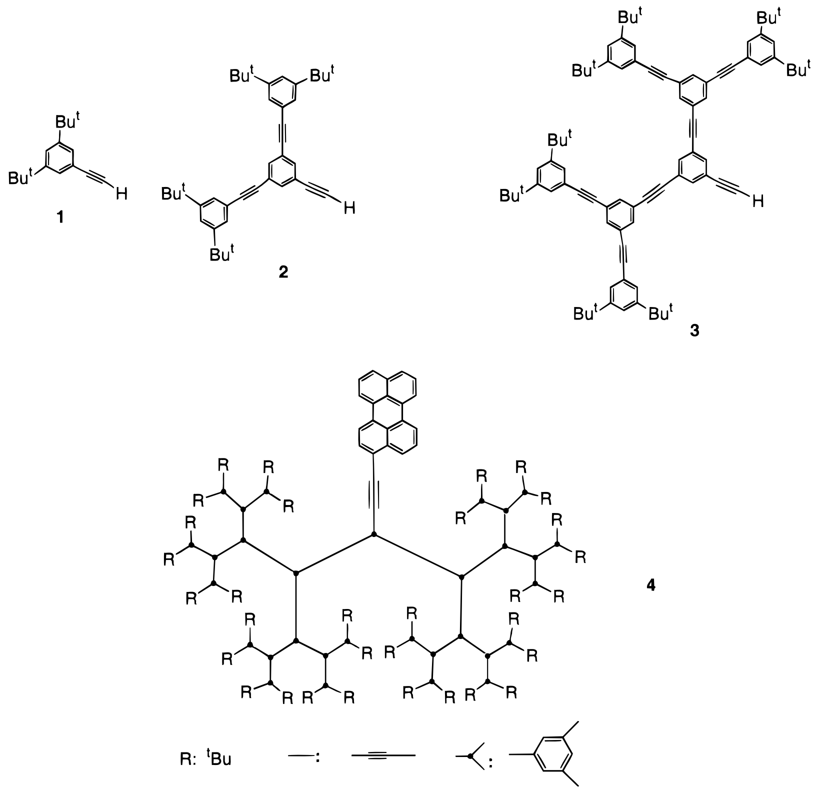
(5) (a) Pu, L. *Chem. Rev.* **1998**, *98*, 2405. (b) Rosini, C.; Franzini, L.; Raffaelli, A.; Salvadori, P. *Synthesis* **1992**, 503. (c) Whitesell, J. K. *Chem. Rev.* **1989**, *89*, 1581. (d) Bringmann, G.; Walter, R.; Weirich, R. *Angew. Chem., Int. Ed. Engl.* **1990**, *29*, 977. (e) Noyori, R.; Takaya, H. *Acc. Chem. Res.* **1990**, *23*, 345.

(6) (a) Hu, Q.-S.; Vitharana, D.; Liu, G.; Jain, V.; Wagaman, M. W.; Zhang, L.; Lee, T. R.; Pu, L. *Macromolecules* **1996**, *29*, 1082. (b) Hu, Q.-S.; Vitharana, D.; Liu, G.; Jain, V.; Pu, L. *Macromolecules* **1996**, *29*, 5075. (c) Ma, L.; Hu, Q.-S.; Musick, K.; Vitharana, D.; Wu, C.; Kwan, C. M. S.; Pu, L. *Macromolecules* **1996**, *29*, 5083. (d) Ma, L.; Hu, Q.-S.; Vitharana, D.; Wu, C.; Kwan, C. M. S.; Pu, L. *Macromolecules* **1997**, *30*, 204. (e) Hu, Q.-S.; Zheng, X.-F.; Pu, L. *J. Org. Chem.* **1996**, *61*, 5200. (f) Hu, Q.-S.; Vitharana, D.; Zheng, X.-F.; Wu, C.; Kwan, C. M. S.; Pu, L. *J. Org. Chem.* **1996**, *61*, 8370. (g) Huang, W.-S.; Hu, Q.-S.; Zheng, X.-F.; Anderson, J.; Pu, L. *J. Am. Chem. Soc.* **1997**, *119*, 4313. (h) Hu, Q.-S.; Huang, W.-S.; Vitharana, D.; Zheng, X.-F.; Pu, L. *J. Am. Chem. Soc.* **1997**, *119*, 12454. (i) Huang, W.-S.; Hu, Q.-S.; Pu, L. *J. Org. Chem.* **1998**, *63*, 1364. (j) Musick, K. Y.; Hu, Q.-S.; Pu, L. *Macromolecules* **1998**, *31*, 2933. (k) Hu, Q.-S.; Huang, W.-S.; Pu, L. *J. Org. Chem.* **1998**, *63*, 2798. (l) Pu, L. *Acta Polym.* **1997**, *48*, 116.

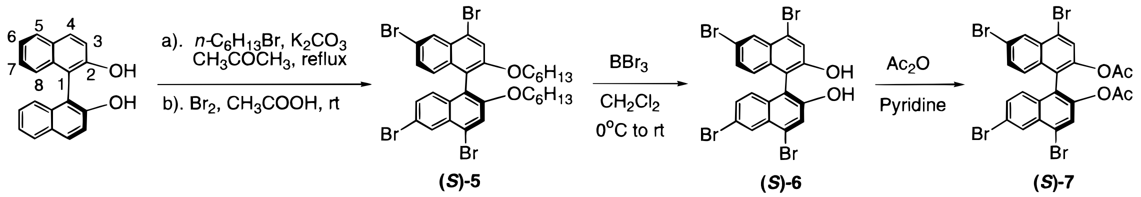
(7) Chiral binaphthyl core-based dendrimers with flexible dendrons were reported recently: (a) Chen, Y.-M.; Chen, C.-F.; Xi, F. *Chirality* **1998**, *10*, 661. (b) Yamago, S.; Furukawa, M.; Azuma, A.; Yoshida, J.-i. *Tetrahedron Lett.* **1998**, *39*, 3783.

10.1021/jo990856q CCC: $18.00

Chart 1



Scheme 1. Synthesis of Chiral 1,1′-Binaphthyl Molecules As the Dendritic Cores



Results and Discussion

1. Synthesis and Characterization of the Structurally Rigid Chiral Dendrimers. Our effort to synthesize the novel rigid chiral dendrimers has been focused on building these materials on an optically pure 1,1′-bi-2-naphthol core. The two hydroxyl groups on the binaphthol unit in these dendrimers can be used to generate Lewis acid metal complexes for applications in asymmetric catalysis. They also make it easy to further functionalize the dendritic core and allow modification of the chemical and physical properties of the dendrimers.

The convergent method to build dendrimers originated by Fréchet and others[8] is adopted in the synthesis of the binaphthyl-based dendrimers. We have chosen rigid phenylacetylenes as the building blocks because of their well-established cross-coupling chemistry[9] and the extensive work done by Moore on the phenylacetylene-based achiral dendrimers.[2] The phenylacetylene-based dendrons **1**−**3** are synthesized by Moore and co-workers to prepare rigid dendrimers such as **4** (Chart 1).[2e] Following similar synthetic procedures, we have prepared these dendrons for the synthesis of the novel chiral cross-conjugated dendrimers.

