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# Synthesis and Retrostructural Analysis of Libraries of $AB_3$ and Constitutional Isomeric $AB_2$ Phenylpropyl Ether-Based Supramolecular Dendrimers

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***Abstract:*** We report the synthesis of methyl esters of 3-(4-hydroxyphenyl)propionic, 3-(3,4-dihydroxyphenyl)-propionic, 3-(3,5-dihydroxyphenyl)propionic, and 3-(3,4,5-trihydroxyphenyl)propionic acids and their use in a convergent iterative strategy to prepare up to four generations of three libraries, one of 3,4,5- and two of constitutional isomeric 3,4- and 3,5-substituted 3-phenylpropyl dendrons. Each library contains 3-[3,4,5-tris(dodecyl-1-oxy)phenyl]propyl-, 3-[3,4-bis(dodecyl-1-oxy)phenyl]propyl-, 3-{3,4-bis[3-(4-dodecyl-1-oxyphenyl)propyl-1-oxy]phenyl}propyl-, and 3-{3,4,5-tris[3-(4-dodecyl-1-oxyphenyl)propyl-1-oxy]phenyl}propyl ether first-generation dendrons on their periphery and $-CO_2CH_3$, $-COOH$, and $-CH_2OH$ groups at their apex. Regardless of their generation number and their periphery, internal, and apex structures, these dendrons self-assemble into supramolecular dendrimers that self-organize into all periodic and quasi-periodic assemblies encountered previously and in several unencountered with architecturally related benzyl ether-based supramolecular dendrimers. A variety of porous columnar lattices that were previously obtained only from dendritic dipeptides and hollow supramolecular spheres were also discovered from these building blocks. The more flexible and less compact 3-phenylpropyl ether repeat units are stable under acidic conditions, facilitate a simpler synthetic strategy, provide faster dynamics of self-assembly into higher-order supramolecular structures of larger dimensions, exhibit lower transition temperatures than the corresponding benzyl ether homologues, and demonstrate the generality of the self-assembly concept based on amphiphilic dendrons.

## Introduction

Dendrimers and dendrons[1] synthesized by divergent[2] and convergent[3] iterative methods provide some of the most powerful monodisperse architectural motifs currently explored at the interface between chemistry, biology, physics, medicine, and nanoscience.[4] Self-assembling dendrons that provide supramolecular dendrimers with the structural perfection that allows self-organization in lattices[5] are generated from dendrons based on anisotropic mesogenic repeat units,[6a−f,r] mesogenic dendrons, and dendrimers,[6g,k] from conventional dendrimers functionalized with mesogenic groups on their periphery,[6h,j] from amphiphilic dendrons based on benzyl ether units,[7−11] and from other amphiphilic dendrons,[12] as well as from polymers dendronized with self-assembling dendrons.[13,14] Several periodic[7d,10,11a,15] and quasi-periodic[11b] assemblies that were not previously encountered in organic or biological molecules have been discovered with the aid of self-assembling dendrons. Benzyl ether-based self-assembling dendrons functionalized at their apex are currently used to investigate the structural origin of functions and to create functions, according to biological principles, via their 3D tertiary and quatenary structures.[15] Self-

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assembling benzyl ether-based dendrons have limited stability under acidic conditions,[7d] and therefore, their accelerated synthesis requires the preparation of $AB_n$ ($n = 1-3$) benzyl chlorides from the corresponding benzyl alcohols and $SOCl_2$ followed by their subsequent Williamson etherification in the presence of the expensive 2,6-di-*tert*-butylpyridine or 2,6-di-*tert*-butyl-4-methylpyridine proton traps.[7d,16]

This article addresses one of the most fundamental questions of the self-assembling benzyl ether dendrons. Is the benzyl ether repeat unit that exhibits only two conformers (trans and gauche) a structural requirement for the design of self-assembling amphiphilic dendrons employed in the construction of functional supramolecular architectures exhibiting 3D internal order, or are the repeat units that allow more than two conformers sufficient for this self-assembly process?[15] To answer this question, the number of methylene groups was increased from one in benzyl ether-based building blocks to three. This led to the design and synthesis of the homologous series of $AB_n$ ($n =$ 1, 2, 3) 3-phenylpropyl building blocks. This selection was based on the hypothesis that the all *trans*-benzyl ether and phenylpropyl ether dendrimers can adopt closely related conformations. This article reports the synthesis of three libraries of 3-phenylpropyl ether dendrons and the structural and the retrostructural analysis of their supramolecular dendrimers[8b,9,15] and compares their self-assembly with that of the homologous libraries of self-assembling benzyl ether dendrons.[8b]

## Results and Discussion

**Synthesis of Dendritic Building Blocks.** 4-Hydroxy, 3,4-dihydroxy, 3,5-dihydroxy, and 3,4,5-trihydroxy-substituted methyl 3-(phenyl)propionate building blocks are most conveniently accessible by the catalytic reduction of the benzyl ether protected or unprotected hydroxy-substituted methyl or ethyl cinnamates. The precursor cinnamic acid derivatives are synthesized by the Wittig reaction of the benzyl ether protected or unprotected hydroxy benzaldehydes[17] or by the Knoevenagel[18] condensation of the same derivatives with malonic acid followed by esterification.[19] Alternatively, the 4-hydroxy-substituted 3-phenylpropionates can be synthesized from their protected 4-hydroxy-substituted benzyl chloride by the malonic ester synthesis.[20] After considering the methods available in the literature, we

