(*S*)-*S*-*tert*-Butyl 3-hydroxy-5-phenylpentanethioate (15): $[\alpha]^{28}_D$ -7.5° (*c* 4.27, PhH) (85% ee); IR (neat) 1680 cm^{-1}; ^{1}H NMR (CCl_4) δ 1.45 (s, 9 H), 1.55-1.95 (m, 2 H), 2.45-2.95 (m, 7 H), 3.95 (m, 1 H), 7.15 (m, 5 H); precise mass for $C_{15}H_{22}O_2S$, calcd *m/z* 266.1340, found 266.1254.

(*S*)-*S*-Ethyl 3-hydroxy-4-methylpentanethioate (16): $[\alpha]^{22}_D$ -52.0° (*c* 3.16, PhH) (95% ee); IR (neat) 1680 cm^{-1}; ^{1}H NMR (CCl_4) δ 0.90 (d, 6 H, *J* = 7.0 Hz), 1.25 (t, 3 H, *J* = 7.0 Hz), 1.40-1.80 (m, 1 H), 2.50-2.75 (m, 3 H), 2.85 (q, 2 H, *J* = 7.0 Hz), 3.70 (m, 1 H). Anal. ($C_8H_{16}O_2S$) C, H, S.

(*S*)-*S*-Ethyl 3-hydroxy-4,4-dimethylpentanethioate (17): $[\alpha]^{24}_D$ -60.9° (*c* 3.96, PhH) (>98% ee); IR (neat) 1680 cm^{-1}; ^{1}H NMR (CCl_4) δ 0.90 (s, 3 H), 1.25 (t, 3 H, *J* = 7.0 Hz), 2.45-2.75 (m, 3 H), 2.85 (q, 2 H, *J* = 7.0 Hz), 3.65 (m, 1 H). Anal. ($C_9H_{18}O_2S$) C, H, S.

(2*S*,3*S*)-*S*-Ethyl 3-hydroxy-3-phenyl-2-methylpropanethioate (19): $[\alpha]^{24}_D$ -85.2° (*c* 2.70, PhH) (>98% ee); IR (neat) 3450, 1675 cm^{-1}; ^{1}H NMR (CCl_4) δ 1.10 (d, 3 H, *J* = 7.0 Hz), 1.20 (t, 3 H, *J* = 7.0 Hz), 2.65 (br s, 1 H), 2.55-2.95 (m, 1 H), 2.80 (q, 2 H, *J* = 7.0 Hz), 5.00 (d, 1 H, *J* = 4.0 Hz), 7.20 (m, 5 H); precise mass for $C_{12}H_{16}O_2S$, calcd *m/z* 224.0889, found 224.0880.

(2*S*,3*S*)-*S*-Ethyl 3-hydroxy-3-(4-chlorophenyl)-2-methylpropanethioate (24): $[\alpha]^{29}_D$ +86.4° (*c* 2.47, PhH) (>98% ee); IR (neat) 3450, 1675 cm^{-1}; ^{1}H NMR (CCl_4) δ 1.10 (d, 3 H, *J* = 7.0 Hz), 1.20 (t, 3 H, *J* = 7.0 Hz), 2.70 (m, 1 H), 2.80 (q, 2 H, *J* = 7.0 Hz), 3.00 (br s, 1 H), 4.95 (d, 1 H, *J* = 4.0 Hz), 7.20 (m, 4 H); precise mass for $C_{12}H_{15}O_2SCl$, calcd *m/z* 258.0482, found 258.0473.

(2*S*,3*S*)-*S*-Ethyl 3-hydroxy-3-*p*-tolyl-2-methylpropanethioate (25): $[\alpha]^{30}_D$ +93.4° (*c* 3.29, PhH) (>98% ee); IR (neat) 3450, 1675 cm^{-1}; ^{1}H NMR (CCl_4) δ 1.10 (d, 3 H, *J* = 7.0 Hz), 1.20 (t, 3 H, *J* = 7.0 Hz), 2.30 (s, 3 H), 2.70 (br s, 1 H), 2.70 (m, 1 H), 2.80 (q, 2 H, *J* = 7.0 Hz), 4.95 (d, 1 H, *J* = 4.0 Hz), 7.10 (m, 4 H); precise mass for $C_{13}H_{18}O_2S$, calcd *m/z* 238.1028, found 238.1041.

(2*S*,3*S*)-*S*-Ethyl 3-hydroxy-3-(4-methoxyphenyl)-2-methylpropanethioate (26): $[\alpha]^{28}_D$ +99.7° (*c* 2.90, PhH) (>98% ee); IR (neat) 3475, 1675 cm^{-1}; ^{1}H NMR (CCl_4) δ 1.10 (d, 3 H, *J* = 7.0 Hz), 1.20 (t, 3 H, *J* = 7.0 Hz), 2.50 (br s, 1 H), 2.65 (m, 1 H), 2.75 (q, 2 H, *J* = 7.0 Hz), 3.20 (s, 3 H), 4.80 (d, 1 H, *J* = 4.0 Hz), 6.60 (d, 2 H, *J* = 9.0 Hz), 7.00 (d, 2 H, *J* = 8.0 Hz); precise mass for $C_{13}H_{18}O_3S$, calcd *m/z* 254.0977, found 254.0973.

(2*S*,3*R*)-*S*-Ethyl 3-hydroxy-2-methyldecanethioate (27): $[\alpha]^{26}_D$ +32.1° (*c* 2.70, PhH) (>98% ee); IR (neat) 3450, 1680 cm^{-1}; ^{1}H NMR (CCl_4) δ 0.80-1.70 (m, 21 H), 2.25 (br s, 1 H), 2.35-2.65 (m, 1 H), 2.85 (q, 2 H, *J* = 7.0 Hz), 3.45-3.95 (m, 1 H). Anal. ($C_{13}H_{26}O_2S$) C, H. S.

(2*S*,3*R*)-*S*-Ethyl 3-cyclohexyl-3-hydroxy-2-methylpentanethioate (28): $[\alpha]^{28}_D$ +33.8° (*c* 2.50, PhH) (>98% ee); IR (neat) 3475, 1680 cm^{-1}; ^{1}H NMR (CCl_4) δ 0.50-2.10 (m, 11 H), 1.15 (d, 3 H, *J* = 7.0 Hz), 1.25 (t, 3 H, *J* = 7.0 Hz), 2.25 (br s, 1 H), 2.75 (m, 1 H), 2.90 (q, 2 H, *J* = 7.0 Hz), 3.40-3.70 (m, 1 H). Anal. ($C_{12}H_{22}O_2S$) C, H, S.

(2*S*,3*R*)-*S*-Ethyl 3-hydroxy-2,4-dimethylpentanethioate (29): $[\alpha]^{30}_D$ +14.4° (*c* 1.80, PhH) (>98% ee); IR (neat) 3450, 1680 cm^{-1}; ^{1}H NMR (CCl_4) δ 0.70-1.45 (m, 9 H), 1.25-1.95 (m, 1 H), 2.25 (br s, 1 H), 2.45-2.80 (m, 1 H), 2.30 (q, 2 H, *J* = 7.0 Hz), 3.25-3.60 (m, 1 H). Anal. ($C_9H_{18}O_2S$) C, H, S.

(2*S*,3*R*)-*S*-Ethyl 3-hydroxy-2,5-dimethylhexanethioate (30): $[\alpha]^{30}_D$ + 39.9° (*c* 2.70, PhH) (>98% ee); IR (neat) 3425, 1680 cm^{-1}; ^{1}H NMR (CCl_4) δ 0.95 (d, 6 H, *J* = 6.0 Hz), 1.20 (d, 3 H, *J* = 7.0 Hz), 1.25 (t, 3 H, *J* = 7.0 Hz), 1.55-2.00 (m, 2 H), 2.20 (br s, 1 H), 2.30-2.60 (m, 1 H), 3.65-4.10 (m, 1 H). Anal. ($C_{10}H_{20}O_2S$) C, H, S.

(2*S*,3*R*)-*S*-Ethyl 3-hydroxy-2-methyl-*trans*-4-hexenethioate (31): $[\alpha]^{26}_D$ +50.7° (*c* 2.10, PhH) (>98% ee); IR (neat) 3400, 1665 cm^{-1}; ^{1}H NMR (CCl_4) δ 1.20 (d, 3 H, *J* = 7.0 Hz), 1.25 (t, 3 H, *J* = 7.0 Hz), 1.70 (d, 3 H, *J* = 5.0 Hz), 2.35-2.75 (m, 1 H), 2.55 (br s, 1 H), 2.80 (q, 2 H, *J* = 7.0 Hz), 4.05-4.35 (m, 1 H), 5.05-5.95 (m, 2 H). Anal. ($C_9H_{16}O_2S$) C, H, S.

(2*S*,3*R*)-*S*-Ethyl 3-hydroxy-2-methyl-5-phenyl-*trans*-4-pentenethioate (32): $[\alpha]^{29}_D$ +84.4° (*c* 3.50, PhH) (>98% ee); IR (neat) 3400, 1665 cm^{-1}; ^{1}H NMR (CCl_4) δ 1.20 (t, 3 H, *J* = 7.0 Hz), 1.25 (d, 3 H, *J* = 7.0 Hz), 2.55 (br s, 1 H), 2.55-2.95 (m, 1 H), 2.80 (q, 2 H, *J* = 7.0 Hz), 4.30-4.65 (m, 1 H), 6.05 (dd, 1 H, *J* = 5.0, 16.0 Hz), 6.60 (d, 1 H, *J* = 16.0 Hz), 7.05-7.45 (m, 5 H). Anal. ($C_{14}H_{18}O_2S$) C, H, S.

(2*S*,3*R*)-*S*-Ethyl 3-hydroxy-2-methyl-*trans*-4-octenethioate (33): $[\alpha]^{25}_D$ +39.8° (*c* 2.70, PhH) (>98% ee); IR (neat) 3400, 1665 cm^{-1}; ^{1}H NMR (CCl_4) δ 0.60-1.70 (m, 9 H), 1.80-2.45 (m, 4 H), 2.30 (br s, 1 H), 2.45-2.85 (m, 1 H), 2.80 (q, 2 H, *J* = 7.0 Hz), 4.10-4.35 (m, 1 H), 5.05-5.90 (m, 2 H). Anal. ($C_{11}H_{20}O_2S$) C, H, S.

(2*S*,3*S*)-*S*-Ethyl 3-(2-furyl)-3-hydroxy-2-methylpropanethioate (34): $[\alpha]^{25}_D$ +39.3° (*c* 3.00, PhH) (>98% ee); IR (neat) 3475, 1675 cm^{-1}; ^{1}H NMR (CCl_4) δ 1.15 (d, 3 H, *J* = 7.0 Hz), 1.20 (t, 3 H, *J* = 7.0 Hz), 2.75 (br s, 1 H), 2.75 (q, 2 H, *J* = 7.0 Hz), 2.90 (m, 1 H), 4.85 (d, 1 H, *J* = 5.0 Hz), 6.10 (m, 2 H), 7.15 (m, 1 H). Anal. ($C_{10}H_{14}O_3S$) C, H, S.

(2*S*,3*S*)-*S*-Ethyl 3-(3-thienyl)-3-hydroxy-2-methylpropanethioate (35): $[\alpha]^{31}_D$ + 58.4° (*c* 3.30, PhH) (>98% ee); IR (neat) 3425, 1680 cm^{-1}; ^{1}H NMR (CCl_4) δ 0.75-1.40 (m, 6 H), 2.45-3.20 (m, 3 H), 2.80 (br s, 1 H), 5.15 (d, 1 H, *J* = 5.0 Hz), 6.55-7.15 (m, 2 H), 7.15-7.40 (m, 1 H). Anal. ($C_{10}H_{14}O_2S$) C, H, S.

