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Constitution, Configuration, and the Optical Activity of Chiral Dendrimers

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Abstract: Three series of zeroth to second generation chiral dendrimers, **7**−**9**, **10**−**12**, and **13**−**15**, were prepared by convergent methods using chiral, nonracemic AB_2 monomers **1**, **2**, and **3**, respectively. Chiroptical data revealed a significant change in molar rotation per subunit ($[\Phi]_D/n$) as dendrimer generation increased for dendrimers **7**−**9** and **10**−**12**, but not for dendrimers **13**−**15**, a possible indication of chiral conformational order in the former two series of dendrimers, but not in the last. However, the optical activities ($[\Phi]_D$) of low-molecular-weight model compounds **16** (+262) and **17** (+122), prepared to simulate different regions of the dendrimer structure, suggest that as generation size increases slight constitutional changes have a strong effect on the chiroptical properties of the dendrimer subunits. Using the $[\Phi]_D$ values of these and other (**18**−**23**) low-molecular-weight model compounds, we calculated $[\Phi]_D$ values for dendrimers **7**−**15** that agree within 14% of the observed values. Agreement between the optical activity of the model compounds and the dendrimers leads to the conclusion that the conformational equilibria of the dendrimer subunits are not perturbed relative to those of the model compounds. Therefore, we interpreted the change in $[\Phi]_D/n$ as dendrimer generation increased for dendrimers **7**−**12** to be based solely on constitutional changes in the dendritic structure and not chiral conformational order.

Introduction

Dendrimers, well-defined macromolecules with highly branched structures, have attracted increasing interest.[1] However, while the diversity of dendritic structures reported has grown quite rapidly, corresponding studies on the conformation of dendrimers have been more limited.[2] The conformation of chiral dendritic macromolecules[3] is of particular interest because these materials have the potential for enantioselective clathration, leading to applications in separation, catalysis, and sensor technology. While much is known of the effects of stereoregularity[4] and chirality[5] on the conformation of linear macromolecules,[6] research on the effect of configurational stereochemistry on the conformational order of chiral dendritic macromolecules is still progressing.[3]

Asymmetric conformational order, or macromolecular asymmetry,[7] in linear macromolecules[8] is crucial for their application to, for example, chiral chromatographic separations,[9] preparation

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(2) For the distinctions among constitution, configuration, and conformation used here, see: Eliel, E. L.; Wilen, S. H. *Stereochemistry of Organic Compounds*; Wiley: New York, 1994; pp 18−24.

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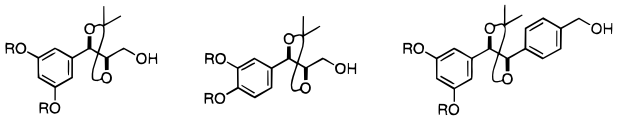
of cholesteric liquid crystals,[5] and the development of organic materials for nonlinear optics.[10] Likewise, the utility of dendrimers, as well as other well-defined macromolecules, will depend on our ability to drive their properties and function through their 3-dimensional organization.[11] It is important, therefore, to delineate the factors which govern macromolecular asymmetry in dendrimers as well as standard methods for assessment of dendritic conformational order.

Efforts by Newkome,[12] Meijer,[13,14] Seebach,[15−17] Chow,[18,19] and Sharpless[20] have established that macromolecular asymmetry is, at this point, rare in dendrimers.[21] Both Newkome and Meijer have shown that chiral terminal groups have little to no effect on macromolecular asymmetry with too densely packed a surface, in concert with hydrogen bonding, actually resulting in destruction of optical activity.[12,13] Current evidence also indicates that dendrimers with fully chiral branches based on tartaric acid subunits[19] or chiral ethers[20] do not adopt chiral conformations, the observed rotations being the sum of the rotations for the individual chiral subunits. Two reports by Seebach and co-workers, however, present chiroptical data that suggests chiral conformations. In the first, dendrimers with chiral central cores and achiral branches exhibit anomalous chiroptical behavior depending on the size (generation) of the achiral branch.[16,17] This study is significant in that it suggests that a single chiral subunit, in this case the core, can impart conformational order in a distal portion of the molecule.[22] In the second study, dendrimers with fully chiral branches were observed to undergo changes in the sign of optical rotation on increasing generation, a possible indication of conformationally chiral substructures in the dendrimer branches.[15]

The conclusions in these studies are largely based on the assumption, similar to that made in the study of linear macromolecules,[6] that the contribution of a chiral subunit to the overall optical activity of a dendrimer is relatively independent of the subunit's position within the structure. Hence, information concerning polymer conformation can be obtained by comparing the optical activity of the polymer with that of a single low-molecular-weight model compound.[23−25] Any disparity in optical activity is attributed to different positions of the respective conformational equilibria for the model compound and the monomeric units of the polymer.[23,26] In a recent chiroptical study of chiral dendrons prepared convergently from nonracemic, synthetic AB_2 monomers **1**−**3**,[27] we illustrated that



1: R = H
4: R = Bn

2: R = H
5: R = Bn

3: R = H
6: R = Bn

this assumption for dendritic molecules has a distinct limitation.[28] Subunits closer to the core of a dendrimer—or focal point of a dendron—are different in constitution from subunits nearer the periphery, necessitating the use of several low-molecular-weight model compounds to account for the optical activity of the entire dendritic structure. Thus, anomalies in optical activity of the dendrons with increasing generation were shown to arise from the nature of the dendritic structure (constitution), not chiral conformations or perturbation of conformational equilibria.[28]

In the present paper, we report a chiroptical study of the corresponding chiral dendrimers and an investigation of the role of molecular constitution on their optical activity.[29] The dendrimers reported here are part of our recently initiated program to develop strategies for the incorporation of asymmetric units into dendrimers,[28−31] which aims toward the development of materials active for the selective clathration of

(8) Macromolecular asymmetry in linear polymers can be induced by either (i) stereogenic centers in the main or side chains or (ii) conformational constraints inherent in the primary structure. Typical examples of the former class of materials are polypeptides and polysaccharides. Examples of the latter class are polychloral, poly(triphenylmethyl methacrylate), poly(isocyanides), and poly(isocyanates). See (a) Poland, D.; Scheraga, H. A. *Theory of Helix-Coil Transitions in Biopolymers*; Academic Press: New York, 1970. (b) Corley, L. S.; Vogl, O. *Polym. Bull.* **1980**, *3*, 211−217. (c) Okamoto, Y.; Suzuki, K.; Ohta, K.; Hatada, K.; Yuki, H. *J. Am. Chem. Soc.* **1979**, *101*, 4763−4765. (d) van Beijen, A. J. M.; Nolte, R. J. M.; Naaktgeboren, A. J.; Zwikker, J. W.; Drenth, W.; Hezemans, A. M. F. *Macromolecules* **1983**, *16*, 1679−1689. (e) Green, M. M.; Reidy, M. P.; Johnson, R. J.; Darling, G.; O'Leary, D. J.; Willson, G. *J. Am. Chem. Soc.* **1989**, *111*, 6452−6454.

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(20) Chang, H.-T.; Chen; C.-T.; Kondo, T.; Siuzdak, G.; Sharpless, K. B. *Angew. Chem., Int. Ed. Engl.* **1996**, *35*, 182−186.

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(22) For other examples of dendrimers with stereogenic cores and achiral branches, see: (a) Kremers, J. A.; Meijer, E. W. *J. Org. Chem.* **1994**, *59*, 4262−4266. (b) Struijk, M. P.; Peerlings, H. W. I.; Meijer, E. W. *Am. Chem. Soc., Div. Polym. Chem., Preprints* **1996**, *37(2)*, 497−498. (c) Peerlings, H. W. I.; Trimbach, D.; Meijer, E. W. *Polym. Mater. Sci. Eng.* **1997**, *77*, 73−74.

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(24) Low-molecular-weight model compounds are no longer appropriate when the optically active electronic transitions of the polymer are modified by mutual interactions among the chromophoric systems existing in different monomeric units, e.g., in polypeptides or polyacetylenes. See previous reference.

(25) For a recent example, see: Coates, G. W.; Waymouth, R. M. *J. Am. Chem. Soc.* **1991**, *113*, 6270.

(26) Perturbation of the conformational equilibria can imply a helical sense of the main chain. However, additional data is usually warranted before such a conclusion can be drawn. See: Ciardelli, F. In *Encyclopedia of Polymer Science and Engineering*; Mark, H. F., Bikales, N. M., Overberger, C. G., Menges, G., Kroschwitz, J. I., Eds.; Wiley: New York, 1985; Vol. 10, pp 463−493.

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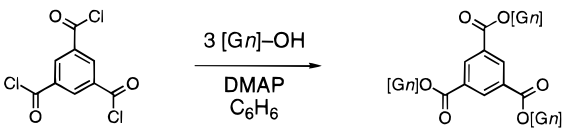
(29) For a preliminary account see: McElhanon, J. R.; McGrath, D. V. *Am. Chem. Soc., Div. Polym. Chem., Preprints* **1997**, *38(1)*, 278−279.