The chiral core of the desired dendrimers can be derived from a tetrabromobinaphthyl molecule (*S*)-**7** which is prepared from the optically pure (*S*)-1,1′-bi-2-naphthol [(*S*)-BINOL] by a four-step synthetic sequence (Scheme 1). Alkylation of (*S*)-BINOL with 1-bromohexane in the presence of potassium carbonate followed by bromination in acetic acid yielded (*S*)-**5**. Removal of the alkyl groups in (*S*)-**5** by treatment with boron tribromide followed by hydrolysis gives (*S*)-4,4′,6,6′-tetrabromo-1,1′-bi-2-naphthol, (*S*)-**6**, which is then converted to diacetate (*S*)-**7** by reaction with acetic anhydride. From this four-step reaction sequence, (*S*)-**7** is produced in an overall yield of 62.5% with no need to purify the crude intermediate compounds in each step except by filtering through silica gel. In a similar manner, (*R*)-**7** is prepared.

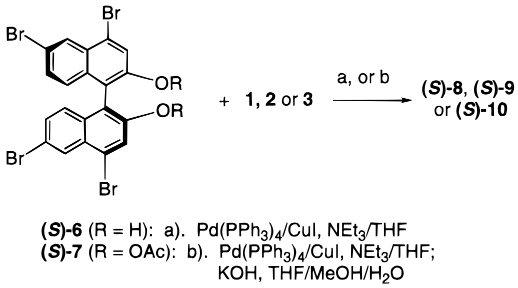
Initially, we have attempted to carry out the direct cross-coupling of (*S*)-**6** with dendrons **1**−**3** in order to prepare the desired chiral cross-conjugated dendrimers (Scheme 2). Although the coupling of (*S*)-**6** with **1** proceeds smoothly in the presence of $Pd(PPh_3)_4$ and CuI, this strategy has proven to be problematic when **2** and **3** are used. The desired dendrimers are obtained only in low yields (25% when **2** is used and 23% when **3** is used)

---

[8] (a) Hawker, C.; Fréchet, J. M. J. *J. Chem. Soc., Chem. Commun.* **1990**, 1010. (b) Hawker, C. J.; Fréchet, J. M. J. *J. Am. Chem. Soc.* **1990**, *112*, 2, 7638. (c) Miller, T. M.; Neenan, T. X. *Chem. Mater.* **1990**, *2*, 346.

[9] (a) Grushin, V. V.; Alper, H. *Chem. Rev.* **1994**, *94*, 1047. (b) Sonogashira, K.; Tohda, Y.; Hagihara, N. *Tetrahedron Lett.* **1975**, 4467. (c) Cassar, L. *J. Organomet. Chem.* **1975**, *93*, 253. (d) Dieck, H. A.; Heck, R. F. *J. Organomet. Chem.* **1975**, *93*, 259.

Scheme 2. Synthesis of the 1,1′-Binaphthyl-Based Rigid Chiral Dendrimers



even with excess **2** or **3** (1.5 equiv per bromine). The main side products are partially coupled compounds. The incomplete conversion may be due to the deprotonation of (*S*)-**6** under the basic reaction condition which makes the binaphthyl molecule very electron rich and reduces the aryl bromide−alkyne coupling rate. It is generally observed that introducing electron-withdrawing groups to the para position of an aromatic halide increases the reactivity of the halide in the palladium-catalyzed cross-coupling reaction with terminal acetylenes.[9] Therefore, (*S*)-**7** is prepared for the dendrimer synthesis where the hydroxyl groups of (*S*)-**6** are converted to the much weaker electron-donating acetate groups. As expected, (*S*)-**7** couples with the dendrons much more efficiently than (*S*)-**6**. The coupling of (*S*)-**7** with **1**, **2**, or **3** is conducted under the same condition as in the coupling of (*S*)-**6** by using a cocatalyst of $Pd(PPh_3)_4/CuI$. The reaction is carried out in a cosolvent of THF/Et_3N at 65−70 °C over 36 h. After hydrolysis of the coupling products under basic condition (aqueous KOH), the novel optically active and structurally rigid dendrimers (*S*)-**8** (generation 0), (*S*)-**9** (generation 1), and (*S*)-**10** (generation 2) are obtained (Chart 2) in very high yields (82−90% total yields from the two-step reaction sequence). By a similar procedure, (*R*)-**10**, the enantiomer of (*S*)-**10**, is also synthesized from the coupling of (*R*)-**7** with **3**. All of these chiral dendrimers are pale yellow solids with excellent solubility in many organic solvents including hexane, diethyl ether, THF, methylene chloride, chloroform, benzene, and toluene. (*S*)-**8** is also soluble in methanol but (*S*)-**9** and (*S*)-**10** are not.

Previously we have shown that the conditions for the coupling of aryl bromides with alkynes (at ∼ 70 °C) do not racemize the binaphthyl structure.[6c,l] Therefore, we expect dendrimers (*S*)-**8**, (*S*)-**9**, (*S*)-**10**, and (*R*)-**10** to retain their enantiomeric purity. This is supported by a HPLC analysis of **10** using a Chiralcel-OD column. Although a partial overlap is observed for the HPLC signals of the two enantiomers of racemic **10**, there is an 1.5 min peak separation. The signal overlap is due to a significant tailing of the HPLC peaks probably a consequence of their large sizes. When either (*R*)-**10** or (*S*)-**10** is analyzed individually, no signal of the other enantiomer can be detected.

All of these dendrimers give very well-resolved ^1H and ^{13}C NMR spectra consistent with their structures. For example, the ^{13}C NMR spectra show the expected four alkyne carbon signals for (*S*)-**8**, eight for (*S*)-**9**, and twelve for (*S*)-**10** (Figure 1). The NMR spectra indicate that these dendrimers maintain a C_2 symmetry in solution. As shown in Table 1, fast atom bombardment (FAB) mass spectroscopic analysis of (*S*)-**8** and (*S*)-**9** gives the expected molecular ions. The matrix-assisted laser desorption/ionization (MALDI) mass spectra of (*S*)-**10** and (*R*)-**10** show peaks at 4882.5 and 4883.0, respectively, matching the calculated value for $M + H^+$. Besides the molecular ions, other peaks corresponding to $M + Na^+$ and M + matrix (*trans*-3-indoleacrylic acid) are also observed in the MALDI spectra of (*S*)-**10** and (*R*)-**10**. Gel permeation chromatography analysis (GPC, polystyrene standards) demonstrates that all of these molecules are monodisperse with PDI very close to unit.

The optical rotation data of these materials are also collected in Table 1. It is found that when the molecular weight increases over 4 times from the zero generation dendrimer to the second generation, there is only 36% increase in the molar optical rotation. Thus, the dendritic arms attached to the binaphthyl core in these molecules do not lead to major chiral amplification.

Figure 2 is an energy-minimized structure of (*S*)-**10** obtained by using the MM2 force field of Macromodel 4.5 implemented on a Silicon Graphics Indigo2 Extreme computer. The final steric energy is 211.93 kcal/mol. The calculated dihedral angle of the binaphthyl core for (*S*)-**10** is 83.6°.

2. Optical Spectroscopic Studies of the Chiral Dendrimers. The circular dichroism (CD) spectra of these dendrimers in methylene chloride solution are obtained with the concentration of the dendrimers at $1.6{-}3.7 \times 10^{-6}$ M (Figure 3). The molar ellipticities ([Θ]) of the Cotton effects are listed in Table 2. There is no significant change in the Cotton effects going from the generation 0 to the generation 2 dendrimer. This also indicates no chiral amplification in these rigid dendrimers and no chiral order achieved by the rigid phenylacetylene dendrons.