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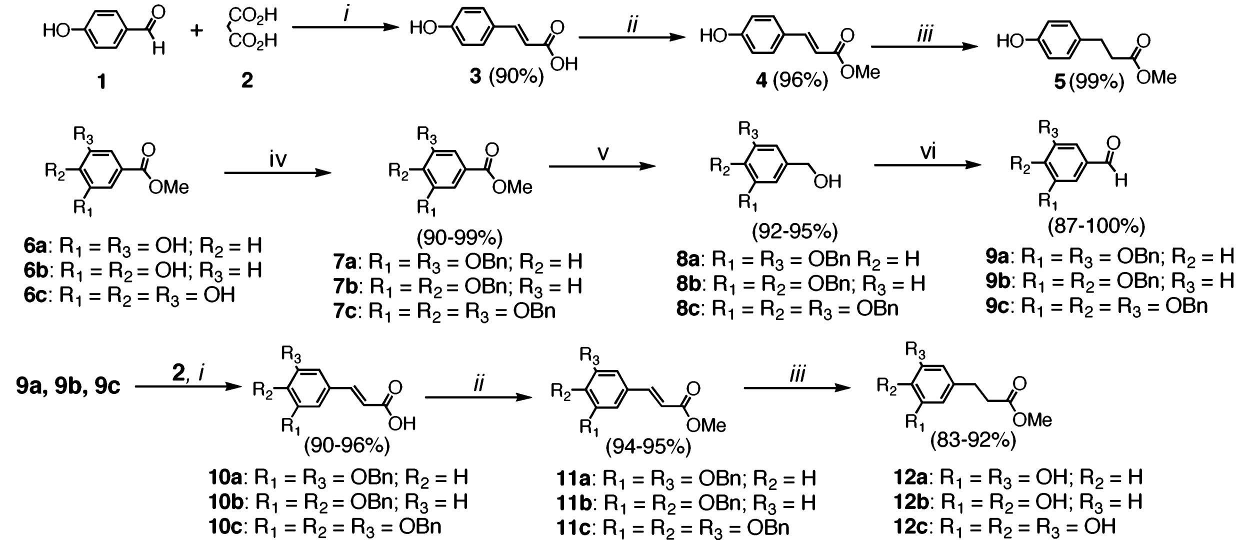
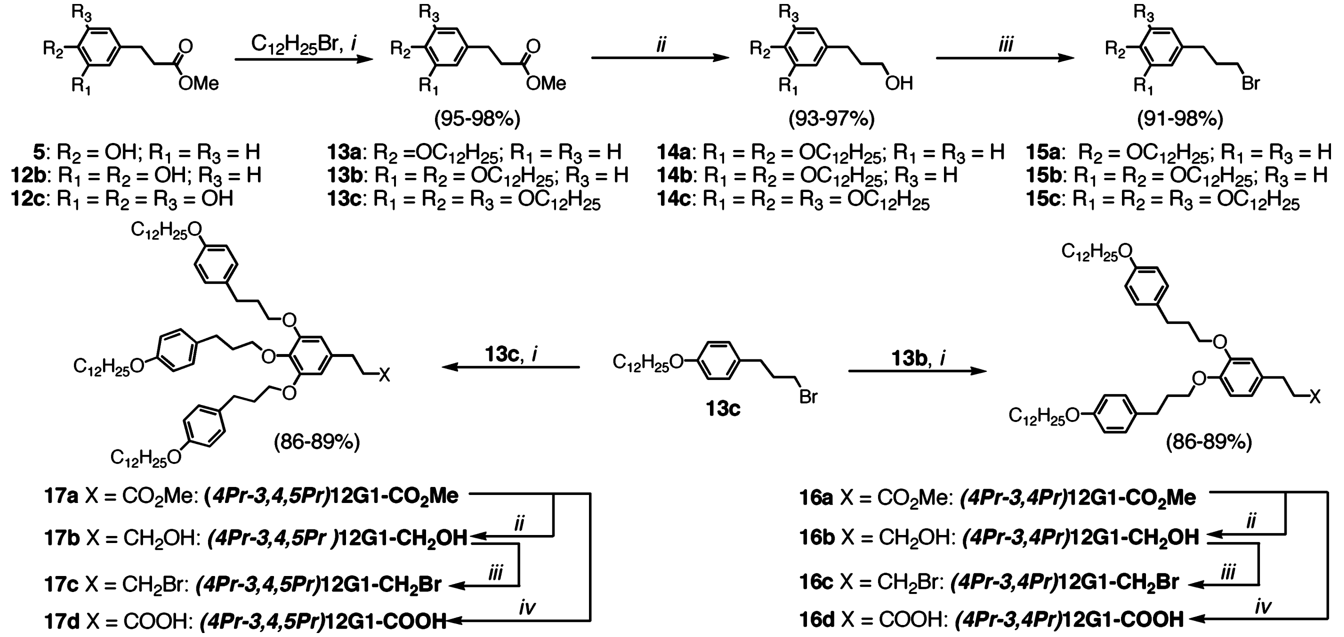
*Scheme 1.* Synthesis of the First-Generation Dendritic Building Blocks[a]



[a] Reagents and conditions: (i) morpholine, AcOH, reflux; (ii) $H_2SO_4$ cat./MeOH, reflux; (iii) $H_2$, Pd/C, EtOH; (iv) BnCl, DMF, 80 °C; (v) $LiAlH_4$, THF; (vi) PCC, $CH_2Cl_2$, 1 h.