(30) McElhanon, J.; Wu, M.-J.; Escobar, M.; McGrath, D. V. *Am. Chem. Soc., Div. Polym. Chem., Preprints* **1996**, *37(2)*, 495−496.

small guest molecules. Hence, these materials contain not only chiral, nonracemic subunits in the interior for shape selectivity, but also vicinal diol moieties, here in protected form, capable of specific interactions with encapsulated guests.[32] Once unmasked in the final dendrimer, the vicinal diol moieties should be capable of engaging in hydrogen bonding interactions with small clathrated guest molecules[33] or acting as chiral auxiliaries[34,35] or ligands for transition metals[36] in catalytic asymmetric synthesis.[37,38]

Results and Discussion

Zeroth, first, and second generation dendrimers **7**−**15** (Charts 1 and 2) were prepared from chiral, nonracemic AB_2 monomers **1**−**3**[27] via the corresponding monodendrons.[28] The monodendrons were allowed to react with C_3-symmetric central linker 1,3,5-benzenetricarbonyl trichloride in refluxing benzene or toluene under Dean−Stark conditions (eq 1).[20] Dendrimers



(1)

7−**15** were isolated as colorless, glassy solids in 37−80% yield after purification by flash chromatography on silica gel. The chiral vicinal diol unit of each dendritic subunit in **7**−**15**, masked as an acetonide derivative for synthetic purposes, was readily introduced during the preparation of **1**−**3** by the asymmetric dihydroxylation reaction.[27,39] All dendrimers were characterized by ^{1}H/^{13}C NMR, MALDI MS, and combustion analysis for confirmation of primary structure. ^{13}C NMR analysis was particularly useful, especially for nonsymmetrically 3,4-linked dendrimers **10**−**12**, since overlapping resonances limited the utility of ^{1}H NMR. Full assignment of all ^{13}C NMR spectra of **7**−**15** was possible using the information provided by chemical shift calculations and resonance intensity, which confirmed generational growth (Figure 1).

Specific and molar rotations for dendrimers **7**−**15** are reported in Table 1 (columns 4 and 5). In initial comparisons of optical activity of the dendrimers as a function of generation, we considered the molar rotation per chiral subunit ($[\Phi]_D/n$, Figure 2). From these data there was revealed a significant change in $[\Phi]_D/n$ as dendrimer generation increased for dendrimers **7**−**9** and **10**−**12**, but not for dendrimers **13**−**15**, a possible indication of chiral conformational order in the former two series of dendrimers, but not in the last. Indeed, the closer packing of subunits in dendrimers **7**−**12**, relative to that in **13**−**15**,[40] suggests that intramolecular communication between chiral subunits might result in conformational order in the former dendrimers, but not the latter.

However, slight changes in constitution, rather than conformation, could also be responsible for the observed changes in optical activity. Indeed, the optical activities of neither monomer units **1** and **2**, nor zero generation monodendrons **4** and **5**, correlate with the observed optical activities of the corresponding dendrimers (cf. Table 1, column 5 and Table 2, column 4). Considering the chiral dioxolane rings in the subunits of **7**−**12**, we noted that those in the zeroth generation shell, adjacent to the central linker, are constitutionally dissimilar to those in the outer generational shells. The former dioxolane rings are flanked by benzoyloxymethyl and bis(benzyloxy)-phenyl groups, while the latter are flanked by phenoxymethyl and bis(benzyloxy)phenyl groups. In contrast, the chiral dioxolane rings in the subunits of dendrimers **13**−**15** are all in a more constant environment, flanked by 4-(oxymethyl)phenyl and bis(benzyloxy)phenyl groups throughout the structure.

Accordingly, compounds **16** and **17** (Chart 3) were prepared as low-molecular-weight model compounds for the subunits of dendrimers **7**−**9**. While compound **16** models subunits in the outer shells, including those on the periphery, **17** models subunits directly attached to the central linker. As can be seen from polarimetry data in Table 3, small changes in constitution distal to the dioxolane ring do indeed greatly affect the optical activity of the model compounds. The simple replacement of a proton with a phenyl group at the focal point of zeroth generation dendron **4** ($[\Phi]_D = -17$) to give phenyl ether **16** (+262) results in a change in sign of the $[\Phi]_D$ value. In addition, the $[\Phi]_D$ value of phenyl ether **16** (+262) is more than twice that of benzoyl derivative **17** (+122).

The significantly higher $[\Phi]_D$ value of **16**, relative to **17**, suggests that the addition of subunits of this approximate constitution to a dendritic structure consisting of subunit **17**, such as zeroth generation dendrimer **7**, would result in a higher overall $[\Phi]_D$ per subunit for the larger structure, as was observed for first generation dendrimer **8** (Figure 2). Indeed, using the individual $[\Phi]_D$ values obtained for **16** and **17**, calculated molar rotations for dendrimers **7**−**9** agree within 15% of the observed values (Table 1, column 6). Interestingly, the optical activities of dendrimers **10**−**12** are also successfully modeled with low-molecular-weight compounds **16** and **17** within 16% of the observed values (Table 1, column 6), indicating that the change in constitution from 3,5- to 3,4-linkages does not significantly

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(40) Monte Carlo conformational searches (Macromodel 5.0) were carried out on model subunits **A** and **B**, derived from monomers **1** and **3**, respectively, and convergence was found on a series of low-energy conformations for each subunit. The distance between the "focal" and "branching" oxygens of the two model subunits in these low-energy conformations exhibited the ranges shown below.

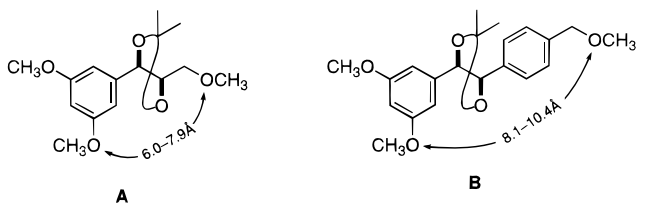
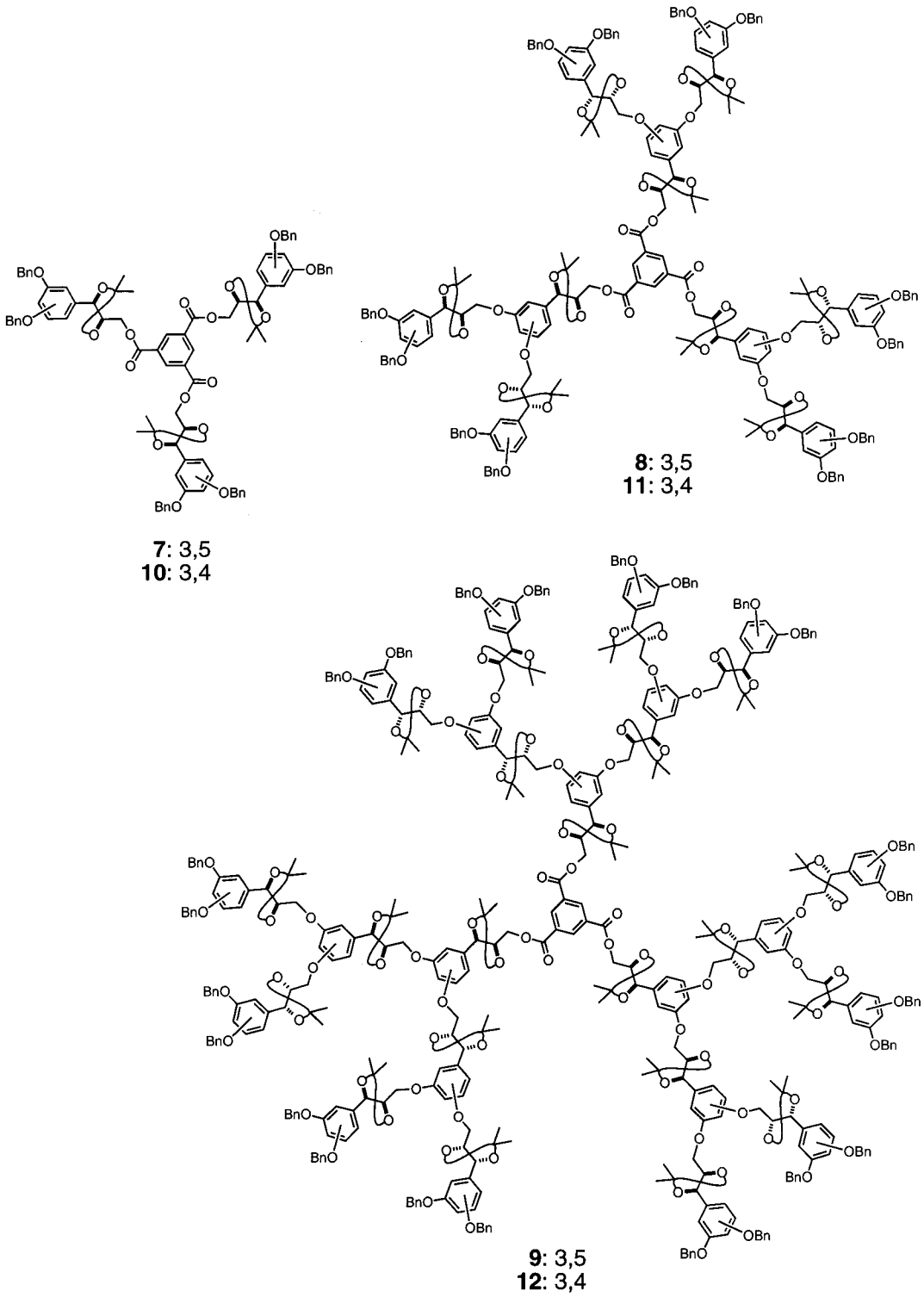


Chart 1

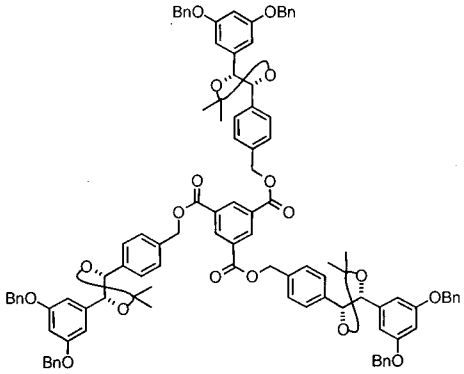


affect the optical activity of the subunits in this system. Individual model compounds with a 3,4-substitution pattern were not prepared.