Both the solution and solid forms of the binaphthyl-based dendrimers emit intense blue light under UV irradiation. The UV−vis absorption spectra of (*S*)-**8**, (*S*)-**9**, and (*S*)-**10** in methylene chloride at room temperature are shown in Figure 4, where the molar concentrations of these dendrimers are the same ($c = 1.0 \times 10^{-6}$ M). The absorption maximums and molar extinction coefficients of the chiral dendrimers as well as the dendrons are collected in Table 3. Two absorption bands are seen in the spectra: a strong band around 250−330 nm and a weak band around 340−400 nm. The former is due to both the phenylacetylene dendrons and the binaphthyl moieties and the latter the more conjugated 4,4′,6,6′-tetraphenylethynyl-1,1′-bi-2-naphthol core. The absorptions in the 250−330 nm region become much stronger as the dendritic generation grows because of the exponential increase in the number of the light absorbing phenylacetylene units. The molar extinction coefficient of these dendrimers at ∼310 nm is increased by about 9 times from the zero generation dendrimer (S)-**8** to the second generation dendrimer (S)-**10**. There is very little change for the absorption around 380 nm of the conjugated core. The absorption maximums show only very small red-shift with increasing generation. This is expected since the meta linkage of the phenylacetylene units should cause little change in conjugation as the dendrimer grows.

We have measured the fluorescences of monodendrons **2** and **3** in methylene chloride solution. Monodendron **3** has an emission maximum at ca. 359 nm and a shoulder at ca. 370 nm, and monodendron **2** has emission maximums at ca. 348 and 360 nm. The fluorescence spectra of the dendrimers in methylene chloride solution are also

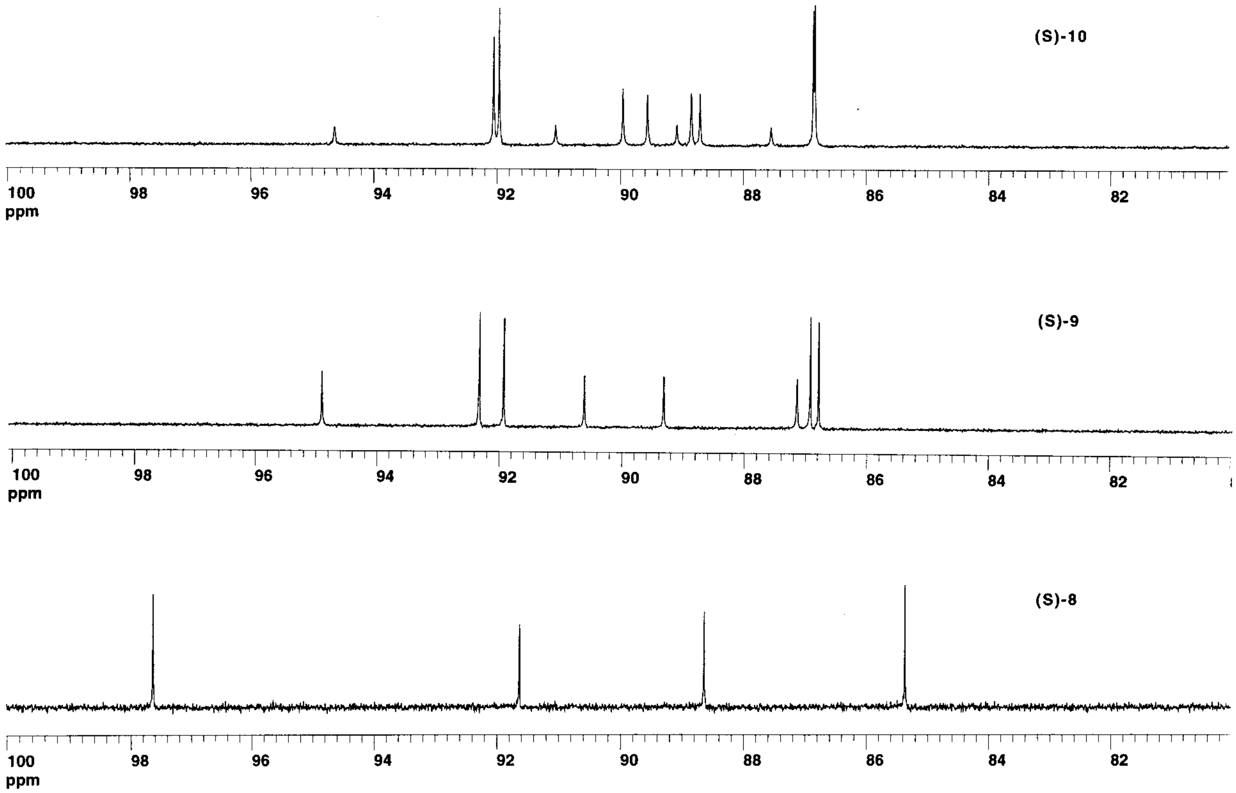
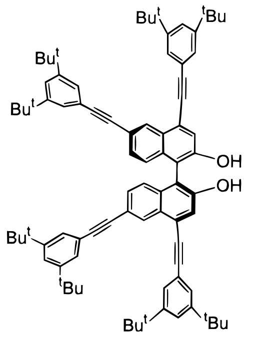
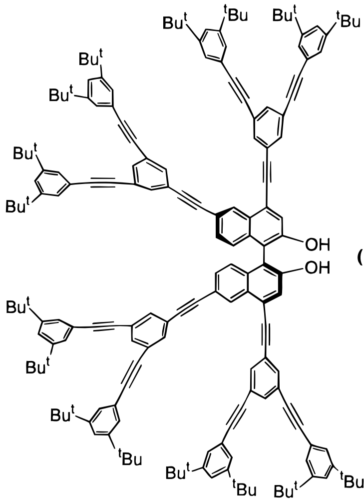


Figure 1. The alkyne carbon signals in the ^{13}C NMR spectra of the dendrimers.

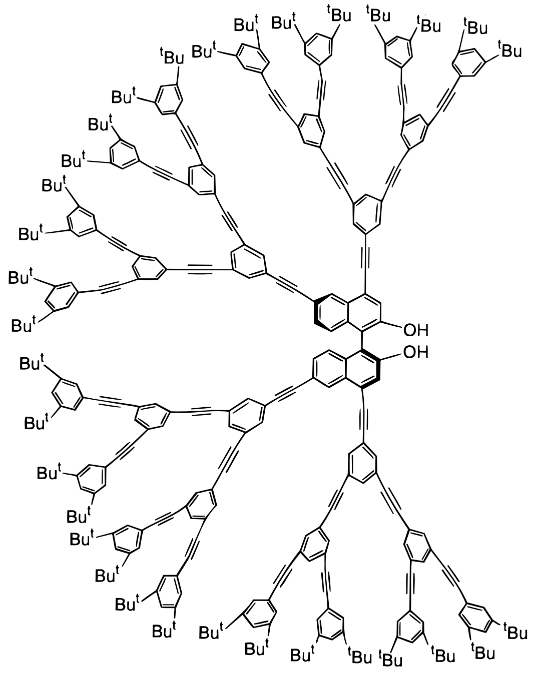
Chart 2



(*S*)-8



(*S*)-9



(*S*)-10

recorded with the concentration of the materials at 4.0 × 10^{-8} M (Figure 5). When the dendrimer samples are excited at 310 nm where most of the irradiation is absorbed by the diphenylacetylene units, the emission wavelengths of these rigid dendrimers are almost identical with a maximum at 421–422 nm as well as a shoulder at 441 nm for (*S*)-**8**, (*S*)-**9**, and (*S*)-**10** (Figure 5).