*Scheme 2.* Synthesis of the First-Generation Dendrons[a]



[a] Reagents and conditions: (i) $K_2CO_3$, DMF, 80 °C; (ii) $LiAlH_4$, THF (95−98%); (iii) $CBr_4$, $PPh_3$, $CH_2Cl_2$ (90−98%); (iv) 1. KOH, THF/EtOH; 2. $H_2SO_4$ 1 M (88−90%).

developed the strategy outlined in Scheme 1 for the synthesis of the required building blocks. Due to their unsatisfactory purity and high price, the commercially available 4-hydroxy and 3,4-dihydroxy 3-phenylpropionic acids were also synthesized by this method. The strategy outlined in Scheme 1 represents a modified and improved procedure of a previously reported method.[19d]

The synthesis of **5** does not involve protective groups since the inexpensive **1** is commercially available in satisfactory purity. The preparation of **12a**, **12b**, and **12c** started from the commercial **6a**, **6b**, and **6c** that were used as building blocks for the synthesis of self-assembling dendritic benzyl ethers.[7d] Their hydroxy groups were protected as benzyl ethers. Reduction of **7a**, **7b**, and **7c** with $LiAlH_4$ produced **8a**, **8b**, and **8c**. Oxidation of **8a**, **8b**, and **8c** with PCC[21] and the Knoevenagel condensation of resulting **9a**, **9b**, and **9c** with malonic acid produced **10a**, **10b**, and **10c**, which were esterified under acidic conditions to yield **11a**, **11b**, and **11c**. Catalytic hydrogenation/hydrogenolysis of **11a**, **11b**, and **11c** with Pd/C in ethanol cleaved their benzyl ether protective groups and simultaneously

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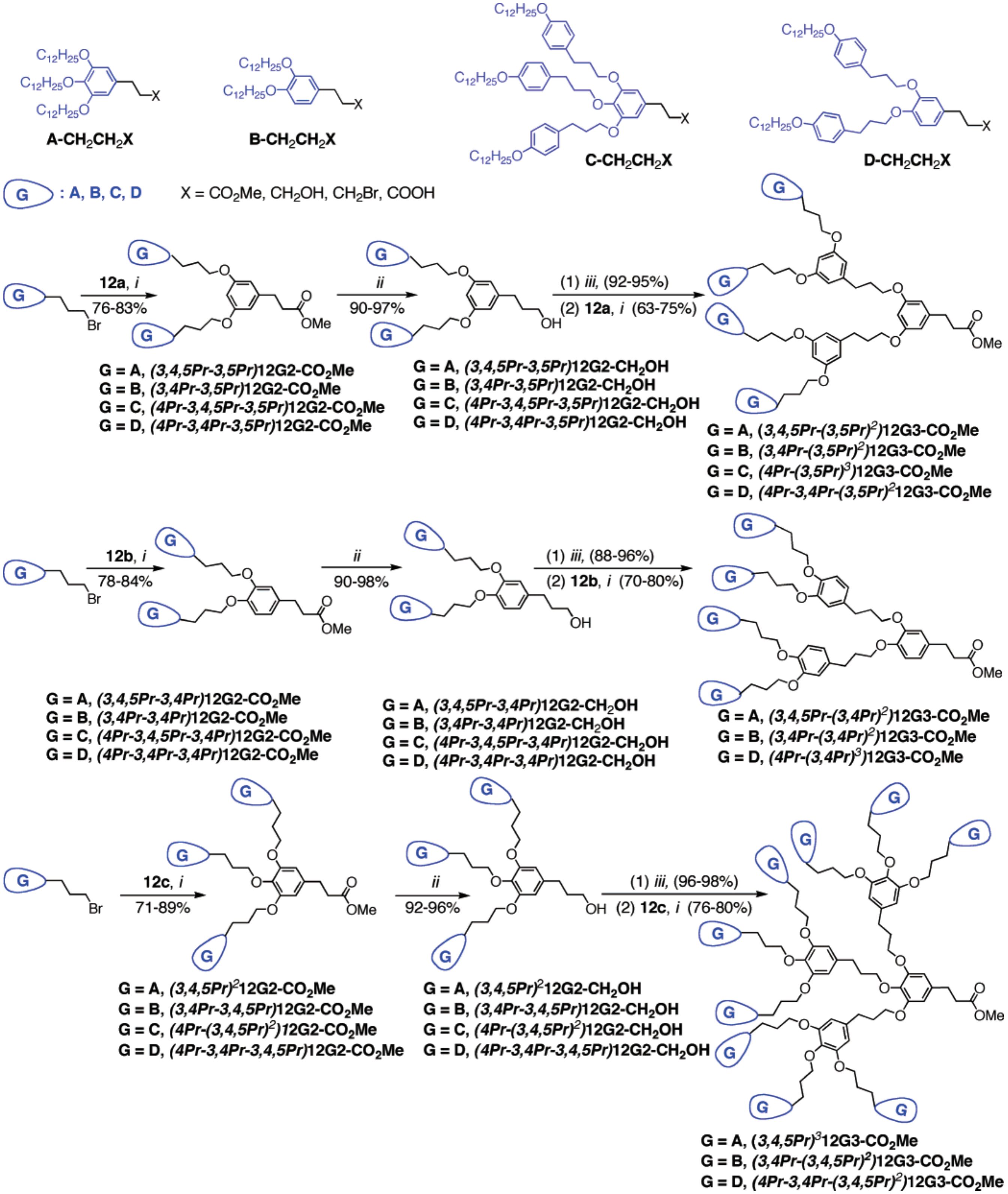
***Scheme 3.*** Synthesis of Higher-Generation Dendrons[a]