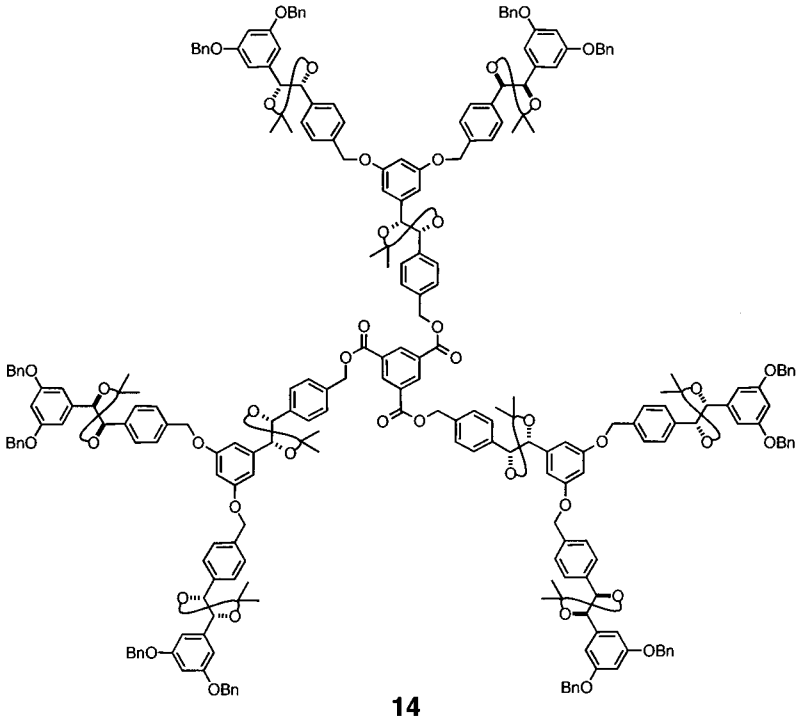
This quite general agreement between the optical activity of the model compounds and the dendrimers leads to the conclusion that the conformational equilibria of the dendrimer subunits are not perturbed relative to those of the model compounds.[23] Therefore, we interpret the chiroptical changes in dendrimers **7**−**12** as dendrimer generation increases to be *based solely on constitutional changes in the dendritic structure and not chiral conformational order*.

Low-molecular-weight model compounds which more accurately match the constitution of dendrimers **7**−**9** were also prepared. Model compounds **18** and **19** were prepared as potential improvements over **17** and **16**, respectively. It was anticipated that the strong electronic influence of the additional ester groups in **18** and the *m*-methoxy group in **19** might affect the observed optical activities. Both **18** (+134) and **19** (+271) exhibit slightly different $[\Phi]_D$ values than **17** (+122) and **16** (+262), respectively, and result in a marginal increase in accuracy in calculating the rotation of first and second generation dendrimers **8**, **9**, **11**, and **12** (Table 1, columns 7 and 8). Model

Chart 2



13



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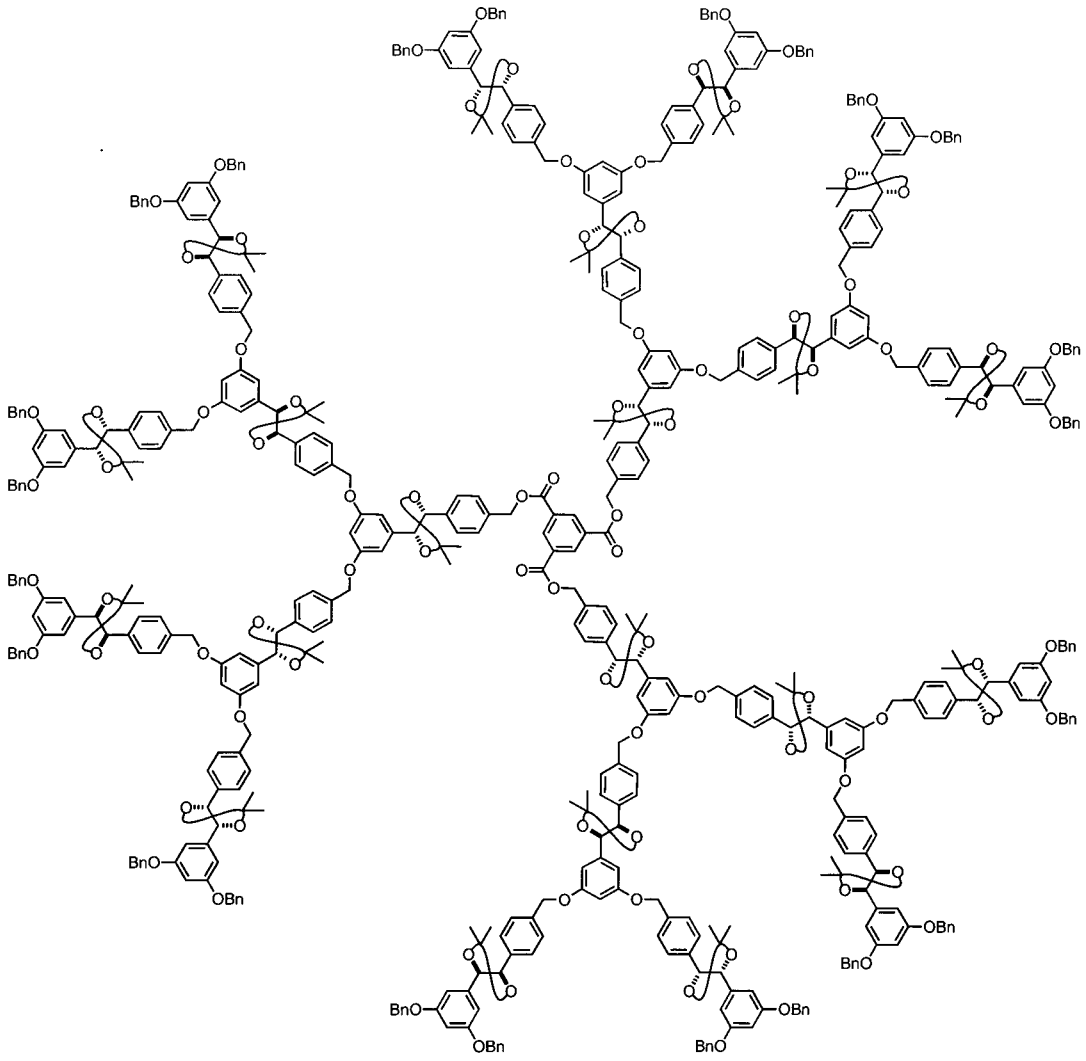


15

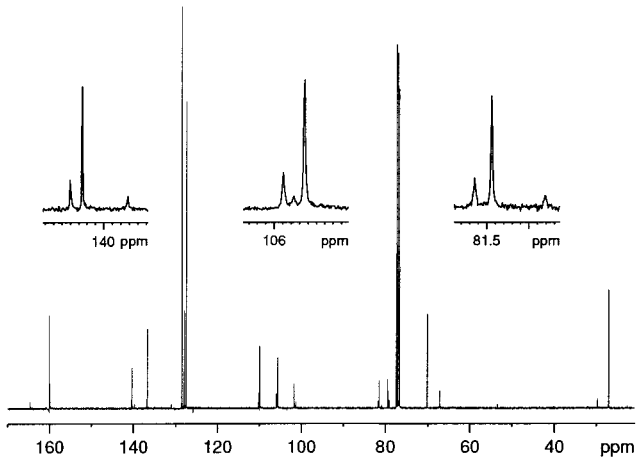


Figure 1. ^{13}C NMR ($CDCl_3$) spectrum of second generation dendrimer **9**. Insets show regions where the 4:2:1 ratio of nuclei in a second generation dendrimer with a branching ratio of 2:1 are evident.

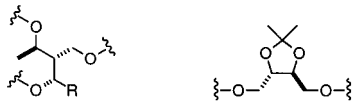
compound **20b** was prepared from first generation monodendron **20a**.[28] The relative $[\Phi]_D$ values of **20a** (+625) and **20b** (+837) mimic the same positive trend also seen for compounds **4** (−17) and **16** (+262) on replacement of a proton with a phenyl group at the focal point of the dendron (vide supra). Using the $[\Phi]_D$ value of **20b**, the optical activities of second generation dendrimers **9** and **12** are calculated within 10% (Table 2, column 8). An oligomeric model compound, **20b** could contain the same possible interactions between chromophoric systems as in the dendrimers. That its optical activity can be also predicted with reasonable accuracy (+804, within 3.9% using models **16** and **19**) is further evidence for the lack of ordered conformation in this system.[23]

The constant optical activity of dendrimers **13**−**15** in relation to number of subunits implies that the conformational equilibria of the subunits in these dendrimers is similar to that of a single low-molecular-weight model compound. We found it curious, however, that the average $[\Phi]_D/n$ value for **13**−**15** (ca. +540) was significantly different than the $[\Phi]_D$ value of zeroth generation dendron **6** (+468). Hence, we prepared model compounds **21**−**23**, analogous to **16**−**18**, to investigate the influence of constitutional environment on subunit optical activity in these dendrimers. Substitution distal to the chiral dioxolane moiety again affects the $[\Phi]_D$ values, although not as dramatically as above. The $[\Phi]_D$ values of **21**−**23** are all rather similar (Table 3, column 4), and quite close to the average $[\Phi]_D/n$ value for **13**−**15**. Calculated $[\Phi]_D/n$ values for **13**−**15** using these compounds now agree within 6.0% of the observed values (Table 1, columns 6 and 7), but use of the different model compounds here is not as critical as in the above system. Actually, using **21**, **22**, or **23** as the sole model compound for dendrimers **13**−**15** results in calculated $[\Phi]_D$ values all within 8.4% of those observed.