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Hyperbranched Macromolecules via a Novel Double-Stage Convergent Growth Approach

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Abstract: A novel double-stage convergent growth approach for the preparation of dendritic macromolecules is described. In the first stage, convergent growth with 4,4-bis(4'-hydroxyphenyl)pentanol as the building block is used to create symmetrical dendritic structures containing a large number of phenolic "surface" functionalities. In the second stage of growth, these polyphenolic dendritic macromolecules are utilized as cores for the attachment of other dendritic macromolecules, derived from 3,5-dihydroxybenzyl alcohol, that contain a single benzylic bromide reactive group at their focal point. This two-stage process affords hyperbranched spherical macromolecules consisting of a flexible inner core surrounded by a more rigid outer layer. The double-stage convergent growth approach allows for the preparation of larger dendrimers in less time and with greater ease than the single-stage approach while retaining the advantages of near monodispersity and ease of purification and characterization.

Introduction

Spherical dendritic macromolecules have received considerable attention as a new class of polymers.[1] This interest is due to their novel highly branched structure, which may result in a variety of new and improved properties. Two fundamentally different approaches have been developed to synthesize these molecules. The first is a "divergent-growth" approach, best known for the preparation of "starburst"[2] and "arborol"[3] dendrimers. An ex-

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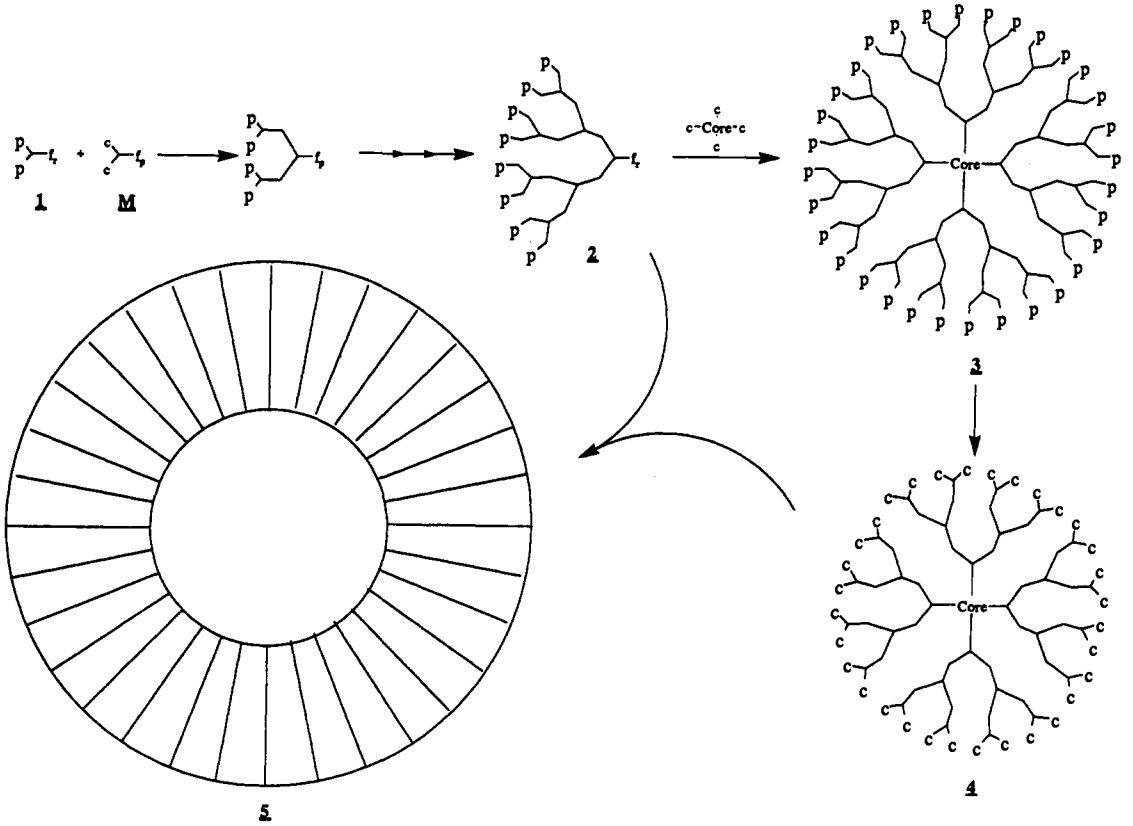
0002-7863/91/1513-4252$02.50/0

Scheme I



tensive review[4] of this approach and related synthetic[5,6] or theoretical[7,8] work has appeared. Several other novel applications of the divergent approach have recently appeared, leading to dendritic macromolecules based on siloxane[9] or phosphonium cation[10] repeating units. The divergent growth strategy involves the initial reaction of an AB_x monomer with a polyfunctional core followed by activation of the peripheral functional groups. Repetition of this two-step process allows growth to proceed radially outward with a rapid increase in the number of reactive groups at the chain ends of the growing macromolecules. At higher molecular weights, the large number of functionalities at the periphery may increase the probability of imperfections occurring in the subsequent growth steps and usually requires that large excesses of reagents be used to force reactions to completion and prevent side reactions such as the coupling of "starburst" molecules.[11] These large excesses must be completely removed before continuing with the next-generation growth step in order to prevent the initiation of new growth centers.[11]

A second route to dendritic molecules demonstrated earlier[12-14] for the preparation of hyperbranched polyethers involves a convergent process in which growth begins at what will become the periphery of the final macromolecule and proceeds inward, the final reaction being attachment to a polyfunctional core. This novel methodology has since been used for the preparation of low molecular weight polyphenylenes.[15] The convergent growth approach offers a number of features less readily accessed by the "divergent-growth" approach such as control over surface functionality,[14] involvement of a very limited number of reactive sites (typically three) for generation growth, essentially monodisperse products, ease of purification, and ease of characterization. One limitation of the convergent growth approach is that, as the sizes of the dendrimers increase, they are increasingly more susceptible to steric inhibition at the focal point group. This effectively limits the size of the macromolecules that may be prepared in conventional fashion. This limitation is not as significant with the divergent or starburst approach, though a somewhat similar steric inhibition is reported to manifest itself as "dense packing".[4,11]

To allow higher molecular weight products of low polydispersity to be prepared in multigram quantities, we have investigated a novel "double-stage" convergent growth approach to spherical dendritic macromolecules. In this process, a dendritic molecule that carries at least one reactive functional group at each of its numerous chain extremities is prepared by convergent growth and is then used as a core to attach other preformed dendritic fragments through their single focal point[13] reactive group.

A particular feature of this technique is that the inner hyperbranched core ("hypercore") may be constituted of flexible segments, providing for ample spacing between the reactive groups at each chain end. As a result, the coupling of dendritic fragments

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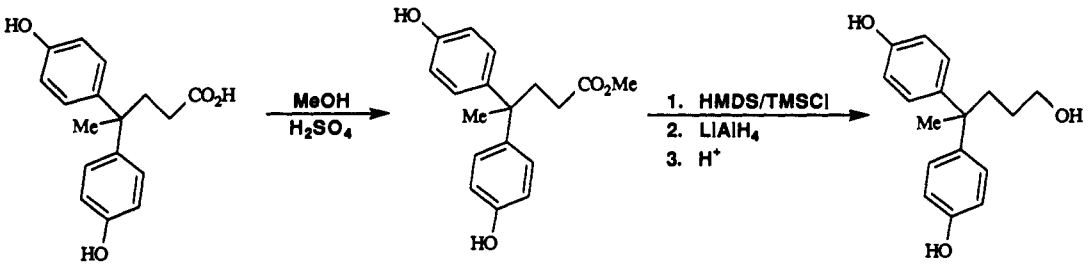
Scheme II



to this loose hypercore is facilitated and less subject to the steric constraints we had encountered[12] earlier with very compact cores having three phenolic functionalities linked to a single tetrahedral carbon atom.

Results and Discussion

Double-Stage Strategy. The first stage of this approach is the preparation of the flexible hypercore moiety. This synthesis starts at what will become the periphery or chain ends of the hypercore through coupling of protected surface moiety (**1**) with a monomer unit (M) that carries at least two coupling sites (c) and a protected functional group (f_p). As shown in Scheme I, surface moiety **1** should contain at least two protected functional groups (p) and one reactive functional group (f_r). Repetition of the previously described[12,13] convergent strategy leads to dendritic fragments such as **2**. Coupling of **2**, which contains a single reactive functional group (f_r) and a large number of protected surface groups (p), to a *normal* core molecule gives a dendritic macromolecule (**3**), which in the illustration of Scheme I has exactly 32 protected groups at the periphery. Deprotection of these groups gives the desired hyperfunctionalized core molecule **4**, which contains 32 coupling sites (c). The second stage of this approach involves reaction of a dendritic fragment such as **2** with the hypercore **4** to give hyperbranched macromolecules **5** of higher molecular weight than were previously obtainable by the single-stage convergent growth approach. The hyperbranched macromolecule **5** is shown schematically in two dimensions with the dendritic fragments pictured as wedges attached to the central circular hypercore. Theoretically, this process may be repeated several times and may incorporate several different monomer or dendrimer units to produce a variety of extremely large hyperbranched structures.

Preparation of *Hypercores*. The monomer unit for the initial convergent preparation of the hypercores was 4,4-bis(4′-hydroxyphenyl)pentanol (**6**). This was chosen in order to increase the flexibility of the hypercores when compared to our previous and significantly more compact core unit 1,1,1-tris(4′-hydroxyphenyl)ethane. Protection of the peripheral phenolic groups is necessary since they are the "external" or core reactive groups that will be used for coupling in the second stage of the overall synthesis. Benzyl ethers were selected as the protecting groups since regioselective cleavage of these ethers is possible using reagents that do not affect the aliphatic ether linkages within the hypercores. Monomer **6** was prepared as shown in Scheme II. Esterification of the commercially available acid **7** with methanol/H_2SO_4 gave the methyl ester **8** in 90% yield after recrystallization. Protection of the phenolic groups of **8** as their trimethylsilyl ethers followed by reduction with lithium aluminum hydride gave the desired monomer **6** in 84% yield after purification.