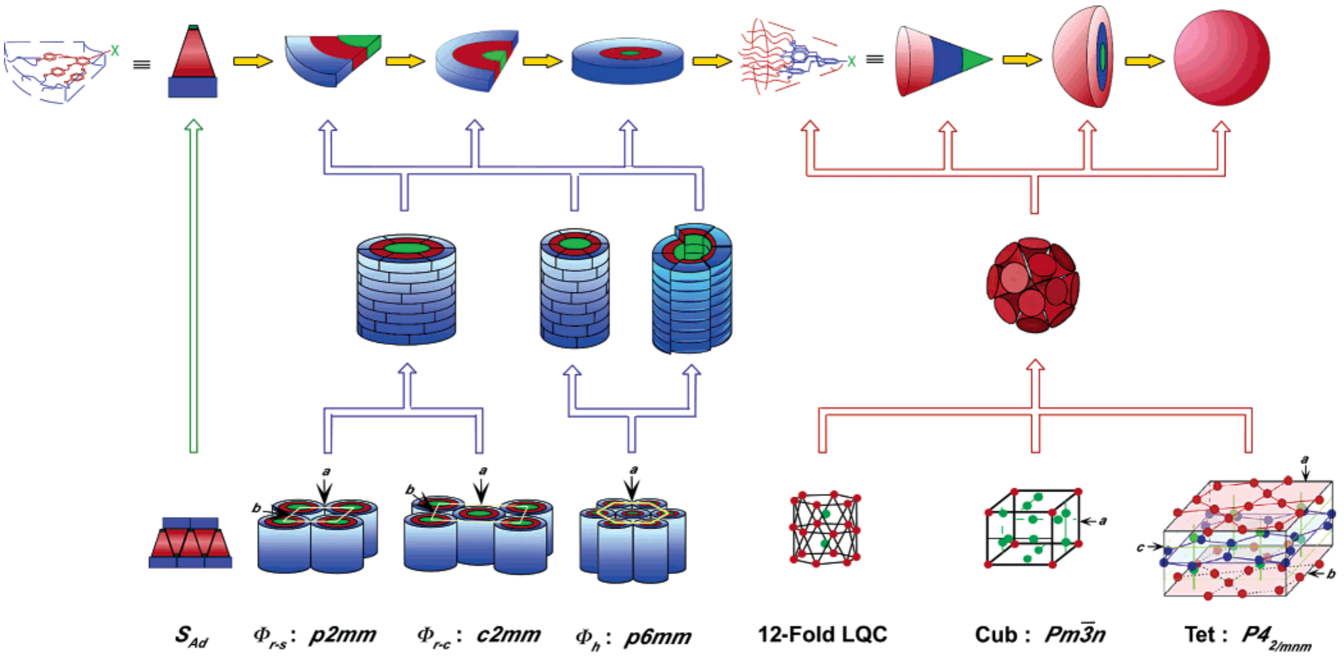


[a] Reagents and conditions: (i) $K_2CO_3$, DMF or DMF/THF, 75 °C; (ii) $LiAlH_4$, THF; (iii) $CBr_4$, $PPh_3$, $CH_2Cl_2$.

hydrogenated their double bond to produce **12a**, **12b**, and **12c**. The overall yields for the multistep synthesis outlined in Scheme 1 ranged from 63 to 70%.