Circular dichroism (CD) and absorption spectra have been obtained for all dendrimers reported. Representative examples are shown in Figure 3. All exhibit positive Cotton effects throughout the absorption range. The null at ca. 203 nm arises from a weak excitonic coupling also evident in the CD spectra of monomeric units.[41] No additional exciton coupling is observed. The absence of excitonic coupling in the CD traces of the dendrimers can be interpreted as the dendrimer arms in solution adopting no prevailing conformation suitable for exciton interactions.[42] The magnitudes of the Cotton effects for all compounds are proportional to the number of chromophores contained.

That we can accurately predict the optical activity of dendrimers **7**−**12** based on two low-molecular-weight model compounds and dendrimers **13**−**15** with one low-molecular-weight model compound indicates that the conformational equilibria for the model compound(s) and the monomeric units of the dendrimers are similar. This conclusion might also suggest that (a) few conformations are available to the subunits and model compounds and/or (b) the different available conformations have similar optical properties. We propose that both (a) and (b) are most likely the case here. The subunits in dendrimers **7**−**15** are indeed fairly rigid. The acetonide protecting moiety restricts rotation about the bond between the asymmetric centers and precludes any conformations in which the oxygen atoms attached to the asymmetric centers are anything but synperiplanar. As a result, while the conformation of the subunits with respect to each other could potentially vary, the conformation of the subunits themselves, and their individual optical activities, is relatively invariable. In addition, the dependence of the rotations of **7**−**15** on temperature were measured and found to be <0.5% per °C over the range 10−25 °C.[43]

In dendrimers with more flexible subunits, e.g., **7**−**15** after deprotection of the vicinal diol moieties, analysis using low-molecular-weight model compounds, as presented in this paper, is more likely to reveal perturbation of conformational equilibria. Two other systems in the literature are of interest in this regard. First, the work of Seebach and co-workers on fully chiral dendrimers with subunits of type **24a**,**b** revealed $[\Phi]_D$ values



24a: R = *p*-($C_6H_4CH_2O$–)
24b: R = *t*Bu, Et, *i*Pr, Bn

25a
25b: ent

that change with generation.[15] The preparation of several low-molecular-weight model compounds and their $[\alpha]_D$ values were reported, although a detailed analysis using $[\Phi]_D$ values was not undertaken;[44] it remains unclear whether the observed optical activities in this system reflect contributions from perturbed conformational equilibria. What also remains to be elucidated is the nature of the intriguing chiroptical anomalies observed in dendrimers with chiral cores of type **24b** and achiral branches.[16,17] While suggestive of conformational order in the achiral branches, these observations may simply reflect a perturbation of the conformational equilibria of the flexible central linker as a function of achiral branch size. Second, in the work of Chow and co-workers, while the $[\Phi]_D$ values of a series of tartrate-derived dendrimers and dendrons were roughly proportional to the number of (L)- and (D)-tartrate units (**25a** and **b**) in the structure,[18,19] CD data suggested that subunits in inner layer of the first generation dendrimers have different chiroptical properties than those in the outer layer.[18] Again, it remains

(41) McGrath, D. V., et al. Unpublished results.
(42) Altomare, A.; Ciardelli, F.; Tirelli, N.; Solaro, R. *Macromolecules* **1997**, *30*, 1298−1303.
(43) See ref 2, p 1076.
(44) The best evidence for preferred conformations in Seebach's dendrimers may be, in fact, spectacular cases of diastereoselectivity observed in coupling reactions, representing molecular recognition events among chiral dendritic molecules. See: Murer, P. K.; Lapierre, J.-M.; Greiveldinger, G.; Seebach, D. *Helv. Chim. Acta* **1997**, *80*, 1648−1681.

Table 1. Observed and Calculated Chiroptical Data for Dendrimers 7−15

			observed[a]		calculated[b]			
class[c]	gener.	FW	$[\alpha]^{26}_D$[d]	$[\Phi]_D$[e]	$[\Phi]_D$ (% error)[f]	$[\Phi]_D$ (% error)[g]	$[\Phi]_D$ (% error)[h]	$[\Phi]_D$ (% error)[i]
3,5-Cinn	0 (**7**)	1417.61	+25.1	+356	+366 (2.8)	+402 (13)		
	1 (**8**)	3291.81	+66.9	+2204	+1938 (12)	+1974 (10)	+2028 (8.0)	
	2 (**9**)	7040.19	+84.5	+5948	+5082 (15)	+5118 (14)	+5280 (11)	+5424 (8.8)
3,4-Cinn	0 (**10**)	1417.61	+26.7	+379	+366 (3.4)	+402 (6.1)		
	1 (**11**)	3291.81	+67.8	+2232	+1938 (13)	+1974 (12)	+2028 (9.1)	
	2 (**12**)	7040.19	+85.8	+6039	+5082 (16)	+5118 (15)	+5280 (13)	+5424 (10)
3,5-Stil	0 (**13**)	1645.91	+97.1	+1598	+1623 (1.6)	+1524 (4.6)		
	1 (**14**)	3976.69	+125.5	+4992	+5031 (0.8)	+4932 (1.2)		
	2 (**15**)	8638.24	+129.3	+11172	+11847 (6.0)	+11748 (5.2)		

[a] All rotations measured in CH_2Cl_2. [b] Arithmatic sum of the $[\Phi]_D$ values of the appropriate model compounds. [c] Dendrimer class name derives from the linkage geometry (3,4 or 3,5) and the subunit synthetic presursor (stilbene or cinnamate derivatives). [d] Specific rotation in 10^{-1} deg cm^2 g^{-1}. [e] Molar rotation in 10 deg cm^2 mol $^{-1}$. [f] Calculated using model compounds **16** and **17** (Cinn) or **21** and **22** (Stil). [g] Calculated using model compounds **16** and **18** (Cinn) or **21** and **23** (Stil). [h] Calculated using model compounds **18** and **19**. [i]Calculated using model compounds **18** and **20b**.

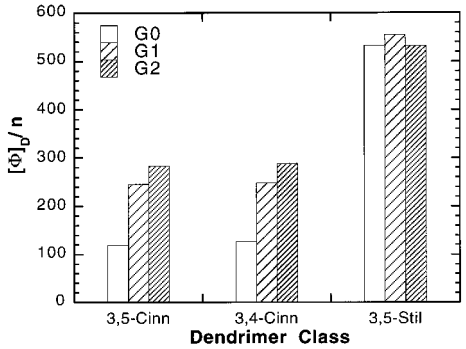


Figure 2. Molar optical rotations (Φ) per chiral unit (*n*) for zeroth (*n* = 3), first (*n* = 9), and second (*n* = 21) generation dendrimers **7**−**15**. 3,5-Cinn = **7**−**9**; 3,4-Cinn = **10**−**12**; 3,5-Stil = **13**−**15**.

Table 2. Chiroptical Data for Monomer Units and Zeroth Generation Monodendrons[27]

cmpd	FW	$[\alpha]^{26}_D$[a,b]	$[\Phi]_D$[c]
1	240.26	−7.08	−17.0
2	240.26	−18.0[d]	−43.2
3	316.35	+122	+355
4	420.50	−4.05	−17.0
5	420.50	−8.31	−34.9
6	496.60	+94.2	+468

[a] Specific rotation in 10^{-1} deg cm^2 g^{-1}. [b] **1**−**3** in EtOH, **4**−**6** in CH_2Cl_2. [c] Molar rotation in 10 deg cm^2 mol $^{-1}$. [d] Incorrectly reported in ref 27.

unclear whether this difference is constitutionally or conformationally based.

Summary and Conclusion

We have prepared and explored the chiroptical properties of three series of chiral dendrimers. Although we observed dramatic changes in optical activity with increasing generation in two of these series, we have determined that chiral conformations do not contribute to this enhancement. Rather, slight constitutional changes appear to have a strong effect on the chiroptical properties of these dendrimers as generation size increases, as revealed by the demonstrated effect of molecular constitution on the optical activity of several low-molecular-weight model compounds. In exploring dendrimer conformation using chiroptical properties, we found it necessary to consider the immediate constitutional environment of the chiral subunits in order to assess the relative contributions of constitution, configuration, and conformation to optical activity.