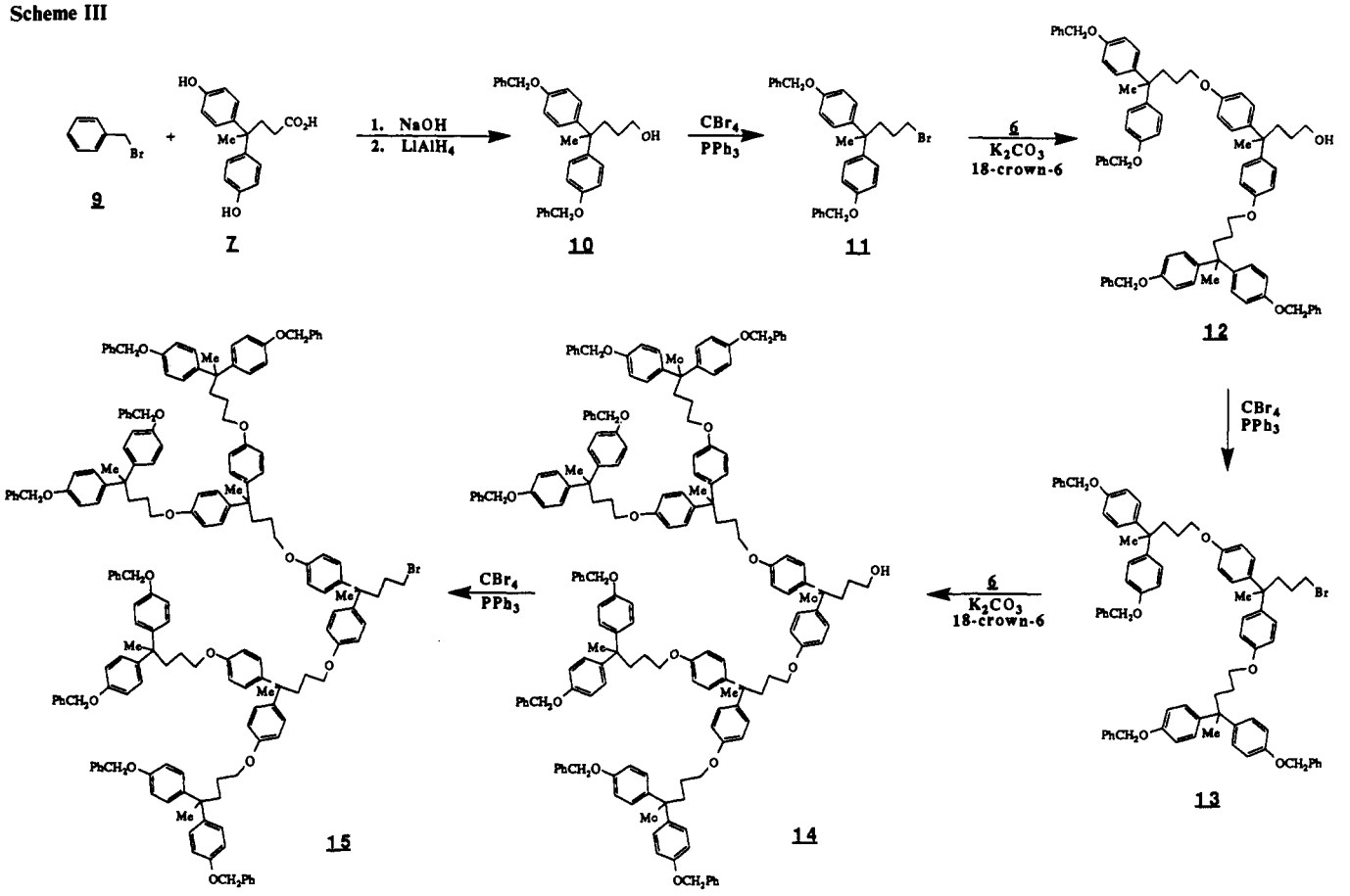
Preparation of the dendritic fragments that will constitute the hypercore is done by convergent growth as shown in Scheme III. Reaction of benzyl bromide (**9**; 2.05 equiv) with 4,4-bis(4′-hydroxyphenyl)valeric acid (**7**) in the presence of sodium hydroxide, followed by reduction with lithium aluminum hydride, gave the first-generation alcohol ([G-1]-OH) **10** in an overall yield of 80%. Activation of the hydroxy functional group with CBr_4 (1.25 equiv) and PPh_3 (1.25 equiv) in dry tetrahydrofuran at room temperature gave the first-generation bromide ([G-1]-Br) **11** in 92% yield after purification. The bromide **11** (2.05 equiv) was allowed to react with the diphenolic monomer unit **6** under our standard[13] alkylation conditions (potassium carbonate and 18-crown-6 in acetone heated at reflux for 48 h) to afford the next-generation alcohol ([G-2]-OH) **12** in 89% yield. The second-generation bromide **13** was obtained in 92% yield by reaction of **12** with CBr_4/PPh_3. Reaction of [G-2]-Br **13** with **6**, as above, gave the third-generation alcohol **14** in 86% yield, which was brominated with CBr_4/PPh_3 to give bromide [G-3]-Br **15** in 90% yield after purification.

Final assembly of the hypercores was by attachment of the intermediate dendritic fragments to a central polyfunctional molecule followed by deprotection of the peripheral groups, as shown in Scheme IV. In a typical reaction, the central polyfunctional molecule, in this case 1,1,1-tris(4′-hydroxyphenyl)ethane (**16**), was alkylated with the second-generation dendritic bromide ([G-2]-Br) **13** (3.10 equiv) with use of once again the same coupling chemistry (K_2CO_3 and 18-crown-6). The product $[G\text{-}2]_3$-[C] **17** was obtained in 74% yield after purification. The final reaction, cleavage of the benzyl ether surface groups by catalytic transfer hydrogenation with cyclohexene and Pd/C in tetrahydrofuran heated at reflux, gave compound **18** or $(HO)_{12}$-[C], in 54% yield. This "hypercore" molecule contains 12 reactive phenolic groups at the periphery. Similarly, hypercore molecules containing six ($(HO)_6$-[C] **20**) or twenty-four ($(HO)_{24}$-[C] **24**; Chart I) phenolic surface groups were prepared by reaction of **16** with the first- or third-generation bromides **11** or **15**, respectively, followed by cleavage of the benzyl ether protecting groups. The deprotection reaction was monitored by observing the disappearance of the resonances due to the benzyl ether groups (7.40–7.25 and 5.02 ppm) in the ^1H NMR spectrum. At each stage of the synthesis, the products were easily purified by flash chromatography.

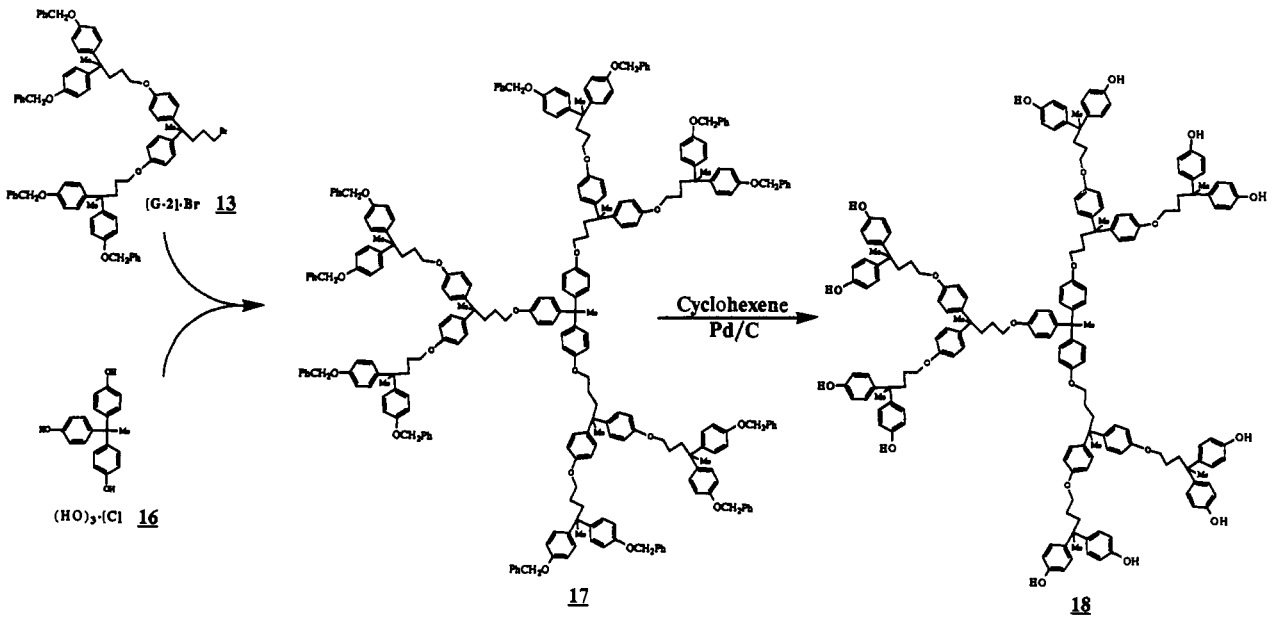
Coupling of Dendritic Fragments to the *Hypercores*. The second stage of convergent synthesis in our "double-convergent" growth approach involves the attachment of dendritic fragments to the hypercores. Reaction of the previously reported[13] fourth-generation bromide ([G-4]-Br) **19** (based on 3,5-dihydroxybenzyl alcohol chemistry) with hypercore **24** or $(HO)_{24}$-[C] under the standard alkylation conditions as discussed above gave $[G\text{-}4]_{24}$-[C] **23**, which has a nominal molecular weight[16] of 84 219, in 61% yield after purification. This reaction of **24**, with its 24 phenolic groups at the periphery, with a dendritic fragment (**19**) having a mass of 3351 results in the production of a spherical dendritic macromolecule (**23**) of MW 84 219 in a single step, demonstrating both that the of the double-stage convergent growth approach is effective and that the coupling step is facilitated when hypercores are used instead of the more compact polyfunctional core molecule used previously.[12-14] Similarly, spherical dendritic macromolecules $[G\text{-}4]_{12}$-[C] **22** and $[G\text{-}4]_6$-[C] **21** with nominal molecular weights of 41 881 and 20 712 were prepared in yields of 51 and 58%, respectively, by reaction of [G-4]-Br **19** with the hypercores $(HO)_{12}$-[C] **18** and $(HO)_6$-[C] **20** as illustrated in Scheme V. These alkylation reactions were monitored by size exclusion chromatography (SEC). SEC traces for the reaction of [G-4]-Br **19** and $(HO)_6$-[C] **20** at various times are shown in Figure 1. It

(16) Calculated on the basis of C = 12.01, H = 1.008, and O = 16.00.

Scheme III



Scheme IV



is apparent that little intermediate di-, tri-, tetra-, or pentasubstituted products are produced, as the peaks that are observed correspond primarily to the starting material and the final hexasubstituted dendrimer. This unusual result is supported by other findings[17] and suggests that the rate of reaction of partially substituted cores is greater than that of the unsubstituted core. This may be due to local polarity or microenvironment effects favoring coupling of the dendritic wedges to the more lipophilic partly substituted cores rather than to their more hydrophilic unsubstituted or less substituted counterparts. Alternate explanations are also possible.[18] All of the final hyperbranched macromolecules were purified by a combination of flash chromatography and fractional precipitation.

Characterization of the *Hypercores*. NMR spectroscopy proved to be essential in the characterization of the intermediate dendritic

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(18) A reviewer has suggested that possibly some aggregates of hydrogen-bonded phenols are broken up if one of the phenolic hydroxyls is substituted by the more lipophilic dendrimer wedge.