**Synthesis of First-Generation Dendrons.** The synthesis of first- (Scheme 2) and higher-generation dendrons involves an iterative process that consists of a combination of two different methods used previously in our laboratory.[6c,7d] The first step consists of the O-alkylation of **5**, **12b**, and **12c** with 1-bromododecane. The reduction of **13a**, **13b**, and **13c** with $LiAlH_4$ and bromination of **14a**, **14b**, and **14c** with $CBr_4/PPh_3$[6b,c,22] produced

***Scheme 4.*** Retrostructural Analysis of 2D Smectic (S), *p*2*mm* Simple Rectangular Columnar ($\Phi_{r-s}$), *c*2*mm* Centered Rectangular Columnar ($\Phi_{r-s}$), and *p*6*mm* Hexagonal Columnar ($\Phi_h$), and Analysis of 3D 12-Fold Quasi-Liquid Crystal (QLC), *Pm*$\bar{3}$*n* Cubic (Cub), and *P*4$_2$/*mnm* Tetragonal (Tet) Lattices



**15a**, **15b**, and **15c**. Etherification of **12b** and **12c** with **15a** and subsequent transformation of the $-CO_2CH_3$ group from the apex into $-COOH$, $-CH_2OH$, and $-CH_2Br$ produced the first-generation dendrons **16a**, **16b**, **16c**, **16d** and **17a**, **17b**, **17c**, **17d**.

**Synthesis of Higher-Generation Dendrons.** The first-generation dendrons **15b**, **c**, **16c**, and **17c** (Scheme 2) were used to construct the periphery of the higher-generation constitutional isomeric 3,4- and 3,5-substituted $AB_2$ and 3,4,5-substituted $AB_3$ dendrons by the O-alkylation of **12a**, **12b**, and **12c** (Scheme 3). Four new dendrons containing the $-CO_2CH_3$ group at the apex are created in each library at each generation. Subsequent hydrolysis and reduction of the $-CO_2CH_3$ followed by the bromination of the resulting $-CH_2OH$ produced 12 additional dendrons per library at each generation. Therefore, 16 new dendrons are produced at each generation in each of the three libraries. This sequence was repeated to construct up to four generations of phenylpropyl ether-based dendrons.

**Structural and Retrostructural Analysis of the $AB_3$ Library of Supramolecular Dendrimers.** Structural and retrostructural analysis of the supramolecular dendrimers was carried out by a combination of analytical methods that involve $^1H$ and $^{13}C$ NMR, MALDI-TOF, gel permeation chromatography (GPC), differential scanning calorimetry (DSC), thermal optical polarized microscopy (TOPM), experimental density ($\rho_{20}$), and small- and wide-angle X-ray diffraction (XRD) experiments performed as a function of temperature on powder and oriented fibers.[6c,7c,d,8b,9,11,13a,b] Scheme 4 outlines the concept of retrostructural analysis of the periodic and quasi-periodic lattices of supramolecular dendrimers. All experimental details, analytical results, and calculation methods of this process are available in the Supporting Information.

The structural and retrostructural analysis was carried out at each generation on supramolecular dendrimers self-assembled from dendrons containing $-CO_2CH_3$, $CH_2OH$, and $-COOH$ groups at their apex. We will discuss first the analysis obtained from powder XRD at small and wide angles. The most representative results for the $AB_3$ library are summarized in Scheme 5. They include the nature of the lattice, the diameter (*D*) of the supramolecular column or sphere, the solid angle ($\alpha'$) of the dendron, and the number of dendrons ($\mu$) forming a sphere or a 4.7 Å cross section of a column. Complete analysis is available in the Supporting Information. The first important result is that all phenylpropyl dendrons self-assemble into supramolecular dendrimers regardless of their generation, functional group at the apex, and their $AB_2$ or $AB_3$ internal and periphery architectures (Supporting Information Figures SF1−SF12, Supporting Information Tables ST7−ST9). In the case of related architectures generated from benzyl ether dendrons, self-assembly was not observed at the first generation for the *(3,4,5)*12G1-X and *(3,4)*12G1-X dendrons regardless of the nature of X.[8b] The benzyl ether dendron *(4-3,4,5)*12G1-X self-assembles only when X = $-COOH$.[8b]

The second important result provided by the phenylpropyl library is the lower transition temperature exhibited by their supramolecular dendrimers. In the case of benzyl ether dendrons at high generations, their transition temperatures were close to or even higher than the decomposition temperature.[8b] A comparison of the results in Scheme 5 with the results from Scheme 6 of ref 8b also demonstrated that the phenylpropyl dendrons exhibit a higher tendency toward self-assembly into supramolecular columnar structures than the corresponding benzyl ether dendrons. For example, *(3,4,5Pr)*12G1-X self-organizes into smectic and columnar supramolecular structures. At low temperatures, even *(3,4Pr-3,4,5Pr)*12G2-X self-assembles into supramolecular columns. The corresponding first-generation benzyl ether dendrons do not assemble, while the second generation self-assembles only in supramolecular spheres.[8b] Various columnar structures were also observed for the first and second generations based on *(4Pr-(3,4,5Pr)$^n$)*12G*n*-X and