In general terms, we conclude that it is indeed possible to gain information on the conformation of chiral dendrimers by comparing the chiroptical properties of the dendrimers with those of appropriate low-molecular-weight model compounds, similar to the approach used in the study of linear polymers.[23] Although two different model compounds, at most, were

Chart 3

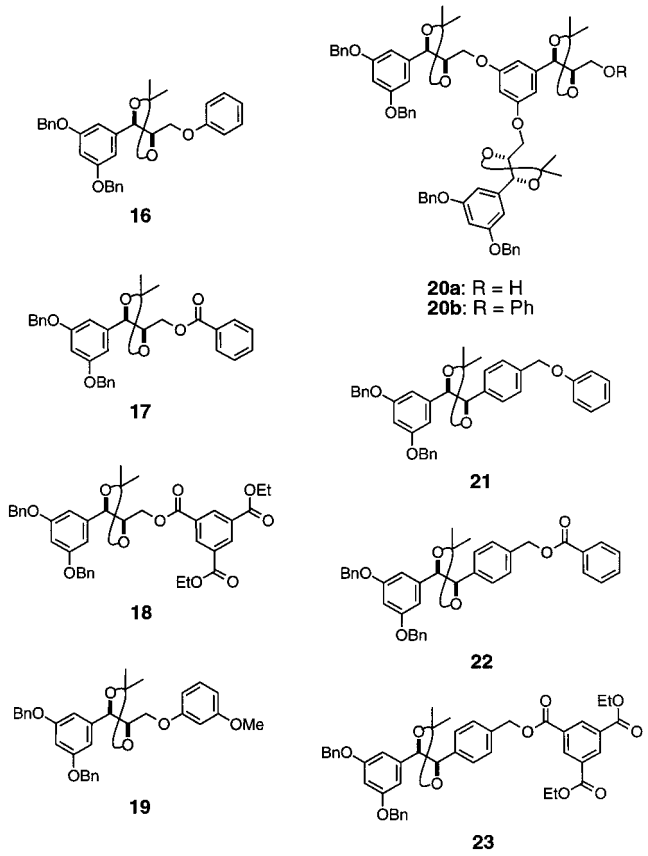


Table 3. Chiroptical Data for Model Compounds

cmpd	FW	$[\alpha]^{26}_D$[a,b]	$[\Phi]_D$[c]
16	496.60	+52.7	+262
17	524.61	+23.2	+122
18	668.74	+20.0	+134
19	526.63	+51.4	+271
20a	1045.24	+59.8	+625
20b	1121.33	+74.6	+837
21	572.70	+99.2	+568
22	600.71	+90.1	+541
23	744.84	+68.2	+508

[a] Specific rotation in 10^{-1} deg cm^2 g^{-1}. [b] All in CH_2Cl_2. [c] Molar rotation in 10 deg cm^2 mol $^{-1}$.

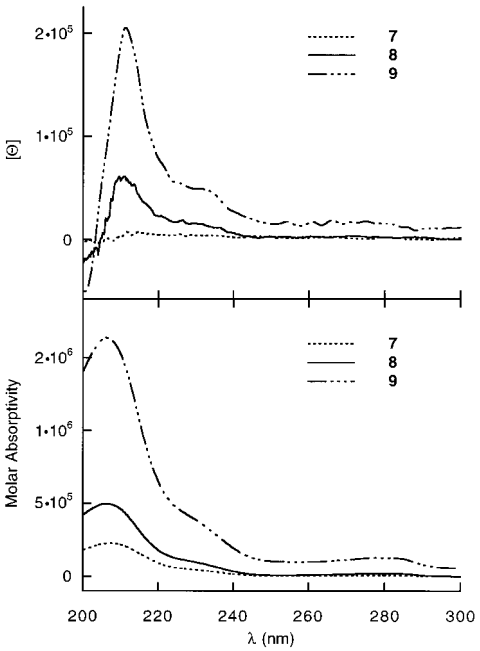


Figure 3. CD (top) and UV (bottom) spectra of dendrimers 7−9 in CH_2Cl_2.

necessary and sufficient in our studies, a greater or fewer number of model compounds may be required in different systems—dendrimers with chiral cores, branching units, and peripheral units may require three or more low-molecular-weight model compounds. If perturbation of conformational equilibria is revealed by a disparity in optical activity, determination of the exact nature of that perturbation will require additional information.[26]

Experimental Section

Materials and Methods. Optical rotations and high performance liquid chromatography (HPLC) were performed on commercially available instrumentation. All NMR spectra were measured at 400 MHz ^{1}H and 100 MHz ^{13}C and in $CDCl_3$ unless otherwise specified. Elemental analyses were performed by NuMega Resonance Labs of San Diego, CA. Mass spectrometry was performed at the University of Illinois School of Chemical Sciences Mass Spectrometry Laboratories. Tetrahydrofuran (sodium-benzophenone), toluene (sodium), methylene chloride (calcium hydride), and dimethylformamide (3 Å molecular sieves, reduced pressure) were distilled under N_2. Acetone was dried over crushed 3 Å molecular sieves. Potassium carbonate (granular, J. T. Baker) was dried at 150 °C at reduced pressure for at least 12 h and stored in a desiccator. Compounds **1**−**6**,[27] **20a**,[28] and the diethyl ester of benzene-1,3,5-tricarboxylic acid[45] were prepared according to the literature. All other reagents were purchased from commercial suppliers and used as received. Flash chromatography was performed by the method of Still et al.[46] using silica gel (32−63μ, Scientific Adsorbants, Inc., Atlanta, GA). Thin-layer chromatography (TLC) was performed on precoated TLC plates (Silica Gel HLO, F-254, Scientific Adsorbants, Inc.).

Preparation of Dendrimers 7−15. Dendrimers were prepared from the corresponding monodendrons[28] and benzene-1,3,5-tricarbonyl trichloride using a procedure adapted from the literature.[20]

3,5-[G0]-Cinn Dendrimer (7): colorless glassy solid, 76% (SiO_2, 1:1 petroleum ether−ethyl acetate); ^{1}H NMR: δ 8.82 (s, 3H), 7.39−7.26 (m, 30H), 6.61 (d, J = 2.2 Hz, 6H), 6.53 (t, J = 2.2 Hz, 3H), 5.02 (s, 12H), 4.74 (d, J = 8.6 Hz, 3H), 4.54 (dd, J = 12.1, 2.9 Hz, 3H), 4.41 (dd, J = 12.1, 5.4 Hz, 3H), 4.09 (ddd, J = 8.6, 5.4, 2.9 Hz, 3H), 1.53 (s, 9H), 1.49 (s, 9H); ^{13}C NMR: δ 164.5, 160.2, 139.7, 136.6, 134.9, 131.0, 128.5, 128.0. 127.5, 110.1, 105.6, 101.9, 80.8, 79.5, 70.1, 64.0, 27.0; MS (MALDI) *m*/*z* 1439.3 (M + Na), 1456.3 (M + K); $[\alpha]^{26}_D$ = +25.1 (c = 0.62, CH_2Cl_2). Anal. Calcd for $C_{87}H_{84}O_{18}$: C, 73.71; H, 5.97. Found: C, 73.81; H, 6.26.

3,5-[G1]-Cinn Dendrimer (8): colorless glassy solid, 80% (SiO_2, 9:1 methylene chloride−ethyl acetate); ^{1}H NMR: δ 8.83 (s, 3H), 7.36−7.25 (m, 60H), 6.61 (d, J = 2.2 Hz, 12 H), 6.57 (d, J = 2.2 Hz, 6H), 6.52 (t, J = 2.2 Hz, 6H), 6.40 (t, J = 2.2 Hz, 3H), 4.96 (s, 24 H), 4.82 (d, J = 8.2 Hz, 6H), 4.70 (d, J = 8.6 Hz, 3H), 4.50 (br d, J = 11.5 Hz, 3H), 4.39 (dd, J = 12.3, 5.7 Hz, 3H), 4.10−4.00 (m, 21H), 1.52−1.45 (m, 54H); ^{13}C NMR: δ 164.5, 160.2, 160.0, 140.3, 139.8, 136.7, 134.9, 130.9, 128.5, 128.0, 127.5, 110.1, 109.9, 105.7, 101.8, 101.6, 81.5, 80.9, 79.4, 79.1, 70.1, 67.2, 63.8, 27.1, 27.04, 27.01; MS (MALDI) 3211.9 (M + Na), 3229.5 (M + K); $[\alpha]^{26}_D$ = +66.9 (c = 0.79, CH_2Cl_2). Anal. Calcd for $C_{201}H_{204}O_{42}$: C, 73.34; H, 6.25. Found: C, 73.66; H, 6.61.

3,5-[G2]-Cinn Dendrimer (9): colorless glassy solid, 45% (SiO_2, 9:1 methylene chloride−ethyl acetate); ^{1}H NMR: δ 8.87 (s, 3H), 7.34−7.22 (m, 120H), 6.59 (d, J = 2.2 Hz, 24H), 6.57 (d, J = 2.0 Hz, 12 H), 6.51−6.50 (m, 18H), 6.42 (br, 3H), 6.37 (br t (unresolved), 6H), 4.94 (s, 48H), 4.83 (d, J = 8.4 Hz, 6H), 4.80 (d, J = 8.1 Hz, 12H), 4.69 (d, J = 8.4 Hz, 3H), 4.51−4.48 (br, 3H), 4.40−4.35 (br, 3H), 4.06−3.96 (m, 57H), 1.55−1.44 (m, 126H); ^{13}C NMR: δ 164.6, 160.12, 160.10, 160.0, 140.4, 140.3, 139.7, 136.6, 131.0, 128.5, 128.0, 127.5, 110.1, 109.93, 109.87, 105.9, 105.8, 105.6, 101.7, 101.3, 81.6, 81.4, 80.8, 79.4, 79.1, 70.1, 67.1, 27.0; MS (MALDI) 7065.3 (M + Na), 7082.5 (M + K); $[\alpha]^{26}_D$ = +84.5 (c = 0.67, CH_2Cl_2). Anal. Calcd for $C_{429}H_{444}O_{90}$: C, 73.19; H, 6.36. Found: C, 73.36; H, 6.54.