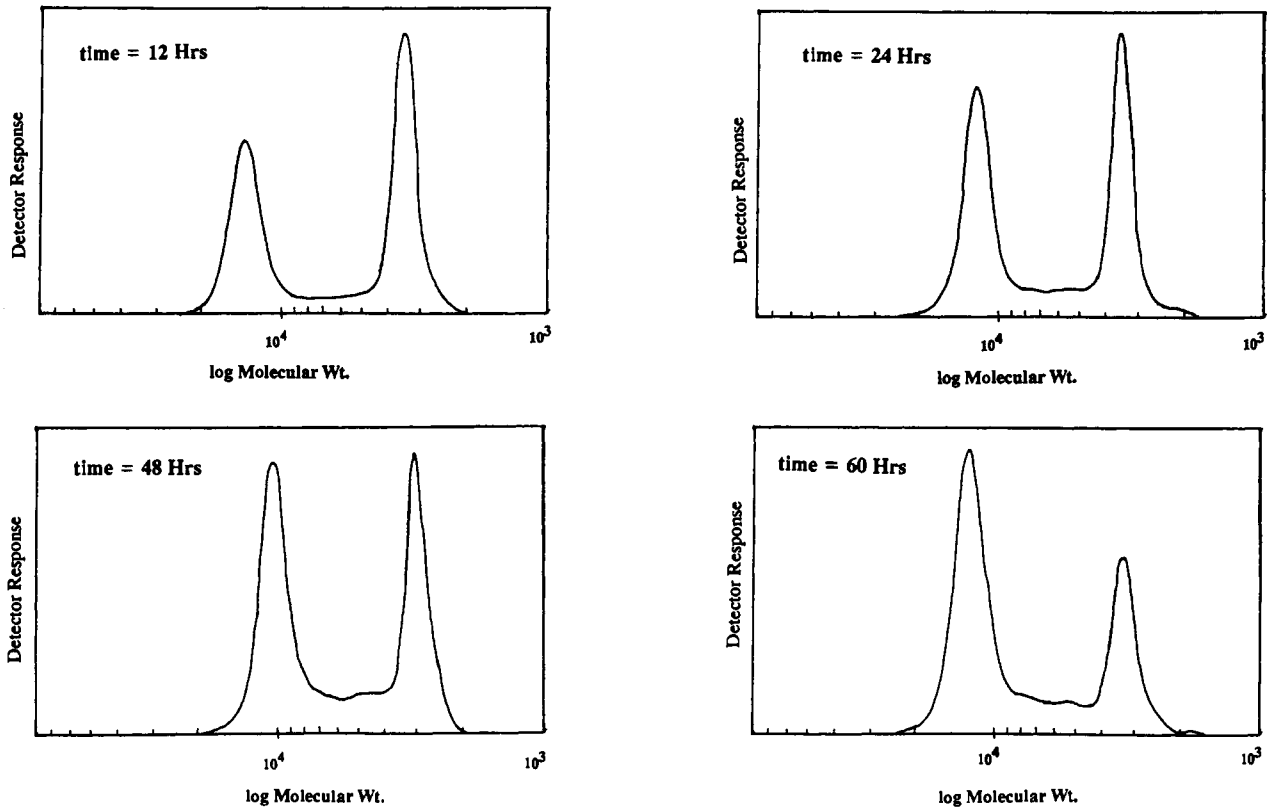
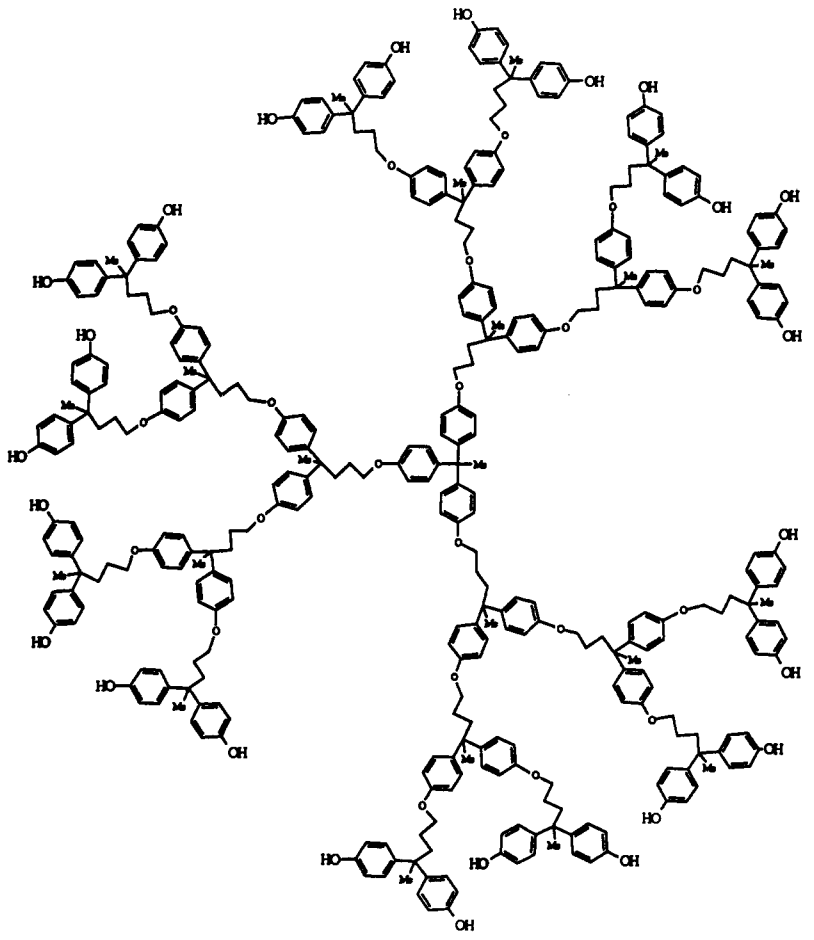
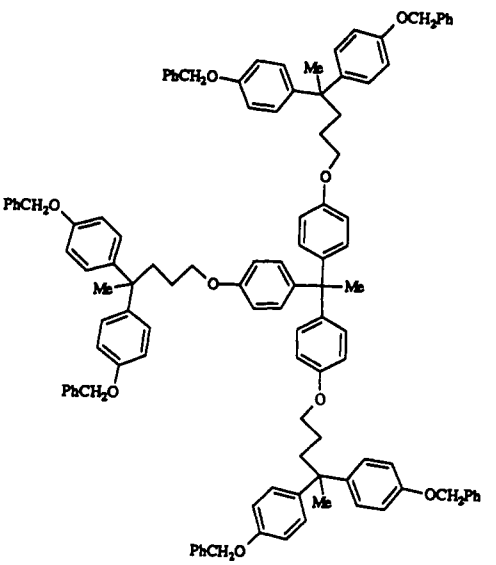


Figure 1. Size exclusion chromatogram for the reaction of **19** and $(HO)_6$-[C] **20** at various times.

Chart I



24



25

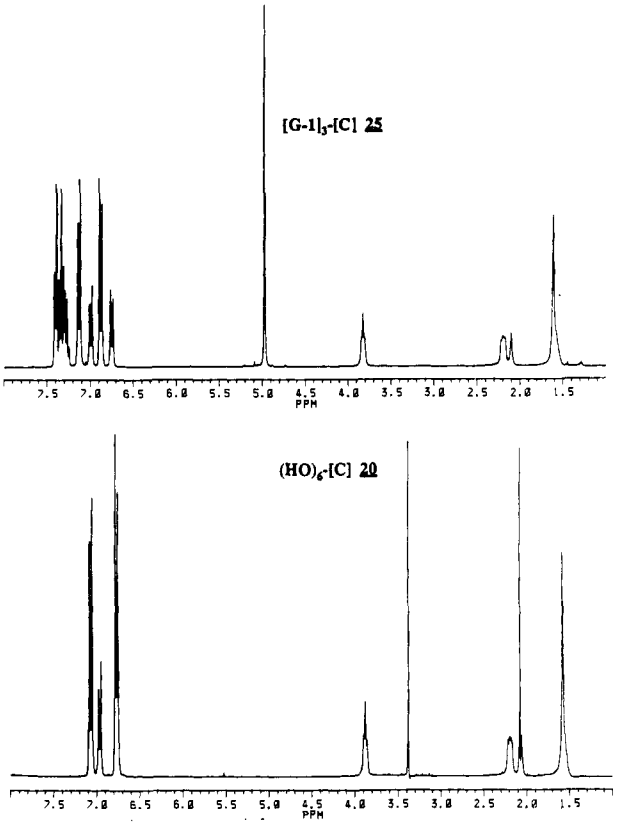


Figure 2. ^1H NMR spectra of $[G\text{-}1]_3$-[C] and $(HO)_6$-[C] compounds **25** and **20**, respectively.

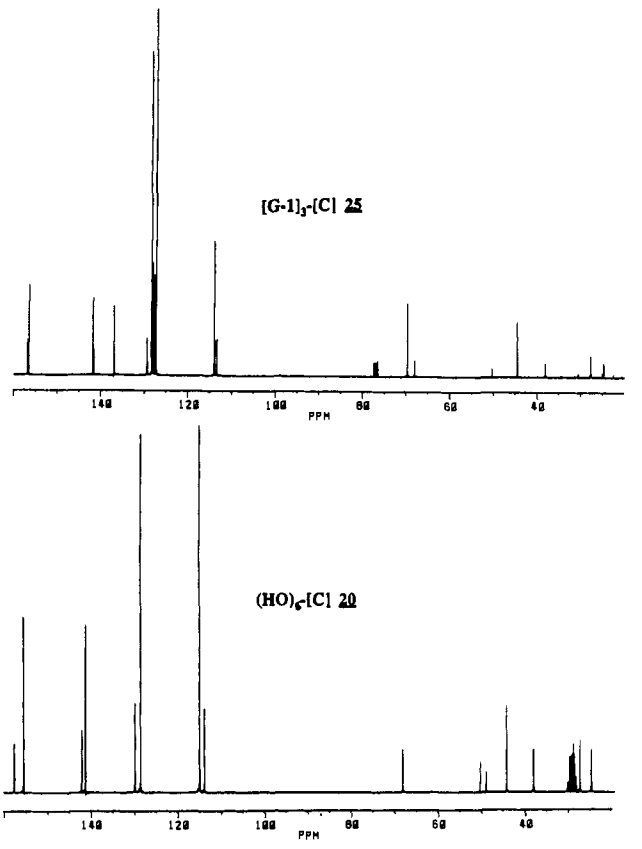


Figure 3. ^{13}C NMR spectra of $[G\text{-}1]_3$-[C] and $(HO)_6$-[C] compounds **25** and **20**, respectively.

fragments. As with the previous convergent growth syntheses, the resonance for the functional group at the focal point was easily observed and distinguished for either the alcohol, bromide, or trifunctional core. The resonance for the CH_2OH group occurred at 3.49–3.60 and 63.11–63.44 ppm in the ^1H and ^{13}C NMR spectra, respectively. Conversely the resonance for the CH_2Br was observed at 3.33–3.40 and 34.57–34.66 ppm, while unique resonances for the trifunctional core **16** occurred at 2.08–2.12, 30.70–30.75, and 50.42–50.50 ppm. The significant differences between these resonances allowed the focal point group to be identified, the dendrimers to be characterized, and their purity to be determined. Comparison of the integration values for these groups to the values for other resonances allowed the generation number to be confirmed.

As discussed above, the removal of the peripheral benzyl groups by hydrogenation was conveniently followed by NMR spectroscopy. Figures 2 and 3 show the ^1H and ^{13}C NMR spectra for the hexabenzylated core **25** and the hexaphenolic core **20**. In both types of spectra, note the complete disappearance of the resonances for the benzyl group at 7.25–7.40 and 5.02 ppm in the ^1H NMR spectra and at 69.77, 127.37, 127.76, 128.18, and 137.01 ppm in the ^{13}C NMR spectra.

The purity of the hypercores was also determined by size exclusion chromatography. Figure 4 shows the composite SEC chromatographs for each of the hypercores (compounds **20**, **18**, and **24** or $(HO)_6$-[C], $(HO)_{12}$-[C], and $(HO)_{24}$-[C], respectively). These have molecular weights[16] in the range from 306 (compound **18**) to 5647 (compound **24** with the formula $C_{377}H_{396}O_{43}$). Only slight broadening and tailing is observed as the hypercores increase in size and molecular weight.

All products were also characterized by infrared spectroscopy, elemental analysis, and for the lower molecular weight products (<2000 amu) mass spectrometry using either EI or FAB ionization.