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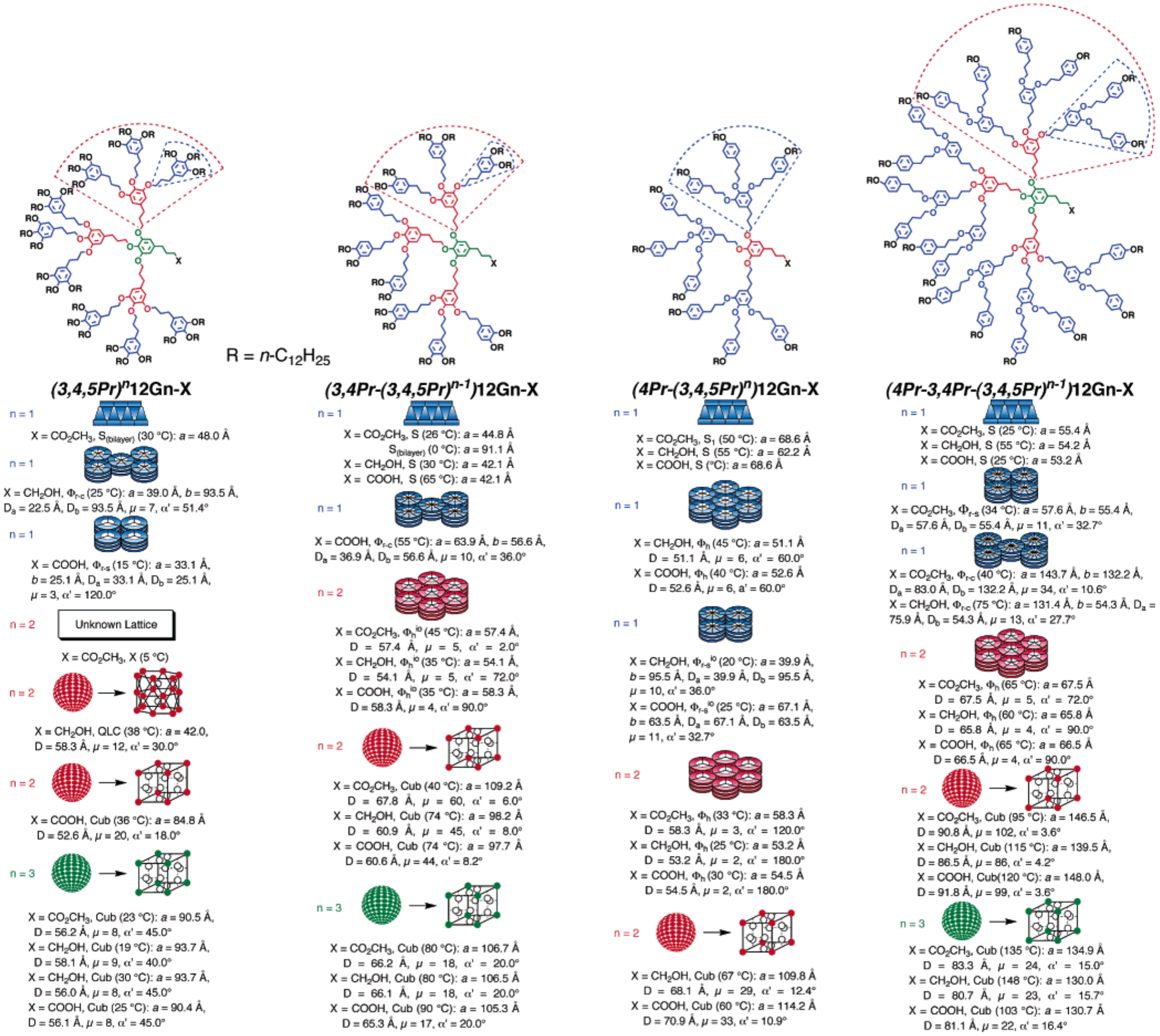
***Scheme 5.*** Retrostructural Analysis of Supramolecular Dendrimers Self-Assembled from $AB_3$ 3,4,5-Trisubstituted Dendrons