The higher generation dendrimer (*S*)-**10** emits about

Table 1. Physical Properties of the Novel Rigid and Optically Active Endrimers

chiral dendrimers	(*S*)-**8** (G0)	(*S*)-**9** (G1)	(*S*)-**10** (G2)	(*R*)-**10** (G2)
mass spectral data (calcd value)	FAB, 1134.7190 (M, 1134.7254)	FAB, 2385.5 (M + H, 2384.5)	MALDI, 4882.5 (M + H, 4882.0)	MALDI, 4883.0 (M + H, 4882.0)
GPC Mn (PDI) (THF, polystyrene standard)	1670 (1.05)	3670 (1.04)	6420 (1.04)	6390 (1.04)
specific optical rotation $[\alpha]_D$ ($c = 1$, CH_2Cl_2)	114.4	67.5	36.2	−36.0
molar optical rotation [M]	1299	1609	1769	−1759

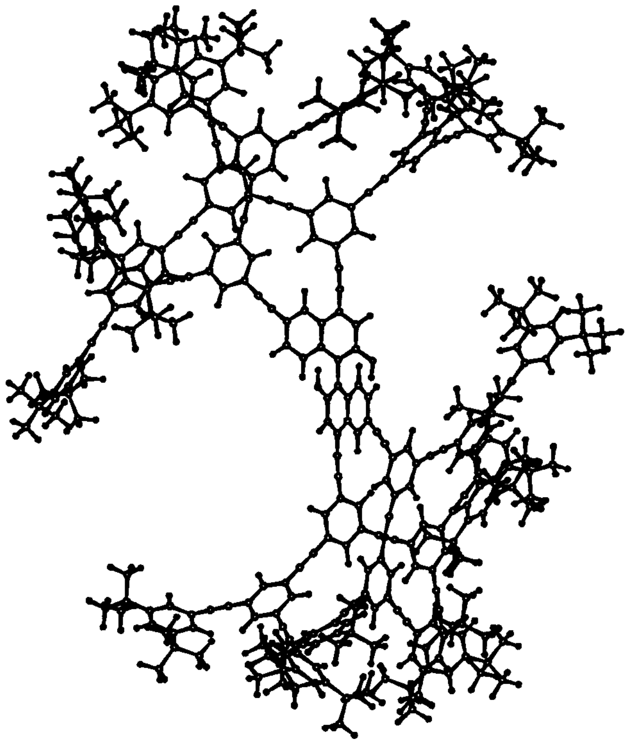


Figure 2. The energy-minimized structure of (*S*)-**10**.

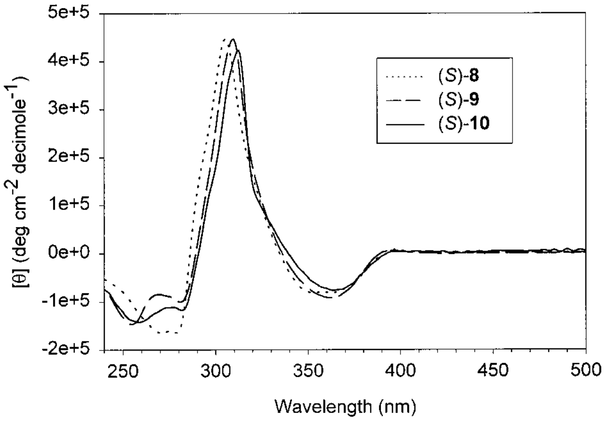


Figure 3. The CD spectra of the chiral dendrimers.

Table 2. The CD Spectral Data of the Chiral Dendrimers

dendrimers	(*S*)-**8**	(*S*)-**9**	(*S*)-**10**
CD [Θ] (λ_{nm})	-8.1×10^4 (363)	-9.2×10^4 (363)	-7.7×10^4 (363)
(CH_2Cl_2)	4.5×10^5 (305)	4.5×10^5 (309)	4.2×10^5 (312)
	-1.6×10^5 (279)	-1.0×10^5 (281)	-1.2×10^4 (282)
	-1.6×10^5 (271)	-1.5×10^5 (255)	-1.4×10^5 (258)

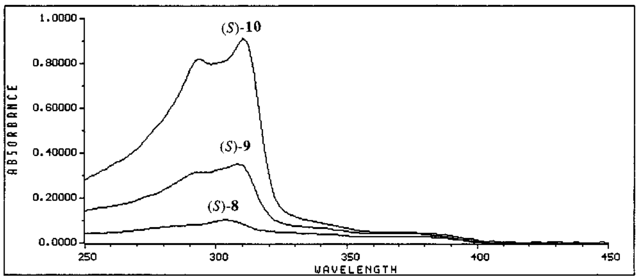


Figure 4. The UV absorption spectra of the chiral dendrimers.

3 times more intense than (*S*)-**9**, and (*S*)-**9** emits about 4 times more intense than (*S*)-**8** at the same molar concentration. The disappearance of the emissions at 340−370 nm for the monodendrons and the strong emissions at >420 nm in the fluorescence spectra of the dendrimers demonstrate that there is a very efficient intramolecular energy transfer from the phenylacetylene dendrons to the more conjugated core. By comparing the emission intensity of the monodendrons **2** and **3** with those of (*S*)-**9** and (*S*)-**10** at 359 nm normalized according to the concentration of the diphenylacetylene units, the energy-transfer yields are estimated to be over 99%.

The excitation spectra of the dendrimers also support the observed efficient energy transfer (Figure 6). While the emissions are set at 422 nm, the excitation maximum of the dendrimers at 310 nm increases significantly going from generation 0 to generations 1 and 2. This points to the fact that with the increasing number of light-absorbing phenylacetylene chromophores, more photons can be harvested by the higher generation dendrimers, and stronger emissions are observed. This is the same as what has been observed by Moore in their phenylacetylene dendrimers such as **4**.[2e]

The fluorescence quantum yields of the chiral dendrimers are measured by using quinine sulfate in 1 N sulfuric acid as the reference.[10,11] When the excitation wavelength is set at 310 nm (i.e., the absorption maximum of the phenylacetylene monodendrons), the estimated quantum yields for the dendrimers (*S*)-**8**, (*S*)-**9**, and (*S*)-**10** are 0.30, 0.32, and 0.40, respectively. The observed increase in fluorescence quantum yield for the higher generation dendrimers may be caused by the possibly decreased conformational flexibility with respect to rotation around the 1,1′-binaphthyl bond when the size of the dendritic arms increases.

In recent years, the use of dendrimers as light-harvesting materials have attracted significant atten-

---

(10) Demas, J. N.; Crosby, J. *J. Phys. Chem.* **1971**, *75*, 991.

(11) (a) Isak, S. J.; Eyring, E. M. *J. Phys. Chem.* **1992**, *96*, 1738. (b) Kamat, P. V.; Ford, W. E. *Chem. Phy. Lett.* **1987**, *135*, 421.