3,4-[G0]-Cinn Dendrimer (10): colorless glassy solid, 70% (SiO_2, 3:2 petroleum ether−ethyl acetate); ^{1}H NMR: δ 8.79 (s, 3H), 7.41−7.25 (m, 30H), 6.96 (br s, 3H), 6.87 (br s, 6H), 5.14 (s, 6H), 5.11 (s, 6H), 4.71 (d, J = 8.7 Hz, 3H), 4.47 (dd, J = 12.0, 3.0 Hz, 3H), 4.39 (dd, J = 12.1, 5.4 Hz, 3H), 4.03 (ddd, J = 8.7, 5.4, 3.0 Hz, 3H), 1.52 (s, 9H), 1.48 (s, 9H); ^{13}C NMR: δ 164.5, 149.3, 149.1, 137.1, 134.9, 130.9, 130.0, 128.4, 127.82, 127.80, 127.3, 127.2, 119.9, 114.9, 113.9, 109.8, 80.7, 79.5, 71.4, 71.2, 64.0, 27.1, 27.0; MS (MALDI) 439.3 (M + Na), 1454.5 (M + K); $[\alpha]^{26}_D$ = +26.7 (c = 1.46, CH_2Cl_2). Anal. Calcd for $C_{87}H_{84}O_{18}$: C, 73.71; H, 5.97. Found: C, 73.46; H, 6.28.

3,4-[G1]-Cinn Dendrimer (11): colorless glassy solid, 69% (SiO_2, 9:1 methylene chloride−ethyl acetate); ^{1}H NMR: δ 8.87 (s, 3H), 7.38−7.24 (m, 60H), 7.00−6.81 (m, 27H), 5.07−5.05 (m, 24H), 4.91 (d, J = 8.3 Hz, 3H), 4.88 (d, J = 8.2 Hz, 3H), 4.73 (d, J = 8.6 Hz, 3H), 4.50 (dd, J = 12.4, 2.4 Hz, 3H), 4.40 (dd, J = 12.1, 5.6 Hz, 3H), 4.16−3.94 (m, 21H), 1.55 (s, 9H), 1.54 (s, 9H), 1.48 (s, 9H), 1.47 (s, 9H), 1.46 (s, 9H), 1.45 (s, 9H); ^{13}C NMR: δ 164.6, 149.33, 149.28, 149.10, 149.07, 149.05, 137.17, 135.0, 131.0, 130.85, 130.80, 130.3, 128.42, 128.40, 127.8, 127.4, 127.3, 127.2, 120.0, 119.93, 119.88, 114.9, 114.5, 113.53, 113.50, 113.0, 109.9, 109.4, 81.83, 81.76, 80.9, 79.1, 79.00, 78.95, 71.3, 71.2, 68.0, 67.8, 63.89, 27.2, 27.1, 27.0, 26.9; MS (MALDI) 3313.2 (M + Na), 3328.2 (M + K), 3223.1 (M − Bn + Na); $[\alpha]^{26}_D$ = +67.8 (c = 1.54, CH_2Cl_2). Anal. Calcd for $C_{201}H_{204}O_{42}$: C, 73.34; H, 6.25. Found: C, 73.44; H, 6.48.

3,4-[G2]-Cinn Dendrimer (12): colorless glassy solid, 37% (SiO_2, 1:1 petroleum ether−ethyl acetate); ^{1}H NMR: δ 8.90 (s, 3H), 7.36−7.20 (m, 120H), 7.00−6.76 (m, 63H), 5.06 (s, 24H), 5.04 (s, 24H), 5.00 (d, J = 8.3 Hz, 3H), 4.97 (d, J = 8.2 Hz, 3H), 4.90 (d, J = 9.5 Hz, 6H), 4.88 (d, J = 8.4 Hz, 6H), 4.73 (d, J = 8.4 Hz, 3H), 4.52−4.49 (br d, J = 11.2 Hz, 3H), 4.41−4.37 (br dd, J = 12.4, 6.0 Hz, 3H), 4.22−3.91 (m, 57H), 1.56−1.43 (m, 126); ^{13}C NMR: δ 164.6, 149.3, 149.2, 149.10,149.07, 149.05, 149.02,137.2,135.0, 131.1, 131.04, 131.01, 130.90, 130.86, 130.83, 130.3, 128.4, 127.7, 127.34, 127.31, 127.2, 120.12, 120.05, 119.9, 119.8, 114.9, 114.5, 114.4, 113.50, 113.48, 113.47, 113.05, 113.00, 112.89, 112.87, 109.8, 109.5, 109.40, 109.38, 81.9, 81.79, 81.75, 80.88, 80.85, 79.0, 78.9, 78.74, 78.70, 71.3, 71.2, 68.0, 67.8, 67.6, 27.22, 27.20, 27.1, 27.0, 26.9; MS (MALDI) 7066.8 (M + Na); $[\alpha]^{26}_D$ = +85.8 (c = 1.39, CH_2Cl_2). Anal. Calcd for $C_{429}H_{444}O_{90}$: C, 73.19; H, 6.36. Found: C, 72.88; H, 6.44.

3,5-[G0]-Stil Dendrimer (13): colorless glassy solid, 76% (SiO_2, 1:1 petroleum ether−ethyl acetate); ^{1}H NMR: δ 8.81 (s, 3H), 7.37−7.21 (m, 42H), 6.53 (t, J = 2.2 Hz, 3H), 6.44 (d, J = 2.2 Hz, 6H), 5.34

(45) Leon, J. W.; Kawa, M.; Fréchet, J. M. J. *J. Am. Chem. Soc.* **1996**, *118*, 8847−8859.

(46) Still, W. C.; Kahn, M.; Mitra, A. *J. Org. Chem.* **1978**, *43*, 2923−2925.

(s, 6H), 4.92 (s, 12H), 4.66 (dd, J = 14.9, 8.4 Hz, 6H), 1.62 (s, 9H), 1.60 (s, 9H); ^{13}C NMR: δ 164.6, 159.9, 139.2, 137.4, 136.7, 135.4, 134.7, 131.2, 128.5, 128.4, 128.0, 127.4, 127.0, 109.5, 105.9, 101.9, 85.1, 84.7, 70.0, 67.0, 27.12, 27.10; MS (MALDI) *m*/*z* 1668.2 (M + Na), 1685.5 (M + K); $[\alpha]^{26}_D = +97.1$ (c = 1.68, CH_2Cl_2). Anal. Calcd for $C_{105}H_{96}O_{18}$: C, 76.62; H, 5.88. Found: C, 76.57; H, 6.08.

3,5-[G1]-Stil Dendrimer (14): colorless glassy solid, 80% (SiO_2, 1:1 petroleum ether−ethyl acetate); ^{1}H NMR: δ 8.81 (s, 3H), 7.19−7.35 (m, 96H), 6.53 (t, J = 2.1 Hz, 6H), 6.50 (t, 3H), 6.45 (d, J = 2.1 Hz, 6H), 6.44 (d, J = 2.2 Hz, 12H), 5.30 (s, 6H), 4.93 (s, 24H), 4.90 (s, 12H), 4.72 (d, J = 8.4 Hz, 3H), 4.69 (d, J = 8.4 Hz, 6H), 4.62 (d, J = 8.3 Hz, 3H), 4.61 (d, J = 8.4 Hz, 6H), 1.60 (s, 54H); ^{13}C NMR: δ 164.6, 159.9, 139.4, 139.3, 137.5, 136.8, 136.7, 135.5, 134.7, 131.2, 128.5, 128.4, 128.3, 127.9, 127.52, 127.47, 127.0, 126.95, 109.54, 109.48, 105.9, 101.9, 101.8, 85.2, 85.1, 84.8, 84.7, 70.1, 69.8, 67.0, 27.2, 27.1; MS (MALDI) *m*/*z* 3998.6 (M + Na), 4016.1 (M + K); $[\alpha]^{26}_D = +125.5$ (c = 1.85, CH_2Cl_2). Anal. Calcd for $C_{255}H_{240}O_{42}$: C, 77.02; H, 6.08. Found: C, 76.72; H, 6.41.

3,5-[G2]-Stil Dendrimer (15): colorless glassy solid, 34% (SiO_2, 19:1 methylene chloride−ethyl acetate); ^{1}H NMR: δ 8.81 (s, 3H), 7.34−7.19 (m, 204 H), 6.52 (t, J = 2.3 Hz, 12H), 6.50 (t, J = 2.3 Hz, 9H), 6.45 (d, J = 2.1 Hz, 18H), 6.44 (d, J = 2.2 Hz, 24H), 5.30 (s, 6H), 4.92 (s, 48 H), 4.90 (s, 24 H), 4.88 (s, 12 H), 4.72 (d, J = 8.4 Hz, 9H), 4.68 (d, J = 8.4 Hz, 12H), 4.64−4.60 (m, 21H), 1.61−1.54 (m, 126H); ^{13}C NMR: δ 164.6, 159.9, 139.5, 139.3, 137.5, 136.9, 136.80, 136.77, 135.5, 134.7, 131.2, 128.52, 128.47, 127.9, 127.55, 127.51, 127.46, 127.05, 127.00, 109.5, 109.4, 105.9, 101.9, 101.8, 85.2, 85.1, 85.0, 84.82, 84.77, 84.70, 70.0, 69.8, 27.14, 27.10; MS (MALDI) *m*/*z* 8663.8 (M + Na); $[\alpha]^{26}_D = +129.2$ (c = 0.705, CH_2Cl_2). Anal. Calcd for $C_{555}H_{528}O_{90}$: C, 77.16; H, 6.16. Found: C, 76.99; H, 6.35.