Characterization of the Dendritic Macromolecules. The dendritic macromolecules obtained from the reaction of the hypercores with the fourth-generation bromide **19** were characterized by standard spectroscopic techniques. Figure 5 shows the ^1H NMR

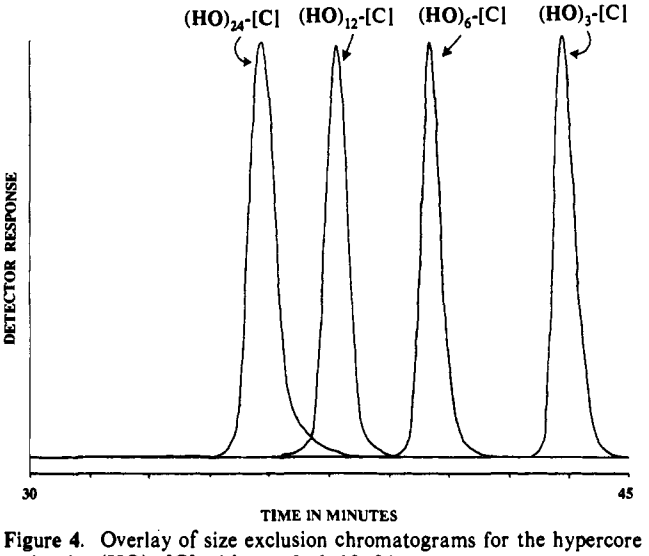


Figure 4. Overlay of size exclusion chromatograms for the hypercore molecules $(HO)_n$-[C] with n = 3, 6, 12, 24.

spectra of the dodecacore **18** and the corresponding alkylated dendrimer $[G\text{-}4]_{12}$-[C] **22**. As expected, the resonance for the phenolic protons at 8.15 ppm disappears completely and the expected resonances for both the hypercore and the dendritic fragment are observed. Integration of the resonances for the hypercore at 3.70, 2.10, and 1.50 ppm and comparison to the values obtained for the methylene protons of the dendritic fragment at 4.80 ppm confirm that there are approximately 12 dendritic fragments attached to the hypercore. The ^{13}C NMR spectra also showed resonances for both the dendritic fragment based on 3,5-dihydroxybenzyl alcohol and the hypercores based on 4,4-bis(4′-hydroxyphenyl)pentanol.

Size exclusion chromatography provided additional information on the purity of the dendritic macromolecules. Figure 6 shows a composite of the SEC traces for $[G\text{-}4]_6$-[C] **21**, $[G\text{-}4]_{12}$-[C] **22**,

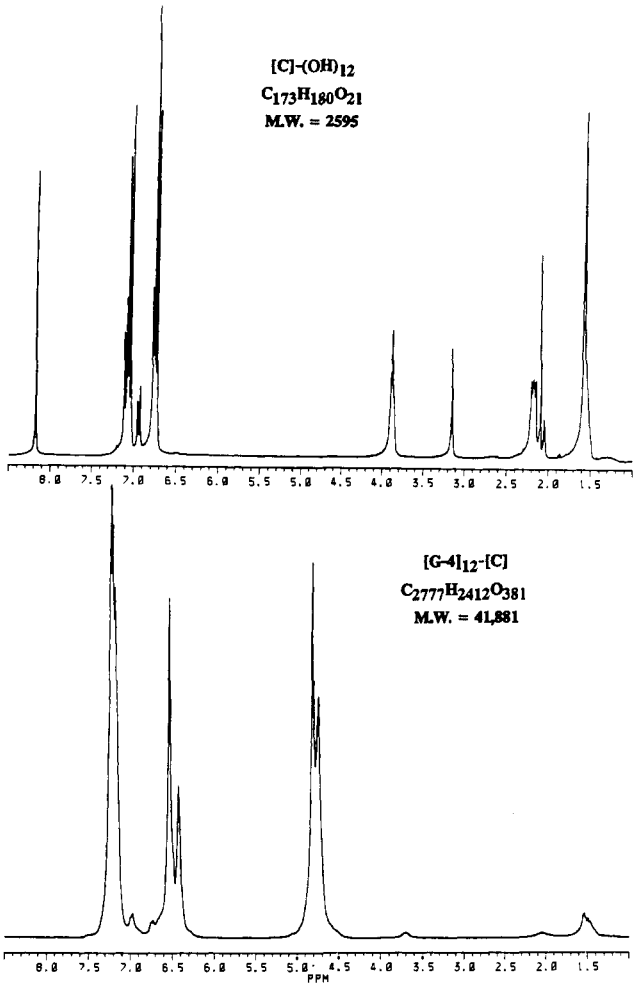


Figure 5. ^{1}H NMR spectra for $(HO)_{12}$-[C] and $[G\text{-}4]_{12}$-[C] compounds **18** and **22**, respectively.

and $[G\text{-}4]_{24}$-[C] **23**. A significant feature of the chromatographs is the presence of a small shoulder at the higher molecular weight side. The percentage of the shoulder increases from ca. 1% for $[G\text{-}4]_6$-[C] **21** to ca. 5% for $[G\text{-}4]_{24}$-[C] **23**. We believe that the shoulder is due to a small amount of C alkylation; the occurrence of C alkylation in similar systems has been noted before.[17] A small amount of C alkylation (ca. 0.25%) for each phenol group would account for the higher molecular weight impurity and for the increase in the percentage of impurity as the number of peripheral phenolic groups increases from six to twenty-four.

Conclusion

We have demonstrated a novel double-stage convergent growth approach that consists of two parts. Part I involves the preparation of essentially monodisperse dendritic macromolecules with a large number of functional groups evenly distributed at the periphery, via the convergent growth approach using 4,4-bis(4′-hydroxyphenyl)pentanol (**6**) as the monomer unit and benzyl ethers as the protecting groups. After removal of the benzyl ether protecting groups, these dendritic macromolecules may be used as cores (hypercores) for further dendritic growth. Part II involves coupling of preformed dendritic fragments, in this case based on 3,5-dihydroxybenzyl alcohol, to the highly functionalized macromolecules (hypercores) of part I. This double-convergent growth approach allows for the preparation of larger dendrimers in less time and with greater ease than the conventional convergent or divergent growth approaches while retaining the advantages of the former approach. An additional advantage of the method is its great versatility that may be used for the preparation of totally new functional globular structures or molecular devices. For example, the hypercore and the outer dendritic layers may be built with use of very different chemistries to provide molecules with

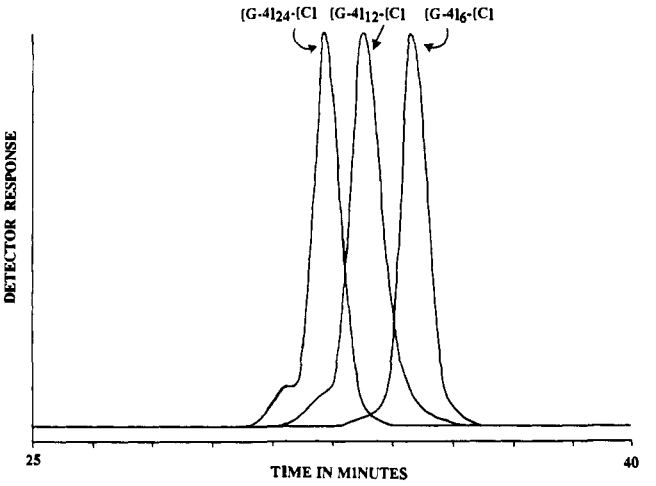


Figure 6. Overlay of size exclusion chromatography traces for the dendritic macromolecules $[G\text{-}4]_n$-[C] obtained by reaction of dendrimer **19** with hypercores $(HO)_n$-[C] with n = 6, 12, 24.

unusual chemical or physical properties. In addition, considerable flexibility can be introduced in the hypercore, thereby reducing the steric problems that may, under certain circumstances, limit the applicability of the convergent growth approach. It may be noted, however, that the use of larger and less compact building blocks in the hypercore *may conceivably* contribute to a minor type of irregularity in the final globular hyperbranched macromolecule. As steric crowding begins to interfere with outward growth in the attachment of dendritic wedges to the hypercore, some inward folding of the dendritic chains toward the less crowded core area may occur. At the present time, we have no evidence to either support or exclude the occurrence of such inward folding. Our current schematic representation of the regular outward growth of these macromolecules may well be somewhat oversimplified, though the overall globular shape is not in question. Characterization of the dendritic fragments, hypercores, and dendritic macromolecules was by standard techniques and proved to be sensitive to impurities and defects. The use of these hypercores in a variety of other applications, such as crosslinking agents, macromonomers, initiating cores, etc., is currently being explored.

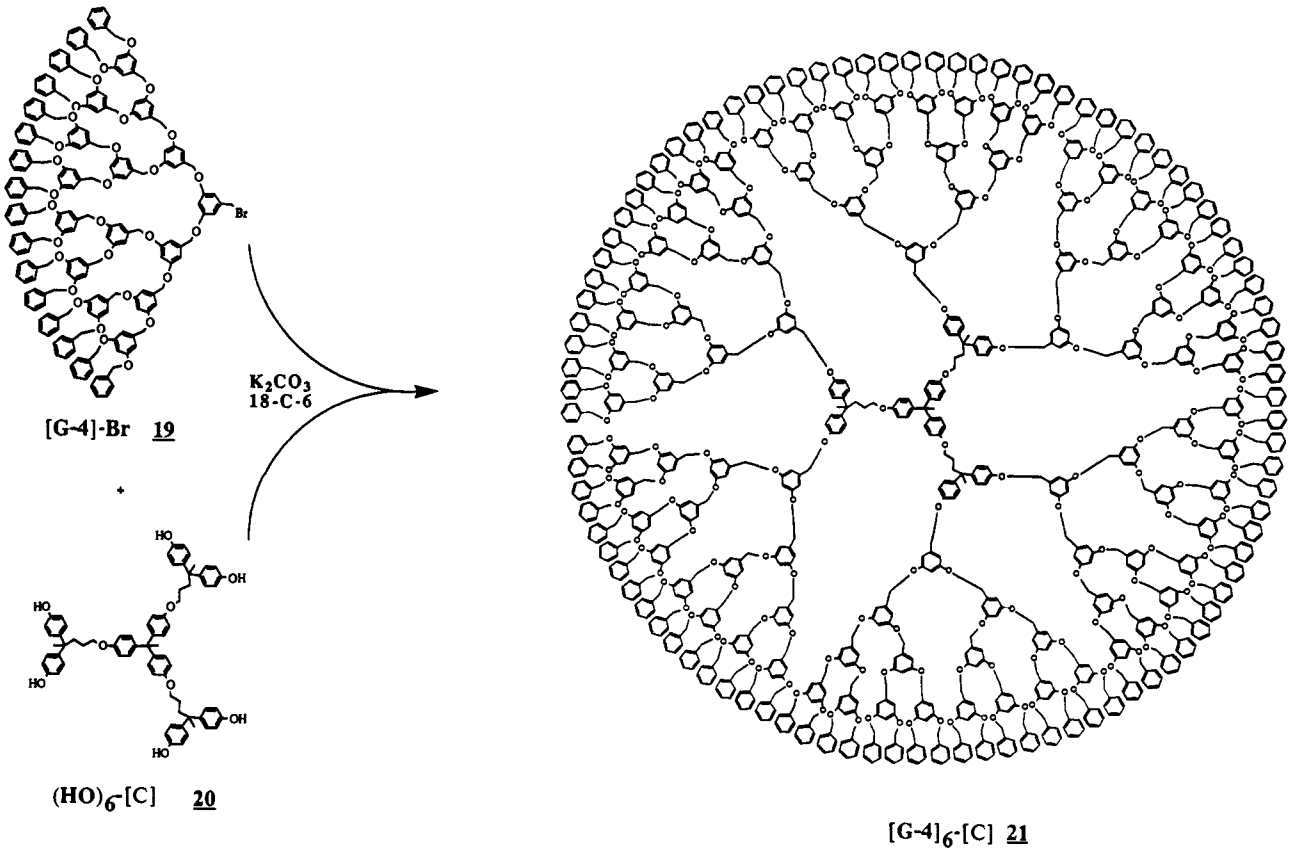
Experimental Section

General Directions. Melting points were determined on a Kofler hot-stage apparatus and are uncorrected. Infrared spectra were recorded on a Nicolet IR/44 spectrophotometer as thin films on NaCl disks. ^{1}H NMR spectra were recorded on solutions in $CDCl_3$ or d_6-acetone on a Bruker WM 300 (300-MHz) spectrometer with use of the solvent proton signal as standard. ^{13}C NMR spectra were recorded at 75 MHz on a Bruker WM300 spectrometer with use of $CDCl_3$ or d_6-acetone as the solvent and the solvent carbon signal as internal standard. Mass spectra were obtained on a Kratos MS890 by using either EI or FAB ionization; the latter were run with use of 3-nitrobenzyl alcohol as the matrix.