(12) (a) Kawa, M.; Fréchet, J. M. J. *Chem. Mater.* **1998**, *10*, 286. (b) Balzani, V.; Campagna, S.; Denti, G.; Juris, A.; Serroni. S.; Venturi, M. *Acc. Chem. Res.* **1998**, *31*, 26. (c) Fox, M. A.; Jones, W. E., Jr.; Watkins, D. M. *Chem. Eng. News* **1993**, *71* (11), 38. (d) Stewart, G. M.; Fox, M. A. *J. Am. Chem. Soc.* **1996**, *118*, 4354.

(13) (a) Bar-Haim, A.; Klafer, J.; Kopelman, R. *J. Am. Chem. Soc.* **1997**, *119*, 6197. (b) Bar-Haim, A.; Klafer, J. *J. Phys. Chem. B* **1998**, *102*, 1662.

(14) (a) Jiang, D.-L.; Aida, T. *J. Am. Chem. Soc.* **1998**, *120*, 10895. (b) Jiang, D.-L.; Aida, T. *Nature* **1997**, *388*, 454.

Table 3. Absorption Maximums and Extinction Coefficients of the Dendrimers and Dendrons

compounds	(*S*)-**8**	(*S*)-**9**	(*S*)-**10**	**2**	**3**
λ_{max} nm (ϵ, M^{-1} cm^{-1})	374 (2.82×10^4) 304 (1.04×10^5) 292 (8.04×10^4)	378 (4.12×10^4) 308 (3.52×10^5) 292 (3.13×10^5)	380 (4.44×10^4) 310 (9.16×10^5) 294 (8.20×10^5)	308 (6.25×10^4) 290 (6.79×10^4)	310 (2.03×10^5) 292 (1.85×10^5)

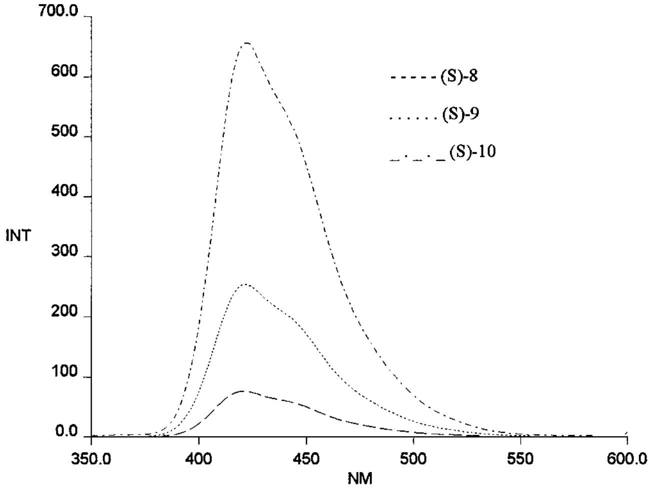


Figure 5. The fluorescence spectra of the chiral dendrimers (uncorrected).

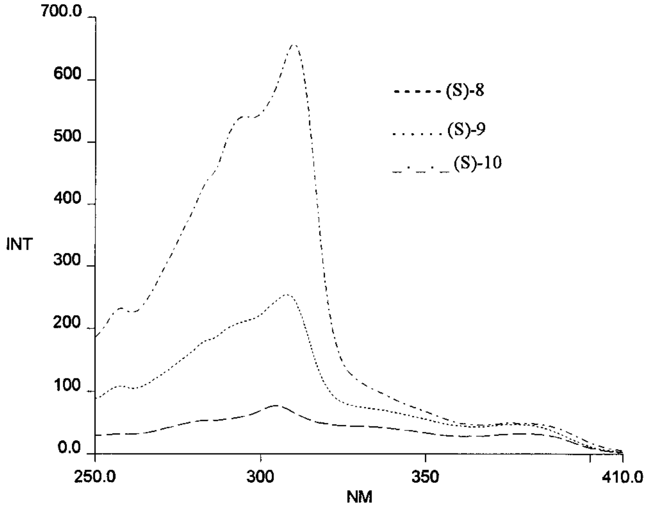
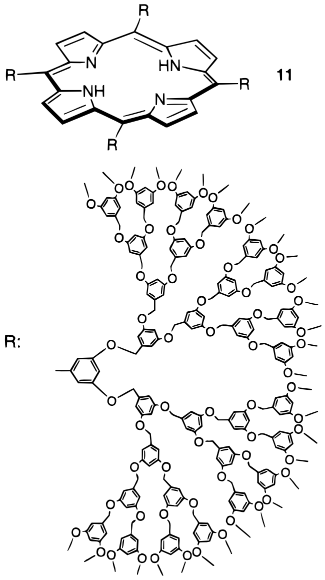
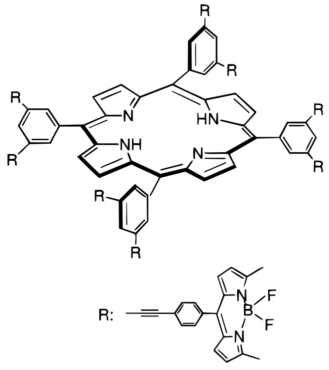


Figure 6. The excitation spectra of the chiral dendrimers (uncorrected).

tion[12–16] because of the importance of energy transfer in the photosynthetic process of the nature.[17] Besides Moore's work on phenylacetylene dendrimers, Jiang and Aida have found that porphyrin-centered dendrimers such as **11** having a continuous array of aryl ether peripheral framework exhibit very efficient energy transfer from the dendritic antenna to the porphyrin core.[14a] Efficient energy migration has been observed in another porphyrin-based material **12** by Lindsey et al.[15] Fox and co-workers have also studied the light-harvesting properties of phenyl benzyl ether dendrimers.[12g] These materials are designed in an effort to mimic the photosynthetic energy-transfer process. Very recently, Fréchet and co-workers also reported the use of dye-labeled dendrimers to carry out energy migration.[16] Our work on (*S*)-**8**, (*S*)-**9**, and (*S*)-**10** represents the first example of an efficient energy-transfer process conducted in an optically pure dendritic system. This makes it possible to design dendrimer-based efficient fluorescence sensors for enantioselective recognition.



11



12

3. Asymmetric Reaction of Aldehydes with Diethylzinc Catalyzed by the Chiral Dendrimer (*S*)-10. We have studied the use of (*S*)-**10** to catalyze the asymmetric reaction of benzaldehyde with diethylzinc (Scheme 3)[18] and have compared the catalytic properties of this dendrimer with the parent BINOL molecule. We find that the nanoscale dendritic material behaves very differently from the small BINOL molecule. (*S*)-**10** shows much higher catalytic activity than (*S*)-BINOL and also generates the opposite enantiomeric product. In the

---

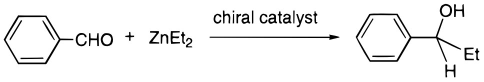
[15] Li, F.; Yang, S. I.; Ciringh, Y.; Seth, J.; Martin III, C. H.; Singh, D. L.; Kim, D.; Birge, R. R.; Bocian, D. F.; Holten, D.; Lindsey, J. S. *J. Am. Chem. Soc.* **1998**, *120*, 10001.

[16] Gilat, S. L.; Adronov, A.; Fréchet, J. M. J. *Angew. Chem., Int. Ed.* **1999**, *38*, 1422.