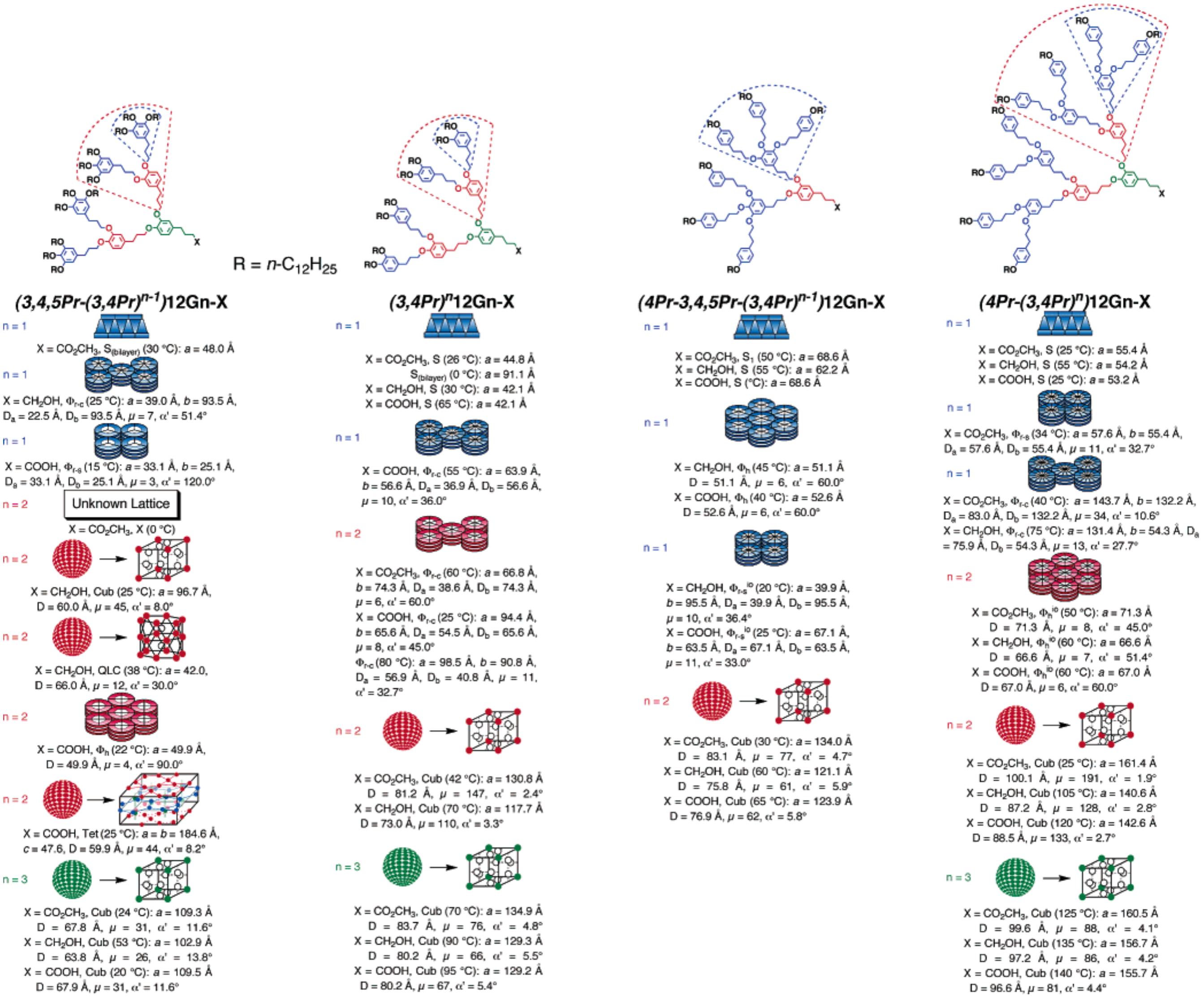


*(4Pr-3,4Pr-(3,4,5Pr)*$^{n-1}$)12G$n$-X. At higher generations, all dendrons from this library self-assemble into supramolecular spheres that self-organize in quasi-liquid crystal (QLC)[11b] and $Pm\bar{3}n$ cubic[7d] lattices. Last but not least all phenylpropyl supramolecular dendrimers exhibit diameters ($D$) that are with up to 16 Å larger than those of the benzyl ether homologous. For the same supramolecular structure, $D$ increases with $n$ and for the same $n$ with the increase in $\mu$ or decrease in $\alpha'$. A new unknown lattice was discovered for the case of *(3,4,5Pr)*$^2$12G2-$CO_2CH_3$.

**Structural and Retrostructural Analysis of the 3,4-Disubstituted Library of $AB_2$ Supramolecular Dendrimers.** The difference between phenylpropyl and benzyl ether dendrons is even more striking in the case of the 3,4-disubstituted $AB_2$ library. This can be observed by comparing the data from Scheme 6 with the results reported in Scheme 4 from ref 8b. Columnar structures are self-assembled from *(3,4,5Pr-(3,4Pr)*$^{n-1}$)12G$n$-X, *(3,4Pr)*$^n$12G$n$-X, and *(4Pr-(3,4Pr)*$^n$*)*12G$n$-X for $n$ = 1 and 2 regardless of X, and for *(4Pr-3,4,5Pr)*12G1-X. The first two series of dendrons from the benzyl ether library self-assemble only in supramolecular spheres regardless of X but only at generations two and higher. The last series of benzyl ether dendrons self-assemble only at first generation in supramolecular columns. *(3,4,5Pr-3,4Pr)*12G2-X provides the largest diversity of supramolecular columns and spheres only by changing the structure of X. This is the first dendron that self-assembles into spheres that self-organize into $Pm\bar{3}n$ cubic,[7d] QLC,[11b] and $P4_2/mnm$ tetragonal[11a] lattices. The compound with X = COOH self-assembles at low temperature in a column while at high temperature in a sphere that self-organizes in the tetragonal lattice. At $n$ = 2 and 3, all phenylpropyl dendrons self-assemble into supramolecular spheres that self-organize in the $Pm\bar{3}n$ cubic lattice.