(*R*,*R*)-4-(Phenoxymethyl)-5-[3′,5′-bis(benzyloxy)phenyl]-2,2-dimethyl-1,3-dioxolane (16). To a cold (0 °C) solution of **4** (347 mg, 0.83 mmol) and CH_2Cl_2 (20 mL) was added Et_3N (173 μL, 1.24 mmol) followed by methanesulfonyl chloride (72 μL, 0.93 mmol) which was added dropwise via syringe over a 10 min period. The reaction was allowed to stir at 0 °C until TLC (SiO_2, 3:2 petroleum ether−ethyl acetate) indicated consumption of starting material (10 min). The reaction mixture was quenched with ice (20 g), diluted with CH_2Cl_2 (80 mL), and the resulting organic layer was washed successively with saturated NH_4Cl (30 mL), saturated $NaHCO_3$ (2 × 30 mL), and brine (50 mL). After drying ($MgSO_4$), concentration gave the corresponding mesylate (367 mg, 89%) as a colorless oil: ^{1}H NMR (270 MHz, $CDCl_3$) δ 7.29−7.42 (m, 10H), 6.61 (d, J = 8.5 Hz, 2H), 6.55 (t, J = 2.2 Hz, 1H), 5.02 (s, 4H), 4.62 (d, J = 8.5 Hz, 1H), 4.39 (dd, J = 2.7, 7.3 Hz, 1H), 4.22 (dd, J = 4.3, 7.3 Hz, 1H), 3.90 (ddd, J = 2.8, 4.3, 7.2 Hz, 1H), 3.04 (s, 3H), 1.53 (s, 3H), 1.49 (s, 3H). A slurry of crude mesylate (367 mg, 0.74 mmol), K_2CO_3 (504 mg, 3.64 mmol), phenol (71 mg, 0.74 mmol), 18-crown-6 (30 mg, 0.11 mmol), and dry acetone (15 mL) was heated at reflux. After TLC (SiO_2, 9:1 petroleum ether−ethyl acetate) indicated consumption of starting material, the reaction mixture was concentrated to dryness, dissolved in CH_2Cl_2 (50 mL) and water (50 mL), and separated; the aqueous layer was extracted with CH_2Cl_2 (2 × 20 mL). The combined organic layers were dried ($MgSO_4$) and concentrated. Flash chromatography (SiO_2, 9:1 petroleum ether−ethyl acetate) of the residue yielded **16** (251 mg, 69%) as a pale yellow solid: ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.40−7.24 (m, 12H), 6.94 (m, 1H), 6.88 (m, 2H), 6.63 (d, J = 2.2 Hz, 2H), 6.55 (t, J = 2.2 Hz, 1H), 5.00 (s, 4H), 4.87 (d, J = 7.7 Hz, 1H), 4.13−4.04 (m, 3H), 1.55 (s, 3H), 1.54 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 160.1, 158.6, 140.4, 136.7, 129.4, 128.5, 127.9, 127.4, 121.1, 114.6, 109.8, 105.6, 101.8, 81.6, 79.5, 70.1, 66.9, 27.0, 26.9; $[\alpha]^{26}_D = +52.7$ (c = 2.36, CH_2Cl_2). Anal. Calcd for $C_{32}H_{32}O_5$: C, 77.40; H, 6.49. Found: C, 77.60; H, 6.64.

(*R*,*R*)-4-(Benzoyloxymethyl)-5-[3′,5′-bis(benzyloxy)phenyl]-2,2-dimethyl-1,3-dioxolane (17). Benzoyl chloride (80 μL, 0.69 mmol) was added to a solution of alcohol **4** (246 mg, 0.58 mmol), DMAP (219 mg, 1.8 mmol), and toluene (20 mL) at room temperature. The reaction was left at room temperature until TLC (SiO_2, 7:3 petroleum ether−ethyl acetate) indicated consumption of starting material. The reaction was diluted with ethyl acetate (100 mL), washed with 1N HCl (50 mL) and brine (50 mL), and dried ($MgSO_4$). Concentration and purification by flash chromatography (SiO_2, 7:3 petroleum ether−ethyl acetate) of the resulting residue gave **17** (217 mg, 71%) as a colorless oil: ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.00−7.97 (m, 2H), 7.55−7.52 (m, 1H), 7.42−7.28 (m, 12H), 6.65 (d, J = 2.2 Hz, 2H), 6.55 (t, J = 2.2 Hz, 1H), 5.00 (s, 4H), 4.81 (d, J = 8.5 Hz, 1H), 4.54 (dd, J = 12.0, 3.8 Hz, 1H), 4.41 (dd, J = 12.0, 4.7 Hz, 1H), 4.08 (ddd (unresolved), 1H), 1.55 (s, 3H), 1.50 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 166.2, 160.2, 140.0, 136.7, 133.1, 129.74, 129.71, 128.6, 128.4, 128.0, 127.6, 109.9, 105.7, 101.9, 80.9, 79.9, 70.2, 63.1, 27.04, 27.02; $[\alpha]^{26}_D = +23.2$ (c = 3.02, CH_2Cl_2). Anal. Calcd for $C_{33}H_{32}O_6$: C, 75.55; H, 6.15. Found: C, 75.69; H, 6.20.

(*R*,*R*)-4-(3′,5′-Dicarbethoxybenzoyloxymethyl)-5-[3′,5′-bis(benzyloxy)phenyl]-2,2-dimethyl-1,3-dioxolane (18). A solution of the diethyl ester of benzene-1,3,5-tricarboxylic acid (501 mg, 1.88 mmol), $SOCl_2$ (8 mL), and 2 drops of DMF was heated to reflux for 4 h, after which time it was cooled to room temperature, concentrated, and dried under high vacuum. The resulting acid chloride (536 mg, 100%) was used without further purification. In a flask fitted with a Dean−Stark trap (filled with 3 Å sieves) and a reflux condenser, a solution of alcohol **4** (778 mg, 1.85 mmol), DMAP (693 mg, 5.67 mmol), and benzene (20 mL) was maintained at reflux for 1.5 h and then allowed to cool to room temperature. A solution of crude acid chloride (536 mg, 1.88 mmol) and benzene (5 mL) was added and the reaction was maintained at reflux for an additional 30 min, after which time TLC (SiO_2, 3:2 petroleum ether−ethyl acetate) indicated consumption of **4**. The reaction mixture was evaporated to dryness and the resulting residue taken up in CH_2Cl_2 (200 mL). The solution was washed successively with 1N HCl (60 mL), saturated $NaHCO_3$ (100 mL), and brine (100 mL), dried ($MgSO_4$), and concentrated. Purification of the residue by flash chromatography (85:15 petroleum ether−ethyl acetate) gave **18** (564 mg, 46%) as a clear pale yellow oil: ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.84 (t, J = 1.6 Hz, 1H), 8.82 (d, J = 1.6 Hz, 2H), 7.40−7.28 (m, 10H), 6.62 (d, J = 2.2 Hz, 2H), 6.53 (t, J = 2.2 Hz, 1H), 5.00 (s, 4H), 4.79 (d, J = 8.6 Hz, 1H), 4.57 (dd, J = 12.1, 3.1 Hz, 1H), 4.44 (dd (unresolved), 1H), 4.40 (q, J = 7.1 Hz, 4H), 4.12−4.09 (m, 1H), 1.55 (s, 3H), 1.52 (s, 3H), 1.40 (t, J = 7.1 Hz, 6H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 164.7, 164.6, 160.1, 139.6, 136.6, 134.6, 134.4, 131.5, 128.4, 127.9, 127.4, 125.7, 109.9, 105.5, 101.8, 80.7, 79.4, 70.0, 63.5, 61.6, 27.0, 26.9, 14.2; $[\alpha]^{26}_D = +20.0$ (c = 5.64, CH_2Cl_2). Anal. Calcd for $C_{39}H_{40}O_{10}$: C, 70.05; H, 6.03. Found: C, 69.98; H, 6.30.

(*R*,*R*)-4-[(3′-Methoxyphenoxy)methyl]-5-[3′,5′-bis(benzyloxy)-phenyl]-2,2-dimethyl-1,3-dioxolane (19). Following the procedure for **16**, alcohol **4** (189 mg, 0.45 mmol), Et_3N (100 μL, 0.75 mmol), methanesulfonyl chloride (38 μL, 0.50 mmol), and CH_2Cl_2 (25 mL) yielded the corresponding mesylate (224 mg, 100%) as a colorless oil. Crude mesylate (224 mg, 0.45 mmol), K_2CO_3 (190 mg, 1.38 mmol), 3-methoxyphenol (56 mg, 0.46 mmol), 18-crown-6 (28 mg, 0.11 mmol) and dry acetone (15 mL) yielded, after purification by flash chromatography (SiO_2, 9:1 petroleum ether−ethyl acetate), **19** (155 mg, 65%) as a colorless glassy solid: ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.40−7.26 (m, 10H), 7.15 (t, J = 8.1 Hz, 1H), 6.63 (d, J = 2.2 Hz, 2H), 6.55 (t, J = 2.2 Hz, 1H), 6.52−6.43 (m, 3H), 5.00 (s, 4H), 4.85 (d, J = 7.8 Hz, 1H), 4.12−4.04 (m, 3H), 3.73 (s, 3H), 1.55 (s, 3H), 1.53 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 160.8, 160.2, 159.8, 140.4, 136.7, 129.8, 128.6, 128.0, 127.5, 106.8, 106.7, 105.7, 101.8, 101.2, 81.6, 79.6, 70.2, 67.1, 55.2, 27.1, 27.0; $[\alpha]^{26}_D = +51.4$ (c = 0.80, CH_2Cl_2). Anal. Calcd for $C_{33}H_{34}O_6$: C, 75.26; H, 6.51. Found: C, 75.24; H, 6.69.