Analytical TLC was performed on commercial Merck plates coated with silica gel GF_{254} (0.25-mm-thick). Silica for flash chromatography was Merck Kieselgel 60 (230–400 mesh). Size exclusion chromatography was carried out on an IBM LC/9560 chromatograph connected to a Milton Roy refractoMonitor IV refractive index detector; data analysis was performed by an IBM system 9000 computer. Five 10-μm IBM GPC/SEC columns (300 × 7.7 mm) connected in series in order of decreasing pore size (IBM type B to F) were used with THF as solvent. The following abbreviations are used: Ar, aromatic rings derived from monomer **6**; Ph, aromatic rings derived from benzyl bromide; Ar′, aromatic rings derived from the core molecule **16**; and Ar″, aromatic rings derived from 3,5-dihydroxybenzyl alcohol. Elemental analyses were performed by MHW laboratories, Phoenix, AZ.

General Procedure for Synthesis of Dendritic Alcohols [G-*n*]-OH. A mixture of the dendritic bromide (2.05 equiv), 4,4-bis(4′-hydroxyphenyl)pentanol (**6**) (1.00 equiv), dried potassium carbonate (2.10 equiv), and 18-crown-6 (0.2 equiv) in dry acetone was heated at reflux and stirred vigorously under nitrogen for 48 h. The mixture was cooled, evaporated to dryness under reduced pressure, and partitioned between CH_2Cl_2 and water. The aqueous layer was extracted with CH_2Cl_2 (3×)

Scheme V



and the combined organic layers were dried and evaporated to dryness. The crude product was purified as outlined below to give the next-generation alcohol.

General Procedure for Synthesis of Dendritic Bromides [G-*n*]-Br. To a solution of the appropriate alcohol (1.00 equiv) in the minimum amount of dry tetrahydrofuran were added carbon tetrabromide (1.25 equiv) and triphenylphosphine (1.25 equiv), and stirring was continued at room temp. under nitrogen for 15 min. Water was added and the aqueous layer extracted with CH_2Cl_2 (3×). The combined organic extracts were dried and evaporated to dryness. The crude product was purified as outlined below.

4,4-Bis(4′-hydroxyphenyl)pentanol (6). A solution of methyl 4,4-bis(4′-hydroxyphenyl)valerate (**8**) (20.0 g, 66 mmol) in hexamethyldisilazane (25 mL) and trimethylsilane (1 mL) was heated at reflux under nitrogen for 5 h and then stirred at room temperature for 12 h. The reaction mixture was then evaporated to dryness, redissolved in dry tetrahydrofuran (30 mL), and added dropwise to a stirred suspension of lithium aluminum hydride (3.4 g, 87 mmol) in dry tetrahydrofuran (100 mL) and the mixture heated at reflux for 4 h. After it was cooled, the reaction mixture was hydrolyzed by the slow addition of ammonium chloride (aqueous) followed by concentrated HCl. The reaction mixture was then filtered, the filter cake was washed with tetrahydrofuran, and the combined filtrates were evaporated to dryness. The crude product was purified by flash chromatography eluting with CH_2Cl_2 gradually increasing to 1:1 ether/CH_2Cl_2 to give the alcohol **6**, as a colorless oil: yield 84%; IR 3500–3200, 1610, 1380, and 1170 cm^{-1}; ^{1}H NMR (d_6-acetone) δ 1.26–1.31 (m, 2 H, CH_2), 1.51 (s, 3 H, CH_3), 2.03–2.09 (m, 2 H, CH_2), 3.50 (t, 2 H, CH_2OH), 3.74 (br s, 1 H, CH$_2$OH), 6.68 (d, 4 H, J = 8 Hz, ArH), 7.00 (d, 4 H, J = 8 Hz, ArH), and 8.18 (br s, 2 H, phenolic OH); ^{13}C NMR (d_6-acetone) δ 27.99, 28.73, 38.71, and 44.74 (*C*H$_3$, 2 × *C*H$_2$, *C*CH$_3$), 62.79 (*C*H$_2$OH), 114.99, 128.61, 141.46, and 155.43 (aromatic *C*); mass spectrum (EI) m/z 272. Anal. Calcd for $C_{17}H_{20}O_3$: C, 74.97; H, 7.40. Found: C, 75.15; H, 7.15.

[G-1]-OH 10. To a stirred suspension of lithium aluminum hydide (2.00 g, 51.0 mmol) in dry tetrahydrofuran (25 mL) was added a solution of 4,4-bis[4′-(benzyloxy)phenyl]valeric acid (10.0 g, 21.5 mmol) in dry tetrahydrofuran (50 mL) dropwise under nitrogen. After addition was complete, the reaction mixture was heated at reflux for 2 h. The mixture was cooled and sodium hydroxide (1 N, 10 mL) added, and then this mixture was heated at reflux for an additional 30 min. After it was cooled, the mixture was filtered, the filter cake was washed with tetrahydrofuran, and the combined filtrates were evaporated to dryness. The crude product was purified by flash chromatography eluting with CH_2Cl_2 increasing to 1:19 ether/CH_2Cl_2 to give the alcohol **10** as a colorless oil: yield 95%; IR 3400–3200, 3030, 2950, 1510, 1375, 1250, and 1025 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ 1.39–1.46 (m, 2 H, CH_2), 1.66 (s, 3 H, CH_3), 1.88 (d, 1 H, CH$_2$OH), 2.13–2.19 (m, 2 H, CH_2), 3.60 (t, 2 H, CH_2OH), 5.07 (s, 4 H, PhCH_2O), 6.94 (d, 4 H, J = 8 Hz, ArH), 7.19 (d, 4 H, J = 8 Hz, ArH), and 7.27–7.50 (m, 10 H, PhH); ^{13}C NMR ($CDCl_3$) δ 27.80, 28.10, 37.91, and 44.60 (*C*H$_3$, 2 × *C*H$_2$, *C*CH$_3$), 63.19 (*C*H$_2$OH), 69.83 (*C*H$_2$O), 114.02, 127.41, 127.64, 128.15, 128.43, 137.02, 142.03, and 156.53 (aromatic *C*); mass spectrum (EI) m/z 452. Anal. Calcd for $C_{31}H_{32}O_3$: C, 82.27; H, 7.13. Found: C, 82.15; H, 7.15.

[G-1]-Br 11. This was prepared from [G-1]-OH **10**, and purified by flash chromatography eluting with 1:1 hexane/CH_2Cl_2 increasing to CH_2Cl_2 to give the bromide **11** as a colorless foam: yield 92%; IR 3030, 2950, 1610, 1250, and 1025 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ 1.67 (s, 3 H, CH_3), 1.71–1.78 (m, 2 H, CH_2), 2.23–2.28 (m, 2 H, CH_2), 3.40 (t, 2 H, CH_2Br), 5.09 (s, 4 H, PhCH_2O), 6.96 (d, 4 H, J = 8 Hz, ArH), 7.20 (d, 4 H, J = 8 Hz, ArH), and 7.27–7.50 (m, 10 H, PhH); ^{13}C NMR ($CDCl_3$) δ 27.97, 28.32, 40.54, and 44.57 (*C*H$_3$, 2 × *C*H$_2$, *C*CH$_3$), 34.57 (*C*H$_2$Br), 69.87 (*C*H$_2$O), 114.14, 127.43, 127.83, 128.12, 128.47, 137.04, 141.62, and 156.68 (aromatic *C*); mass spectrum (EI) m/z 514, 516 (ca. 1:1). Anal. Calcd for $C_{31}H_{31}BrO_2$: C, 72.23; H, 6.06. Found: C, 72.36; H, 6.08.

[G-2]-OH 12. This was prepared from [G-1]-Br **11** and the monomer unit **6**, and purified by flash chromatography eluting with CH_2Cl_2 gradually increasing to 1:50 ether/CH_2Cl_2 to give **12** as a colorless foam: yield 89%; IR 3400–3200, 3030, 2950, 1510, 1360, 1250, and 1025 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ 1.27–1.36 (m, 2 H, CH_2), 1.50–1.65 (m, 13 H, CH_3 and CH_2), 2.10–2.21 (m, 6 H, CH_2), 3.49 (t, 2 H, CH_2OH), 4.04 (t, 4 H, J = 7 Hz, ArCH_2O), 4.97 (s, 8 H, PhCH_2O), 6.65 (d, 4 H, J = 11 Hz, ArH), 6.77 (d, 8 H, J = 8 Hz, ArH), 7.06 (d, 4 H, J = 11 Hz, ArH), 7.11 (d, 8 H, J = 8 Hz, ArH), and 7.27–7.46 (m, 20 H, PhH); ^{13}C NMR ($CDCl_3$) δ 24.83, 27.80, 28.01, 37.88, 38.18, 44.47, and 44.61 (*C*H$_3$, *C*H$_2$, and *C*CH$_3$), 63.11 (*C*H$_2$OH), 68.05, 69.83 (*C*H$_2$O), 113.59, 114.01, 127.32, 127.72, 128.03, 128.12, 128.36, 136.96, 141.59, 141.83, 156.50, and 156.64 (aromatic *C*); mass spectrum (FAB) m/z 1140. Anal. Calcd for $C_{79}H_{80}O_7$: C, 83.12; H, 7.06. Found: C, 82.88; H, 7.11.

[G-2]-Br 13. This was prepared from [G-2]-OH **12** and purified by flash chromatography eluting with 2:3 hexane/CH_2Cl_2 gradually increasing to CH_2Cl_2 to give **13** as a colorless foam: yield 92%; IR 3030, 2950, 1510, 1250, and 1025 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ 1.50–1.65 (m, 15 H, CH_3 and CH_2), 2.14–2.24 (m, 6 H, CH_2), 3.34 (t, J = 6 Hz, 2 H,

CH_2Br), 3.87 (t, 4 H, J = 7 Hz, $ArCH_2O$), 5.03 (s, 8 H, $PhCH_2O$), 6.76 (d, 4 H, J = 11 Hz, ArH), 6.89 (d, 8 H, J = 8 Hz, ArH), 7.07 (d, 4 H, J = 11 Hz, ArH), 7.15 (d, 8 H, J = 8 Hz, ArH), and 7.30–7.46 (m, 20 H, PhH); ^{13}C NMR ($CDCl_3$) δ 24.97, 27.93, 28.07, 28.41, 34.66, 38.38, 44.60, and 44.79 (CH_3, CH_2, and CCH_3), 68.27, 69.96 (CH_2O), 113.78, 114.13, 127.51, 127.89, 128.11, 128.27, 128.54, 137.15, 141.33, 142.01, 156.68, and 156.91 (aromatic C); mass spectrum (FAB) m/z 1202, 1204 (ca. 1:1). Anal. Calcd for $C_{79}H_{79}BrO_6$: C, 78.78; H, 6.61. Found: C, 78.85; H, 6.77.