[17] (a) Horspool, W. M.; Song, P.-S. *Organic Photochemistry and Photobiology*; CRC: Boca Raton, FL, 1995. (b) Horspool, W. M. *Synthetic Organic Photochemistry*; Plenum Press: New York, 1984. (c) Mcdermott, G.; Prince, S. M.; Freer, A. A.; Hawthornwaite-lawless, A. M.; Rapiz, M. Z.; Cogdell, R. J.; Isaacs, N. W. *Nature* **1995**, *374*, 517. (d) Kühlbrandt, W. *Nature* **1995**, *374*, 497.

[18] For reviews on the catalytic asymmetric reaction of aldehydes with diethylzinc, see: (a) Soai, K.; Niwa, S. *Chem. Rev.* **1992**, *92*, 833. (b) Noyori, R.; Kitamura, M. *Angew. Chem., Int. Ed. Engl.* **1991**, *30*, 49.

Scheme 3. The Catalytic Asymmetric Reaction of Benzaldehyde with Diethylzinc



presence of (*S*)-**10** (5 mol %) in toluene solution, a 98.6% conversion of benzaldehyde is observed in 24 h at room temperature. However, only 37% conversion is observed under the same condition when BINOL is used.[6h] Both the enantioselectivities of (*S*)-**10**[19] and BINOL[6h] are very low. The increased catalytic activity of (*S*)-**10** over BINOL indicates that the zinc complex generated from the reaction of (*S*)-**10** with diethylzinc may have much higher Lewis acidity than the zinc complex generated from BINOL. The zinc complex formed from the reaction of BINOL with diethylzinc is found to likely exist as aggregates in solution through intermolecular Zn−O−Zn bonds which should greatly reduce the Lewis acidity of the zinc center.[6h] We expect that such aggregate cannot form in the case of (*S*)-**10** due to the large dendritic arms as indicated by Figure 2. These bulky and rigid dendritic arms prevent (*S*)-**10** from forming oligomers through Zn−O−Zn bonds, yet still allow small molecules such as benzaldehyde and diethylzinc to approach the chiral core for the catalytic reaction. The opposite enantioselectivity of (*S*)-**10** versus (*S*)-BINOL also indicates that the in situ generated catalytically active species when these ligands are used are very different. It may be monomeric for (*S*)-**10** but oligomeric for BINOL.

In the presence of Ti(O−i-Pr)$_4$, (*S*)-**10** becomes highly enantioselective for the reaction of aldehydes with diethylzinc.[20] In toluene, (*S*)-**10** (20 mol %) and Ti(O−i-Pr)$_4$ (1.4 equiv) catalyze the reaction of 1-naphthaldehyde with diethylzinc with 100% conversion and 90% ee in 5 h. No side product is observed. Under similar condition, (*S*)-**10** shows 100% conversion and 89% ee for the reaction of benzaldehyde with diethylzinc in the presence of Ti(O−i-Pr)$_4$. These catalytic properties of (*S*)-**10** are very similar to those of BINOL in the presence of the titanium complex as reported by Chan and co-workers.[20a] The same enantiomeric product is produced by using either (*S*)-**10** or (*S*)-BINOL in the presence of Ti(O−i-Pr)$_4$. This study indicates that unlike the reaction in the absence of Ti(O−i-Pr)$_4$, the asymmetric reaction of aldehydes with diethylzinc in the presence of the titanium complex may involve structurally similar catalytically active species when either the chiral dendrimer (*S*)-**10** or the small molecule BINOL is used. Since the titanium complex of (*S*)-**10** is not expected to generate any dimeric or oligomeric structure through the binaphthyl core, the catalytically active species formed from the interaction of BINOL with Ti(O−i-Pr)$_4$ may also be monomeric. In these catalytic reactions, (*S*)-**10** can be easily recovered from the reaction mixture by precipitation with methanol due to the large size differences between this dendritic molecule and the products and reagents.

Summary

In summary, novel optically active dendrimers containing rigid and cross-conjugated units have been synthesized and characterized. UV absorption and fluorescence spectroscopic studies demonstrate that the energy harvested by the periphery of the dendrimers can be efficiently transferred to the center core of the dendrimer. This is the first example of an energy migration carried out in an optically pure dendritic system which allows us to design efficient dendritic fluorescence sensors for potentially rapid optical determination of the enantiomeric composition of chiral compounds. Work towards this direction is in progress in our laboratory. High enantioselectivity has been observed when the second generation chiral dendrimer is used to catalyze the asymmetric reaction of aldehydes with diethylzinc. Comparison of the dendrimer catalysts with the corresponding small molecule catalysts have provided further information about the catalytic process.

Experimental Section

General Data. The FAB mass spectra were obtained by the University of California−Riverside mass spectroscopy facility. MALDI-TOF mass spectra were obtained by the University of Illinois−Urbana Champaign mass spectroscopy facility. THF and triethylamine were dried with sodium/benzophenone. Tetrakis(triphenylphosphine)palladium(0) and copper(I) iodide were purchased from Strem and used directly. Other chemical reagents were purchased from Aldrich and used directly.

Preparation and Characterization of 4,4′,6,6′-Tetrabromo-1,1′-bi-2-naphthyl Diacetate 7. (1) To a solution of (*S*)-1,1′-bi-2-naphthol [or (*R*)-1,1′-bi-2-naphthol] (6.0 g, 21 mmol) and 1-bromohexane (10 mL) in acetone (100 mL) was added K_2CO_3 (16.0 g). The resulting reaction mixture was refluxed under nitrogen for 69 h. After it was cooled to room temperature, H_2O was added and the mixture was extracted with hexanes. The organic layer was washed with brine. Evaporation of the solvent followed by flash chromatography on silica gel (eluted with hexanes) gave an oily product. (2) The oil was dissolved in AcOH (100 mL), and Br_2 (11 mL, 10 equiv) was added over 30 min at room temperature. The reaction mixture was stirred at this temperature for another 6 h and was monitored by ^1H NMR. After completion of the reaction, $NaHSO_3$ was added to quench the excess Br_2. After extraction with EtOAc, the combined organic solution was washed with $NaHCO_3$ and brine, and was passed through a short silica gel column. After evaporation of the solvent, an oily product [(*S*)-**5**] was obtained. (3) The oil was dissolved in CH_2Cl_2, and BBr_3 (7.0 mL) was then added at 0 °C. The resulting solution was warmed to room temperature and stirred for 12 h. The mixture was then cooled to 0 °C and was quenched with the addition of ice−water. The mixture was extracted with EtOAc, and the organic layer was washed with brine, saturated $NaHCO_3$ solution, and brine. After it was passed through a short silica gel column, the solvent was evaporated to give a solid [(*S*)-**6**]. (4) This crude product was first dissolved in CH_2Cl_2/pyridine and then treated with Ac_2O. After 12 h at room temperature, the reaction was quenched with the addition of H_2O. The mixture was extracted with EtOAc, and the organic layer was washed with brine, saturated $NaHCO_3$ solution, and brine. After evaporation of the solvent and flash chromatography on silica gel, a white solid (*S*)-**7** (9.0 g) was obtained in a total yield of 62.5% for the four-step reaction sequence. Mp: 198.0−199.5 °C. [α] = 14.41 (*c* =

---

[19] (*R*)-1-Phenylpropanol was produced with 11% ee and 83% yield in the presence of (*S*)-**10**. Besides the desired chiral alcohol product, side products including benzyl alcohol and phenyl ethyl ketone were also formed in about 15% yield.