(*R*,*R*,*R*,*R*,*R*)-4-(Phenoxymethyl)-5-[3′,5′-bis({5″-[3‴,5‴-bis(benzyloxy)phenyl]-2″,2″-dimethyl-1″,3″-dioxolan-4″-yl}methoxy)phenyl]-2,2-dimethyl-1,3-dioxolane (20b). Following the procedure for **16**, monodendron **20a**[28] (405 mg, 0.39 mmol), Et_3N (80 μL, 0.60 mmol), methanesulfonyl chloride (36 μL, 0.47 mmol), and CH_2Cl_2 (20 mL) yielded the corresponding mesylate (415 mg, 95%) as a colorless glassy solid: ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.39−7.28 (m, 20H), 6.62 (d, J = 2.2 Hz, 4H), 6.57 (d, J = 2.2 Hz, 2H), 6.54 (t, J = 2.2 Hz, 2H), 6.41 (t, J = 2.2 Hz, 1H), 5.00 (s, 8H), 4.83 (d, J = 8.2 Hz, 2H), 4.77 (d, J = 8.5 Hz, 1H), 4.32−4.25 (m, 2H), 4.10−3.90 (m, 7H), 2.94 (s, 3H), 1.54−1.51 (m, 18H). Crude mesylate (415 mg, 0.37 mmol), K_2CO_3 (256 mg, 1.85 mmol), phenol (35 mg, 0.37 mmol), 18-crown-6 (22 mg, 0.08 mmol), and dry acetone (10 mL) yielded, after purification by flash chromatography (SiO_2, 7:3 petroleum ether−ethyl acetate),

20b (344 mg, 83%) as a colorless glassy solid: ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.38−7.20 (m, 22H), 6.92−6.84 (m, 3H), 6.61 (d, J = 2.2 Hz, 4H), 6.58 (d, J = 2.1 Hz, 2H), 6.54 (t, J = 2.3 Hz, 2H), 6.40 (t, J = 2.1 Hz, 1H), 4.98 (s, 8H), 4.85 (d, 8.2 Hz, 1H), 4.82 (d, J = 8.0 Hz, 2H), 4.12−4.00 (m, 9H), 1.54−1.50 (m, 18H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 160.2, 159.9, 158.5, 140.4, 140.2, 136.6, 129.4, 128.6, 128.0, 127.5, 121.1, 114.6, 109.92, 109.90, 105.8, 105.7, 101.7, 101.4, 81.52, 81.50, 79.5, 79.4, 70.1, 67.1, 67.0, 27.1, 27.03, 27.00, 26.9; $[\alpha]^{26}_D$ = +74.6 (c = 0.84, CH_2Cl_2). Anal. Calcd for $C_{70}H_{72}O_{13}$: C, 74.98; H, 6.47. Found: C, 74.69; H, 6.55.

(*R*,*R*)-4-[4′-(Phenoxymethyl)phenyl]-5-[3′,5′-bis(benzyloxy)-phenyl]-2,2-dimethyl-1,3-dioxolane (21). To a solution of alcohol **6** (1.04 g, 2.09 mmol), CBr_4 (1.06 g, 3.20 mmol), and THF (50 mL) was added PPh_3 (830 mg, 3.17 mmol). The reaction mixture was allowed to stir at room temperature, and additional portions of CBr_4 and PPh_3 in the initial amounts were added until TLC (SiO_2, 9:1 petroleum ether−ethyl acetate) indicated consumption of starting material. The reaction was diluted with CH_2Cl_2 (200 mL) and quenched with water (100 mL). The organic layer was separated, and the aqueous layer was extracted with CH_2Cl_2 (3 × 50 mL). The combined organic extracts were dried ($MgSO_4$) and concentrated. Purification of the residue by flash chromatography (SiO_2, 7:3 petroleum ether−ethyl acetate) gave the corresponding bromide (1.08 g, 92%) as a colorless solid: ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.37−7.29 (m, 12H), 7.20−7.18 (m, 2H), 6.54 (t, J = 2.3 Hz, 1H), 6.43 (d, J = 2.3 Hz, 2H), 4.95 (s, 4H), 4.67 (d, J = 8.5 Hz, 1H), 4.60 (d, J = 8.5 Hz, 1H), 4.47 (s, 2H), 1.62 (s, 3H), 1.61 (s, 3H). A slurry of bromide (195 mg, 0.35 mmol), K_2CO_3 (307 mg, 2.2 mmol), phenol (68 mg, 0.72 mmol), 18-crown-6 (34 mg, 0.13 mmol), and dry acetone (10 mL) was heated at reflux. After TLC (SiO_2, 95:5 petroleum ether−ethyl acetate) indicated consumption of starting material, the reaction mixture was concentrated to dryness, dissolved in Et_2O (50 mL) and water (50 mL), and separated; the aqueous layer was extracted with Et_2O (3 × 50 mL). The residue was purified by flash chromatography (SiO_2, 9:1 petroleum ether−CH_2Cl_2 gradient to CH_2Cl_2), and the resulting product was dissolved in CH_2Cl_2 (20 mL), washed with NaOH (1.25 N), dried over $MgSO_4$, and concentrated to yield **21** (165 mg, 82%) as a colorless solid: ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.38−7.22 (m, 16H), 6.95−6.90 (m, 3H), 6.54 (t, J = 2.2 Hz, 1H), 6.45 (d, J = 2.2 Hz, 2H), 5.04 (s, 2H), 4.95 (s, 4H), 4.70 (d, J = 8.4 Hz, 1H), 4.64 (d, J = 8.4 Hz, 1H), 1.63 (s, 3H), 1.61 (2, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 159.9, 158.7, 139.3, 137.2, 136.8, 136.6, 129.4, 128.6, 128.0, 127.52, 127.47, 127.0, 121.0, 114.8, 109.5, 105.8, 101.9, 85.2, 84.9, 70.1, 69.6, 27.2, 27.1; $[\alpha]^{26}_D$ = +99.2 (c = 0.78, CH_2Cl_2). Anal. Calcd for $C_{38}H_{36}O_5$: C, 79.70; H, 6.34. Found: C, 79.89; H, 6.54.

(*R*,*R*)-4-[4′-(Benzoyloxymethyl)phenyl]-5-[3′,5′-bis(benzyloxy)-phenyl]-2,2-dimethyl-1,3-dioxolane (22). Following the procedure for **17**, benzoyl chloride (85 μL, 0.73 mmol), alcohol **6** (232 mg, 0.47 mmol), DMAP (173 mg, 1.4 mmol), and toluene (15 mL) gave, after purification by flash chromatography (SiO_2, 7:3 petroleum ether−ethyl acetate), **22** (241 mg, 86%) as a colorless solid: ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.09−8.06 (m, 2H), 7.58−7.54 (m, 1H), 7.44−7.26 (m, 16H), 6.58 (t, J = 2.2 Hz, 1H), 6.49 (d, J = 2.2 Hz, 2H), 5.38 (s, 2H), 4.98 (s, 4H), 4.74 (d, J = 8.4 Hz, 1H), 4.67 (d, J = 8.4 Hz, 1H), 1.67 (s, 3H), 1.65 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 166.4, 160.0, 139.3, 137.0, 136.8, 136.1, 133.0, 130.1, 129.6, 128.6, 128.4, 128.2, 128.0, 127.5, 127.0, 109.5, 105.8, 102.0, 85.2, 84.8, 70.1, 66.3, 27.2, 27.1; $[\alpha]^{26}_D$ = +90.1 (c = 1.14, CH_2Cl_2). Anal. Calcd for $C_{39}H_{36}O_6$: C, 77.98; H, 6.04. Found: C, 77.74; H, 6.23.

(*R*,*R*)-4-[4′-(3″,5″-Dicarbethoxybenzoyloxymethyl)phenyl]-5-[3′,5′-bis(benzyloxy)phenyl]-2,2-dimethyl-1,3-dioxolane (23). A solution of the diethyl ester of benzene-1,3,5-tricarboxylic acid (181 mg, 0.68 mmol), $SOCl_2$ (8 mL), and 2 drops of DMF was heated to reflux for 4 h, after which time it was cooled to room temperature, concentrated, and dried under high vacuum. The resulting acid chloride (194 mg, 100%) was used without further purification. Following the procedure for **17**, crude acid chloride (194 mg, 0.68 mmol), alcohol **6** (345 mg, 0.70 mmol), DMAP (254 mg, 2.08 mmol), and toluene (25 mL) gave, after purification by flash chromatography (SiO_2, 7:3 petroleum ether−ethyl acetate), **23** (420 mg, 81%) as a colorless solid: ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.84 (d, J = 1.6 Hz, 2H), 8.82 (t, J = 1.6 Hz, 1H), 7.41−7.26 (m, 14H), 6.54 (t, J = 2.2 Hz, 1H), 6.46 (d, J = 2.2 Hz, 2H), 5.39 (s, 2H), 4.95 (s, 4H), 4.71 (d, J = 8.4 Hz, 1H), 4.63 (d, J = 8.4 Hz, 1H), 4.40 (q, J = 7.1 Hz, 4H), 1.63 (s, 3H), 1.62 (s, 3H), 1.40 (t, J = 7.1 Hz, 6H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 165.0, 164.9, 159.9, 139.2, 137.4, 136.7, 135.5, 134.6, 134.5, 131.5, 131.0, 128.5, 128.4, 128.0, 127.5, 127.0, 109.6, 105.9, 101.9, 85.1, 84.7, 70.1, 67.0, 61.7, 27.17, 27.12, 14.3; $[\alpha]^{26}_D$ = +68.2 (c = 1.24, CH_2Cl_2). Anal. Calcd for $C_{45}H_{44}O_{10}$: C, 72.57; H, 5.95. Found: C, 72.31; H, 6.06.

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