[G-3]-OH 14. This was prepared from [G-2]-Br **13** and the monomer unit **6**, and purified by flash chromatography eluting with CH_2Cl_2 to give **14** as a colorless foam: yield 86%; IR 3350–3200, 3030, 2950, 1510, 1250, and 1025 cm^{-1}; ^1H NMR ($CDCl_3$) δ 1.27–1.36 (m, 2 H, CH_2), 1.50–1.65 (m, 33 H, CH_3 and CH_2), 2.10–2.21 (m, 14 H, CH_2), 3.49 (t, 2 H, J = 6 Hz, CH_2OH), 4.04 (t, 12 H, J = 7 Hz, $ArCH_2O$), 4.97 (s, 16 H, $PhCH_2O$), 6.65 (d, 12 H, J = 11 Hz, ArH), 6.77 (d, 16 H, J = 8 Hz, ArH), 7.06 (d, 12 H, J = 11 Hz, ArH), 7.11 (d, 16 H, J = 8 Hz, ArH), and 7.27–7.46 (m, 40 H, PhH); ^{13}C NMR ($CDCl_3$) δ 24.97, 27.92, 28.28, 38.02, 38.33, 44.64, 44.71, and 44.78 (CH_3, CH_2, and CCH_3), 63.44 (CH_2OH), 68.25, 69.94 (CH_2O), 113.72, 114.13, 127.48, 127.72, 128.05, 128.26, 128.51, 137.15, 141.64, 141.68, 142.01, 156.67, and 156.83 (aromatic C). Anal. Calcd for $C_{175}H_{176}O_{15}$: C, 83.43; H, 7.04. Found: C, 83.38; H, 7.15.

[G-3]-Br 15. This was prepared from [G-3]-OH **14** and purified by flash chromatography eluting with 1:2 hexane/CH_2Cl_2 gradually increasing to CH_2Cl_2 to give **15** as a colorless foam: yield 90%; IR 3030, 2950, 1510, 1250, and 1025 cm^{-1}; ^1H NMR ($CDCl_3$) δ 1.51–1.64 (m, 35 H, CH_3 and CH_2), 2.14–2.24 (m, 14 H, CH_2), 3.33 (t, J = 6 Hz, 2 H, CH_2Br), 3.85 (t, 12 H, J = 7 Hz, $ArCH_2O$), 5.02 (s, 16 H, $PhCH_2O$), 6.74 (d, 12 H, J = 11 Hz, ArH), 6.88 (d, 16 H, J = 8 Hz, ArH), 7.05 (partially obscured d, 12 H, J = 11 Hz, ArH), 7.09 (d, 16 H, J = 8 Hz, ArH), 7.13 (d, 16 H, J = 8 Hz, ArH), and 7.29–7.46 (m, 40 H, PhH); ^{13}C NMR ($CDCl_3$) δ 25.00, 27.95, 28.12, 28.43, 34.66, 38.36, 44.61, 44.75, and 44.81 (CH_3, CH_2, and CCH_3), 68.29, 69.98 (CH_2O), 113.75, 114.15, 127.53, 127.90, 128.12, 128.28, 128.54, 137.17, 141.32, 141.65, 142.04, 156.71, 156.86, and 156.94 (aromatic C). Anal. Calcd for $C_{175}H_{175}BrO_{14}$: C, 81.40; H, 6.83. Found: C, 81.39; H, 6.91.

$[G\text{-}1]_3$-[C] 21. A mixture of [G-1]-Br **11**, (10.0 g, 19.4 mmol), 1,1,1-tris(4′-hydroxyphenyl)ethane (**16**) (1.98 g, 6.47 mmol), potassium carbonate (8.10 g, 60.0 mmol), and 18-crown-6 (800 mg, 3.0 mmol) in dry acetone (200 mL) was heated at reflux for 24 h. After it was cooled, the mixture was evaporated to dryness and partitioned between water (200 mL) and CH_2Cl_2 (200 mL). The water layer was extracted with CH_2Cl_2 (2 × 200 mL), and the combined extracts were dried and evaporated to dryness. The crude product was purified by flash chromatography eluting with 1:1 hexane/CH_2Cl_2 increasing to CH_2Cl_2 to give **21** as a colorless foam: yield 79%; IR 3030, 1610, and 1170 cm^{-1}; ^1H NMR ($CDCl_3$) δ 1.50–1.63 (m, 15 H, CH_3 and CH_2), 2.08 (s, 3 H, CH_3 from core), 2.15–2.18 (m, 6 H, CH_2), 3.80 (t, 6 H, CH_2O), 5.00 (s, 12 H, $PhCH_2O$), 6.76 (d, 6 H, J = 8 Hz, Ar′H), 6.86 (d, 12 H, J = 8 Hz, ArH), 6.97 (d, 6 H, J = 8 Hz, Ar′H), 7.11 (d, 12 H, J = 8 Hz, ArH), and 7.27–7.43 (m, 30 H, PhH); ^{13}C NMR ($CDCl_3$) δ 24.87, 27.85, 38.22, and 44.65 (CH_3, 2 × CH_2, CCH_3), 30.70 (CH_3 from core), 50.42 (CCH_3 from core), 68.10 and 69.77 (CH_2O), 113.44, 114.04, 127.37, 127.76, 128.18, 128.41, 129.44, 137.01, 141.56, 141.86, 156.57, and 156.86 (aromatic C); mass spectrum (FAB) m/z 1608. Anal. Calcd for $C_{113}H_{108}O_9$: C, 84.30; H, 6.76. Found: C, 83.90; H, 6.95.

$(HO)_6$-[C] 20. A mixture of $[G\text{-}1]_3$-[C] **21** (4.80 g, 2.99 mmol), 10% Pd/C (250 mg), and distilled cyclohexane (25 mL) in dry tetrahydrofuran (50 mL) was heated at reflux under nitrogen for 36 h. The reaction mixture was filtered and evaporated to dryness. Evaluation by ^1H NMR spectroscopy indicated ca. 80% reaction; the reaction was then repeated two times under the same conditions as above until there were no benzyl groups present, as determined by ^1H NMR spectroscopy. After filtration and evaporation, the crude product was purified by flash chromatography eluting with CH_2Cl_2 gradually increasing to 1:9 MeOH/CH_2Cl_2 to give hexaphenol **20** as a colorless glass: yield 66%; IR 3400–3200, 1610, 1375, and 1170 cm^{-1}; ^1H NMR (d_6-acetone) δ 1.50–1.63 (m, 15 H, CH_3 and CH_2), 2.06 (s, 3 H, CH_3 from core), 2.15–2.20 (m, 6 H, CH_2), 3.86 (t, 6 H, CH_2O), 6.75 (d, 18 H, J = 8 Hz, Ar- and Ar′H), 6.95 (d, 6 H, J = 8 Hz, Ar′H), 7.05 (d, 12 H, J = 8 Hz, ArH), and 8.10 (br s, 6 H, ArOH); ^{13}C NMR (d_6-acetone) δ 25.37, 27.96, 30.25, 38.60, and 44.74 (CH_3, 2 × CH_2, CCH_3), 30.73 (CH_3 from core), 49.44 and 50.77 (each CCH_3), 68.47 (CH_2O), 113.94, 115.04, 128.56, 129.83, 141.15, 141.99, 155.33, and 157.48 (aromatic C); mass spectrum (FAB) m/z 1068.

$[G\text{-}2]_3$-[C] 17. A mixture of [G-2]-Br **13** (1.25 g, 1.24 mmol), 1,1,1-tris(4′-hydroxyphenyl)ethane (**16**) (123 mg, 0.40 mmol), potassium carbonate (420 mg, 3.00 mmol), and 18-crown-6 (80 mg, 0.30 mmol) was heated at reflux in dry acetone (150 mL) for 24 h. After it was cooled, the mixture was evaporated to dryness and partitioned between water (200 mL) and CH_2Cl_2 (200 mL). The water layer was extracted with CH_2Cl_2 (2 × 200 mL), and the combined extracts were dried and evaporated to dryness. The crude product was purified by flash chromatography eluting with 1:1 hexane/CH_2Cl_2 increasing to CH_2Cl_2 to give **17** as a colorless foam: yield 74%; IR 3010, 1610, and 1170 cm^{-1}; ^1H NMR ($CDCl_3$) δ 1.48–1.64 (m, 45 H, CH_3 and CH_2), 2.12 (s, 3 H, CH_3 from core), 2.18–2.22 (m, 18 H, CH_2), 3.84 (t, 18 H, CH_2OH), 5.03 (s, 24 H, $PhCH_2O$), 6.78 (d, 18 H, J = 8 Hz, Ar- and Ar′H), 6.90 (d, 24 H, J = 8 Hz, ArH), 7.00 (d, 6 H, J = 8 Hz, Ar′H), 7.13 (m, 36 H, ArH), and 7.29–7.45 (m, 60 H, PhH); ^{13}C NMR ($CDCl_3$) δ 24.98, 27.90, 38.34, 44.71, and 44.65 (CH_3, and CH_2), 30.75 (CH_3 from core), 50.50 (CCH_3 from core), 68.23 and 69.92 (CH_2O), 113.55, 113.78, 114.17, 127.37, 127.75, 128.20, 128.42, 129.48, 137.18, 141.58, 141.65, 141.96, 156.70, 156.85, and 156.97 (aromatic C). Anal. Calcd for $C_{257}H_{252}O_{21}$: C, 83.95; H, 6.91. Found: C, 83.73; H, 6.85.

$(HO)_{12}$-[C] 18. A mixture of $[G\text{-}2]_3$-[C] **17** (600 mg, 0.16 mmol), 10% Pd/C (50 mg), and distilled cyclohexene (2.5 mL) in dry tetrahydrofuran (15 mL) was heated at reflux under nitrogen for 36 h. The reaction mixture was filtered and evaporated to dryness. The reaction was then repeated two times under the same conditions as above until there were no benzyl groups present, as determined by ^1H NMR spectroscopy. After filtration and evaporation, the crude product was purified by flash chromatography eluting with CH_2Cl_2 gradually increasing to 1:9 MeOH/CH_2Cl_2 to give the dodecaphenol **18** as a colorless glass: yield 54%, IR 3500–3200, 1610, 1380, 1270, and 1170 cm^{-1}; ^1H NMR (d_6-acetone) δ 1.50–1.64 (m, 45 H, CH_3 and CH_2), 2.08 (s, 3 H, CH_3 from core), 2.15–2.20 (m, 18 H, CH_2), 3.87 (m, 18 H, CH_2O), 6.71–6.75 (m, 42 H, Ar- and Ar′H), 6.93 (A of ABq, 6 H, J = 8 Hz, Ar′H), 7.03–7.08 (m, 36 H, ArH), and 8.13 (s, 12 H, ArOH); ^{13}C NMR (d_6-acetone) δ 25.75, 25.82, 28.30, 28.37, 30.57, 38.90, 45.18, and 45.30 (CH_3, and CH_2), 31.92 (CH_3 from core), 49.70, and 51.22 (each CCH_3), 68.90 (CH_2O), 114.42, 114.59, 115.35, 115.44, 128.83, 128.97, 130.25, 141.55, 142.39, 142.43, 155.86, 157.81, and 157.90 (aromatic C). Anal. Calcd for $C_{173}H_{180}O_{21}$: C, 80.06; H, 6.99. Found: C, 80.17; H, 7.07.