[20] (a) Zhang, F.-Y.; Yip, C.-W.; Cao, R.; Chan, A. S. C. *Tetrahedron: Asymmetry* **1997**, *8*, 585. (b). Schmidt, B.; Seebach. D. *Angew. Chem., Int. Ed. Eng.* **1991**, *30*, 1321. (c) Seebach. D.; Beck, A. K.; Schimdt, B.; Wang, Y. M. *Tetrahedron* **1994**, *50*, 4363.

1.02, CH_2Cl_2). ^1H NMR ($CDCl_3$, 300 MHz) δ 1.91 (s, 6H), 6.99 (d, J = 9.0 Hz, 2H), 7.41 (dd, J = 9.0, 1.8 Hz, 2H), 7.78 (s, 2H), 8.51 (d, J = 1.8 Hz, 2H). ^{13}C NMR ($CDCl_3$, 75 MHz) δ 20.67, 122.24, 122.78, 122.82, 127.32, 128.24, 129.96, 131.54, 131.58, 132.26, 146.61, 168.95. IR (KBr) ν (cm^{-1}) 3081 (w), 1766 (s). UV (CH_2Cl_2) λ_{max} 334, 300, 242 nm. Fluorescence (CH_2Cl_2, λ_{exc} 334 nm) λ_{emi} 359 nm. HRMS (FAB) Calcd for $C_{24}H_{14}Br_4O_4$ + H: 686.7663; found: 686.7655. Anal. Calcd for $C_{24}H_{14}Br_4O_4$: C, 42.02; H, 2.45%. Found: C, 41.80; H, 2.20%.

(*R*)-**7**. Mp: 198.5−200 °C. [α] = −14.35 (c = 1.08, CH_2Cl_2). ^1H NMR ($CDCl_3$, 300 MHz) δ 1.91 (s, 6H), 6.99 (d, J = 9.0 Hz, 2H), 7.41 (dd, J = 9.0, 2.1 Hz, 2H), 7.78 (s, 2H), 8.51 (d, J = 2.1 Hz, 2H). ^{13}C NMR ($CDCl_3$, 75 MHz) δ 20.69, 122.25, 122.79, 122.83, 127.33, 128.26, 129.98, 131.55, 131.60, 132.27, 146.62, 168.96. IR (KBr) ν (cm^{-1}) 3081 (w), 1766 (s). UV (CH_2Cl_2) λ_{max} 334, 300, 242 nm. Fluorescence (CH_2Cl_2, λ_{exc} 334 nm) λ_{emi} 359 nm. Anal. Calcd for $C_{24}H_{14}Br_4O_4$: C, 42.02; H, 2.45%. Found: C, 42.06; H, 2.03%.

Preparation and Characterization of the Chiral Dendrimers. A typical procedure: To a mixture of (*S*)- or (*R*)-**7** (0.3 mmol) and the alkyne dendron **1**, **2**, or **3** (1.56 mmol, 1.3 equiv per bromo unit) were added THF (10 mL) and Et_3N (15 mL). After this solution was degassed by bubbling with N_2 for 30 min, $Pd(PPh_3)_4$ (50 mg) and CuI (15 mg) were added. The mixture was heated at 70 °C for 24 h and was cooled to room temperature. Hexane was used to extract, and the organic layer was washed with 1 N HCl, brine, saturated $NaHCO_3$, and brine. Evaporation of the solvent gave a yellow solid which was directly subjected to hydrolysis by using a mixture of KOH (1.12 g), THF (50 mL), MeOH (20 mL), and H_2O (10 mL) at room temperature for 12 h. Hexane was added, and the mixture was neutralized with 1 N HCl. The organic layer was then washed with brine, saturated $NaHCO_3$, and brine. Evaporation of solvent gave a yellow solid. Flash chromatography on silica gel (eluent: hexane:EtOAc = 100:1.25 to 100:5) gave the desired dendrimer as a pale yellow solid.

(*S*)-**8**. Yield 90.4%. mp: 143−146 °C. [α] = 114.35 (c = 0.99, CH_2Cl_2). [M] = 1298.6. ^1H NMR ($CDCl_3$, 300 MHz) δ 1.35 and 1.42 (two singlets, 72 H), 5.13 (s, 2H), 7.19 (d, J = 9.0 Hz, 2H), 7.42−7.45 (m, 6H), 7.53 (m. 4H), 7.60 (d, J = 2.1 H, 4H), 7.72 (s, 2H), 8.73 (d, J = 2.1 Hz, 2H). ^{13}C NMR ($CDCl_3$, 75 MHz) δ 31.58, 31.62, 35.07, 35.16, 85.36, 88.63, 91.63, 97.63, 111.86, 120.28, 122.06, 122.33, 122.36,123.06, 123.74, 124.80, 125.02, 126.18, 126.37, 129.52, 130.62, 131.11, 132.89, 151.07, 151.37, 152.88. UV (CH_2Cl_2) λ_{max} 370, 304, 288, 232 nm. Fluorescence (CH_2Cl_2, λ_{exc} 370 nm) λ_{emi} 422, 441 (sh) nm. IR (KBr) ν (cm^{-1}) 3543 (m), 2962 (s), 2899 (m), 2867 (m), 2200 (w). HRMS (FAB) Calcd for $C_{84}H_{94}O_2$: 1134.7254. Found: 1134.7190. Anal. Calcd for $C_{84}H_{94}O_2$: C, 88.84; H, 8.34%. Found: C, 88.66; H, 8.80%.

(*S*)-**9**. Yield: 86.5%. [α] = 67.45 (c =1.03, CH_2Cl_2). [M] = 1609. ^1H NMR ($CDCl_3$, 300 MHz) δ 1.32 and 1.33 (two singlets, 144H), 5.16 (s, 2H), 7.22 (d, J = 9.0 Hz, 2H), 7.37 (d, J = 1.8 Hz, 8H), 7.40 (t, J = 1.8 Hz, 4H), 7.42 (m, 12H), 7.53 (dd, J = 9.0, 1.8 Hz, 2H), 7.70 (t, J = 1.8 Hz, 2H), 7.73 (s, 2H), 7.75 (d, J = 1.8 Hz, 4H), 7.81 (t, J = 1.8 Hz, 2H), 7.87 (d, J = 1.8 Hz, 4H), 8.63 (d, J = 1.2 Hz, 2H). ^{13}C NMR ($CDCl_3$, 75 MHz) δ 31.54, 35.03, 86.78, 86.92, 87.13, 89.32, 90.60, 91.92, 92.32, 94.89, 112.32, 119.96, 121.90, 122.04, 123.01, 123.24, 123.39, 123.62, 124.00, 124.52, 124.57, 124.77, 124.97, 126.18, 126.23, 129.32, 130.40, 131.34, 133.11, 134.16, 134.25, 134.48, 135.06, 151.07, 151.15, 153.00. UV (CH_2Cl_2) λ_{max} 374, 308, 292, 232 nm. Fluorescence (CH_2Cl_2, λ_{exc} 374 nm) λ_{max} 422, 441 (sh) nm. IR (KBr) ν (cm^{-1}) 3540 (w), 2962 (s), 2905 (m), 2867 (m), 2213 (w). MS (FAB) Calcd for $C_{180}H_{190}O_2$ + H: 2384.5. Found: 2385.5. Anal. Calcd for $C_{180}H_{190}O_2$: C, 90.63; H, 8.03%. Found: C, 90.34; H, 7.84%.