$[G\text{-}3]_3$-[C] 23. A mixture of [G-3]-Br **15** (1.50 g, 0.91 mmol), 1,1,1-tris(4′-hydroxyphenyl)ethane (**16**) (92 mg, 0.30 mmol), potassium carbonate (420 mg, 3.00 mmol), and 18-crown-6 (80 mg, 0.30 mmol) in dry acetone (200 mL) was heated at reflux for 24 h. After it was cooled, the mixture was evaporated to dryness and partitioned between water (200 mL) and CH_2Cl_2 (200 mL). The water layer was extracted with CH_2Cl_2 (2 × 200 mL), and the combined extracts were dried and evaporated to dryness. The crude product was purified by flash chromatography eluting with 1:1 hexane/CH_2Cl_2 increasing to CH_2Cl_2 to give **23** as a colorless foam: yield 81%; IR 3010, 2950, 1610, and 1170 cm^{-1}; ^1H NMR ($CDCl_3$) δ 1.47–1.65 (m, 105 H, CH_3 and CH_2), 2.09 (s, 3 H, CH_3 from core), 2.16–2.23 (m, 42 H, CH_2), 3.82 (m, 42 H, CH_2O), 5.00 (s, 48 H, $PhCH_2O$), 6.71 and 6.80 (each d, 90 H, J = 8 Hz, Ar- and Ar′H), 6.94 (d, 6 H, J = 8 Hz, Ar′H), 7.04–7.10 (m, 84 H, ArH), and 7.29–7.45 (m, 120 H, PhH); ^{13}C NMR ($CDCl_3$) δ 24.89, 27.86, 38.24, 44.62, and 44.67 (CH_3, and CH_2), 30.72 (CH_3 from core), 50.43 (CCH_3 from core), 68.12 and 69.79 (CH_2O), 113.45, 113.66, 114.06, 127.37, 127.77, 128.15, 128.42, 129.45, 137.06, 141.53, 141.89, 156.58, 156.74, and 156.88 (aromatic C). Anal. Calcd for $C_{545}H_{540}O_{45}$: C, 83.81; H, 6.97. Found: C, 83.86; H, 6.74.

$(HO)_{24}$-[C] 24. A mixture of $[G\text{-}3]_3$-[C] **23** (550 mg, 0.071 mmol), 10% Pd/C (30 mg), and distilled cyclohexene (1.0 mL) in dry tetrahydrofuran (10 mL) was heated at reflux under nitrogen for 36 h. The reaction mixture was filtered and evaporated to dryness. The reaction was then repeated three times under the same conditions as above until there were no benzyl groups present, as determined by ^1H NMR spectroscopy. After filtration and evaporation, the crude product was purified by flash chromatography eluting with CH_2Cl_2 gradually increasing to 1:9 MeOH/CH_2Cl_2 to give **23** as a colorless glass: yield 55%; IR 3500–3200, 1610, 1365, 1270, and 1170 cm^{-1}; ^1H NMR (d_6-acetone) δ 1.48–1.67 (m, 105 H, CH_3 and CH_2), 2.05 (s, 3 H, CH_3 from core), 2.15–2.21 (m, 42 H, CH_2), 3.84 (m, 42 H, CH_2OH), 6.71–6.76 (m, 90 H, Ar- and Ar′H), 6.92 (A of ABq, 6 H, J = 8 Hz, Ar′H), 7.02–7.08 (m, 84 H, Ar′H), 8.14 (s, 24 H, ArOH); ^{13}C NMR (d_6-acetone) δ 25.53, 28.09, 38.61, 38.76, 44.88, and 45.00 (CH_3, and CH_2), 30.92 (CH_3 from core), 50.93, and 51.00 (each CCH_3), 68.59 (CH_2O), 114.29, 115.06, 115.15, 128.63, 128.69, 129.96, 141.27, 142.08, 142.11, 155.45, 155.55, 157.45, and 157.50 (aromatic C). Anal. Calcd for $C_{377}H_{396}O_{45}$: C, 80.18; H, 7.07. Found: C, 79.85; H, 7.05.

$[G\text{-}4]_6$-[C] 21. A mixture of [G-4]-Br **19** (1.50 g, 0.45 mmol), $(HO)_6$-[C] **20** (73.5 mg, 0.069 mmol), potassium carbonate (840 mg, 6.00 mmol), and 18-crown-6 (80 mg, 0.30 mmol) was heated at reflux in dry acetone (150 mL) for 96 h. After it was cooled, the mixture was evaporated to dryness and partitioned between water (200 mL) and CH_2Cl_2 (200 mL). The water layer was extracted with CH_2Cl_2 (2 × 200 mL), and the combined extracts were dried and evaporated to dryness. The

crude product was purified by flash chromatography eluting with 1:1 hexane/CH_2Cl_2 increasing to CH_2Cl_2 and then to 1:19 ether/CH_2Cl_2 followed by fractional precipitation from CH_2Cl_2 into 1:3 propan-2-ol/acetone to give **21** as a colorless foam: yield 58%; IR 1600, 1470, 1360, and 1170 cm^{-1}; ^1H NMR ($CDCl_3$) δ 1.48–1.64 (m, 15 H, CH_3 and CH_2), 2.07 (s, 3 H, CH_3), 2.12–2.17 (m, 6 H, CH_2), 3.78 (br s, 6 H, CH_2O from core), 4.85 and 4.93 (each br s, 372 H, $PhCH_2O$), 6.36–6.69 (m, 276 H, Ar'- and Ar''H), 6.82 and 6.95 (ABq, 24 H, J = 8 Hz, ArH), 7.06 (B of ABq, 6 H, J = 8 Hz, Ar'H), and 7.26–7.35 (m, 480 H, PhH); ^{13}C NMR ($CDCl_3$) δ 26.83, 27.90, and 44.67 (CH_3, and CH_2), 31.66 (CH_3), 50.09 and 53.71 (CCH_3), 69.81 and 69.91 (CH_2O), 101.48, 106.28, 113.44, 114.07, 127.45, 127.88, 128.45, 129.49, 136.70, 139.15, 139.50, 141.58, 142.03, 156.54, 156.96, 159.94, and 160.02 (aromatic C). Anal. Calcd for $C_{1373}H_{1188}O_{189}$: C, 79.62; H, 5.78. Found: C, 79.49; H, 5.93.

[G-4]$_{12}$-[C] 22. A mixture of [G-4]-Br **19** (1.56 g, 0.46 mmol), $(HO)_{12}$-[C] **18** (80 mg, 0.031 mmol), potassium carbonate (300 mg, 2.2 mmol), and 18-crown-6 (20 mg, 0.08 mmol) was heated at reflux in dry acetone (150 mL) for 96 h. After it was cooled, the mixture was evaporated to dryness and partitioned between water (200 mL) and CH_2Cl_2 (200 mL). The water layer was extracted with CH_2Cl_2 (2 × 200 mL), and the combined extracts were dried and evaporated to dryness. The crude product was purified by flash chromatography eluting with CH_2Cl_2 followed by fractional precipitation from CH_2Cl_2 into 1:3 propan-2-ol/acetone to give **22** as a colorless foam: yield 51%; IR 1600, 1470, 1360, and 1170 cm^{-1}; ^1H NMR ($CDCl_3$) δ 1.45–1.70 (m, 45 H, CH_3 and CH_2), 2.00–2.15 (m, 21 H, CH_2 and CH_3), 3.72–3.78 (br s, 18 H, CH_2O from core), 4.84 and 4.91 (each br s, 744 H, $PhCH_2O$), 6.30–6.70 (m, 576 H, Ar'- and Ar''H), 6.80–6.96 (m, 48 H, Ar- and Ar'H), and 7.20–7.40 (m, 960 H, PhH); ^{13}C NMR ($CDCl_3$) δ 26.95, 29.10, 44.51, 53.54 (aliphatic C, some peaks too small to observe), 69.92 (CH_2O), 101.51, 106.31, 113.49, 127.47, 127.88, 128.48, 129.49, 136.73, 139.18, 142.33, 156.76, 159.96, and 160.05 (aromatic C). Anal. Calcd for $C_{2777}H_{2412}O_{381}$: C, 79.64; H, 5.80. Found: C, 79.42; H, 5.82.

[G-4]$_{24}$-[C] 22. A mixture of [G-4]-Br **19** (1.486 g, 0.44 mmol), $(HO)_{24}$-[C] **24** (80 mg, 0.014 mmol), potassium carbonate (300 mg, 2.2 mmol), and 18-crown-6 (20 mg, 0.08 mmol) was heated at reflux in dry acetone (150 mL) for 96 h. After it was cooled, the mixture was evaporated to dryness and partitioned between water (200 mL) and CH_2Cl_2 (200 mL). The water layer was extracted with CH_2Cl_2 (2 × 200 mL), and the combined extracts were dried and evaporated to dryness. The crude product was purified by flash chromatography eluting with CH_2Cl_2 increasing to 1:19 ether/CH_2Cl_2 followed by fractional precipitation from CH_2Cl_2 into 1:19 propan-2-ol/acetone to give **22** as a colorless foam: yield 61%; IR 1600, 1470, 1360, and 1170 cm^{-1}; ^1H NMR ($CDCl_3$) δ 1.45–1.85 (m, 105 H, CH_3 and CH_2), 2.00–2.20 (m, 45 H, CH_2 and CH_3), 3.70–3.82 (br s, 42 H, CH_2O), 4.80–5.00 (m, 1488 H, $PhCH_2O$), 6.40–6.75 (m, 1080 H, Ar''H), 6.90–7.05 (m, 180 H, Ar- and Ar'H), and 7.25–7.50 (m, 1920 H, PhH); ^{13}C NMR ($CDCl_3$) δ 29.10, 44.51, 53.54 (aliphatic C, some peaks too small to observe), 69.80 (CH_2O), 101.54, 106.47, 127.41, 127.78, 128.43, 136.71, 142.13, 159.90, and 160.10 (aromatic C). Anal. Calcd for $C_{5585}H_{4860}O_{765}$: C, 79.65; H, 5.82. Found: C, 79.45; H, 6.03.

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Photoreactivity of Some α-Arylvinyl Bromides in Acetic Acid. Selectivity toward Bromide versus Acetate Ions as a Mechanistic Probe

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Abstract: The photochemical reactions of four α-anisyl-β,β-diarylvinyl bromides (**1a–1d**), three α-phenyl-β,β-diarylvinyl bromides (**1e–1g**), and 9-(α-bromo-*p*-methoxybenzylidene)anthrone (**2**) in acetic acid in the presence of sodium acetate and tetraethylammonium bromide (labeled with ^{82}Br) have been studied quantitatively. Bromide exchange, acetate formation, E/Z isomerization, an anisyl 1,2-shift, stilbene-type cyclization to phenanthrenes, reductive debromination, and oxidation are observed as primary pathways. For all compounds **1**, nucleophilic substitution, accompanied by E/Z isomerization in both starting material and product with **1b,c** and **1f,g** and an anisyl 1,2-shift in **1e** but not in **1f,g**, is quite efficient and by far the most important process. (Quantum yields range from 0.1 to 0.3 as compared to 0.01–0.02 for cyclization and 0.001–0.01 for reduction). The α-anisylvinyl bromide **2** is virtually inert for photosubstitution. The selectivity constants toward bromide and acetate ions, corrected for their temperature dependence, the amounts of E/Z isomerized starting material and product, the occurrence or nonoccurrence of an anisyl 1,2-shift, and the nature of the capturing nucleophile in the acetolysis are all in quantitative agreement with the corresponding data for the thermal reactions of **1** in the same medium. The results strongly support a mechanism for the nucleophilic vinylic photosubstitution reactions that involves the generation of a product-forming intermediate, which is exactly the same as the intermediate formed in the thermal reaction, a "cold" (thermally relaxed) linear free vinyl cation.

Introduction

Interest in the photochemical behavior of vinyl halides has surged since it was discovered[1] that, upon irradiation of such compounds in appropriate media, nucleophilic substitution and rearrangement products are formed in addition to reductive dehalogenation products.[2-7] A nucleophilic vinylic photosubstitution

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