(*S*)-**10**. Yield: 82%. [α] = 36.22 (c = 1.04, CH_2Cl_2). [M] = 1769.4. ^1H NMR ($CDCl_3$, 300 MHz) δ 1.33 and 1.34 (two singlets, 288H), 5.18 (s, 2H), 7.27 (d, J = 8.7 Hz, 2H), 7.39−7.43 (m, 56H), 7.58 (dd, J = 8.7, 1.5 Hz, 2H), 7.64 (m, 8 H), 7.70 (t, J = 1.5 Hz, 4H), 7.72 (m, 8H), 7.77 (m, 6H), 7.90 (d, J = 1.5 Hz, 4H), 8.69 (d, J = 1.5 Hz, 2H). ^{13}C NMR ($CDCl_3$, 75 MHz) δ 31.56, 35.05, 86.83, 86.86, 87.54, 88.71, 88.85, 89.07, 89.56, 89.96, 91.04, 91.96, 92.05, 94.63, 112.42, 119.87, 122.02, 122.36, 122.90, 123.30, 123.48, 123.60, 123.91, 124.08, 124.24, 124.32, 124.53, 124.64, 125.01, 125.26, 125.82, 126.20, 126.56, 127.10, 129.34, 130.57, 131.37, 133.16, 134.14, 134.62, 134.78, 135.14, 151.11, 153.08. UV (CH_2Cl_2) λ_{max} 378, 310, 294, 230 nm. Fluorescence (CH_2Cl_2, λ_{exc} 374 nm) λ_{emi} 422, 441 (sh) nm. IR (KBr) ν (cm^{-1}) 3540 (w), 2962 (s), 2899 (m), 2867 (m), 2213 (w). MS (MALDI) Calcd for $C_{372}H_{382}O_2$ + H: 4882.0. Found: 4882.5. Anal. Calcd for $C_{372}H_{382}O_2$: C, 91.46; H, 7.88%. Found: C, 91.26; H, 7.94%.

(*R*)-**10**. Yield 83.5%. [α] = −36.04 (c = 1.04, CH_2Cl_2). [M]= 1760.6. ^1H NMR ($CDCl_3$, 300 MHz) δ 1.34 and 1.35 (two singlets, 288 H), 5.19 (s, 2H), 7.28 (d, J = 8.7 Hz, 2H), 7.40−7.44 (m, 56 H), 7.58 (dd, J = 8.7, 1.5 Hz, 2H), 7.64 (m, 8H), 7.70 (t, J = 1.5 Hz, 4H), 7.72 (m, 8H), 7.77 (m, 6H), 7.91 (d, J = 1.5 Hz, 4H), 8.69 (d, J = 1.5 Hz, 2H). ^{13}C NMR ($CDCl_3$, 75 MHz) δ 31.55, 35.03, 86.83, 87.55, 88.70, 88.83, 89.06, 89.56, 89.96, 91.06, 91.96, 92.05, 94.62, 112.47, 119.84, 122.00, 123.29, 123.47, 123.58, 123.92, 124.08, 124.24, 124.32, 124.52, 124.64, 125.02, 125.81, 126.18, 126.55, 129.32, 130.56, 131.34, 133.18, 134.13, 134.61, 134.77, 135.12, 151.09, 153.09. UV (CH_2Cl_2) λ_{max} 374, 310, 294, 230 nm. Fluorescence (CH_2Cl_2, λ_{exc} 374 nm) λ_{emi} 422, 441 (sh) nm. IR (KBr) ν (cm^{-1}) 3541 (w), 2962 (s), 2905 (m), 2867 (m), 2213 (w). MS (MALDI) Calcd for $C_{372}H_{382}O_2$ + H: 4882.0; found: 4883.0. Anal. Calcd for $C_{372}H_{382}O_2$: C, 91.46; H, 7.88%. Found: C, 91.12; H, 7.82%.

The Asymmetric Reaction of 1-Naphthaldehyde with Diethylzinc Catalyzed by (*S*)-10 in the Presence of $Ti(O\text{-}i\text{-}Pr)_4$. Under nitrogen, to a solution of (*S*)-**10** (125 mg, 0.025 mmol) and toluene (2 mL) was added Ti(O-*i*-Pr)$_4$ (60 μL, 0.175 mmol). After the solution was stirred at room temperature for 1.5 h, Et_2Zn (37.5 μL, 0.375 mmol) was added and the stirring was continued for 10 min. 1-Naphthaldehyde (17 μL, 0.125 mmol) was then added at 0 °C, and the mixture was allowed to stir at 0 °C for 5 h (TLC showed 100% conversion of the starting material). The reaction was quenched with 1 N HCl and extracted with EtOAc. After precipitation of the dendrimer with the addition of MeOH, the residue was passed through a short silica gel column to give the product 1-(1′-naphthyl)propanol. HPLC (Chiralcel OD column, hexane:2-propanol = 9:1, 1.0 mL/min) showed 90.4% ee (t_S = 9.5 min, t_R = 17.3 min).

Measurement of the Fluorescence Quantum Yields of the Chiral Dendrimers. The fluorescence quantum yield of (*S*)-**10** was estimated by using a quinine sulfate solution in 1 N H_2SO_4 (ϕ_F = 0.55) as the standard. The spectra were recorded on a Spex Fluorolog 2+2 Spectrofluorometer. The excitation slits were set at 2,2 nm and the emission slits at 1,1 nm. The scan speed was set at 60 nm/min. The measured absorbances for a quinine sulfate solution in 1 N H_2SO_4 and a (*S*)-**10** solution in CH_2Cl_2 at 310 nm were 0.0675 and 0.0912, respectively. The intergrations of the areas under the fluorescence signals of the corrected emission spectra excited at 310 nm for quinine sulfate and (*S*)-**10** were 6.86×10^6 and 5.92×10^6, respectively. Following equation is applied to calculate the quantum yield:[11a]

$$\phi_F = \phi_{F,ref}\left(\frac{A_{ref}}{A}\right)\left(\frac{n_D}{n_{D,ref}}\right)^2\left(\frac{a}{a_{ref}}\right)$$

Wherein $\phi_{F,ref}$, A_{ref}, $n_{D,ref}$ and a_{ref} are the reference quantum yield, the reference absorbance, the refraction index of the solvent of the reference, and the integration of the area under the fluorescence signal of the reference, respectively. According to this equation, the calculated fluorescence quantum yield of (*S*)-**10** is 0.40.

Following a similar procedure, the fluorescence quantum yields of (*S*)-**8** and (*S*)-**9** were estimated by using (*S*)-**10** as the standard. The spectra were recorded on a Perkin-Elmer LS-50B Luminescence spectrometer. Both the excitation and emission slits were set at 2.5 nm and scan speed was set at 100 nm/min. The estimated fluorescence quantum yields of (*S*)-**8** and (*S*)-**9** were 0.30 and 0.32, respectively.

Acknowledgment. This work is supported by the National Institute of Health (1R01GM58454). We also thank Professor James. N. Demas and Mr. William Bare at University of Virginia for their help on the quantum yield measurements.

Supporting Information Available: The FAB and MALDI mass spectra of the chiral dendrimers (*S*)-**8**, (*S*)-**9**, (*S*)-**10**, and (*R*)-**10**. This material is available free of charge via the Internet at http://pubs.acs.org.

JO990856Q