It is important to observe that at the same generation the spheres self-assembled from phenylpropyl dendrons have a diameter that can be up to 25 Å larger than that of the corresponding benzyl ether-based supramolecular spheres. At the same generation number, the diameter of the supramolecular

*Scheme 6.* Retrostructural Analysis of Supramolecular Dendrimers Self-Assembled from $AB_2$ 3,4-Disubstituted Dendrons

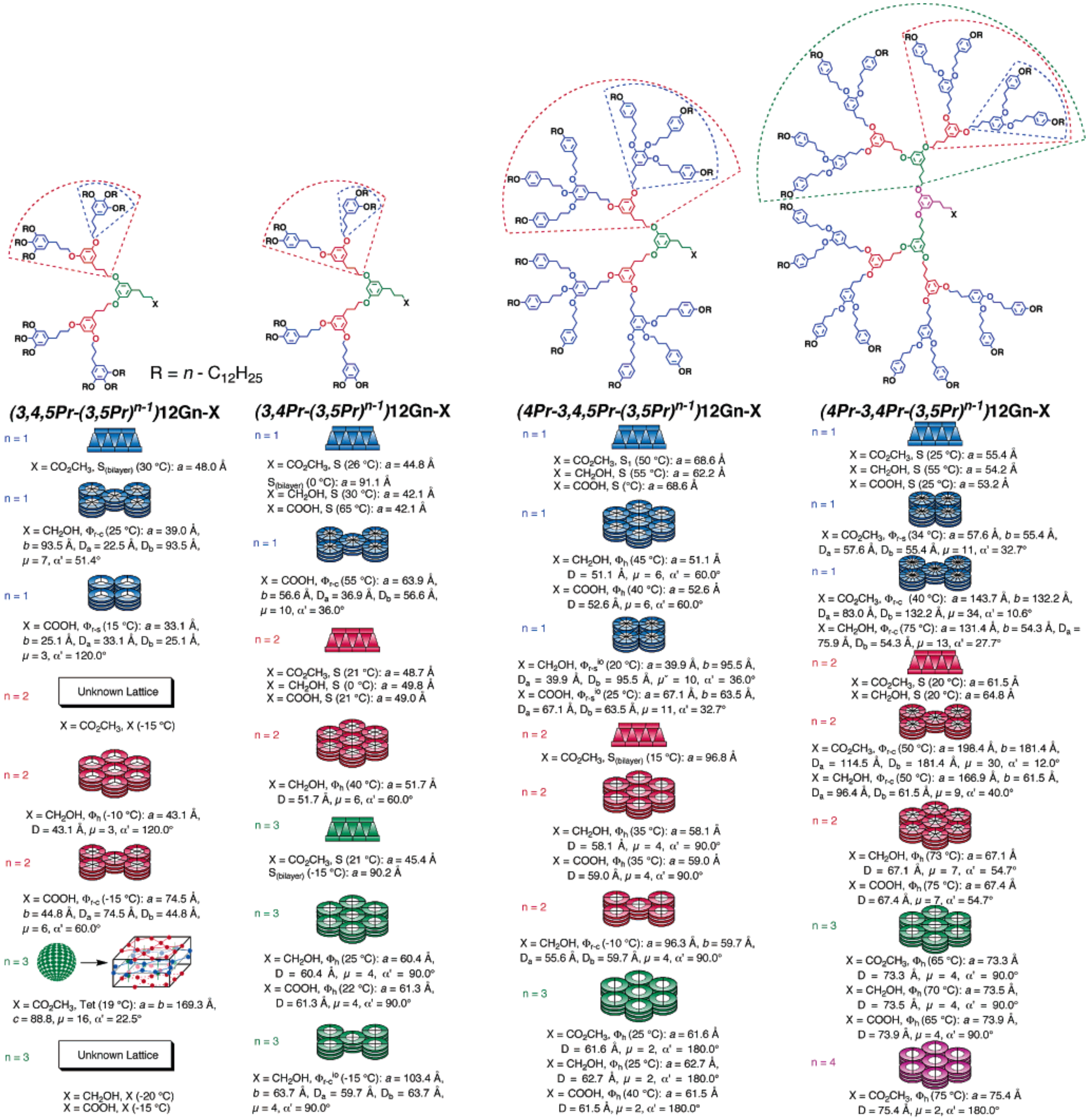


structure generated from the 3,4-disubstituted dendrons (Scheme 6) is larger than that of the similar structure self-assembled from 3,4,5-trisubstituted dendrons (Scheme 5). The dependence of $D$ on $n$, $\mu$, and $\alpha'$ follows the same trend in both libraries. As in the case of the previous library, a new unknown lattice was discovered in the case of *(3,4,5Pr-3,4Pr)*12G2-$CO_2CH_3$. The phenylpropyl dendrons have a smaller solid angle than the benzyl ether dendrons, increasing the probability of generating hollow supramolecular structures.

**Structural and Retrostructural Analysis of the 3,5-Disubstituted Library of $AB_2$ Supramolecular Dendrimers.** Scheme 7 summarizes the structural and retrostructural analysis of supramolecular dendrimers self-assembled from 3,5-disubstituted dendrons. As in the previous two libraries, all compounds self-assemble regardless of $n$ and X. This contrasts the benzyl ether homologous library (Scheme 5, ref 8b). For example, the first-generation benzyl ether homologues of *(3,4,5Pr)*12G1-X and *(3,4Pr)*12G1-X do not self-assemble. Two new structures were discovered in the *(3,4,5Pr)-(3,5Pr)*$^{n-1}$)12G2-X series with $n = 2$, X = $CO_2CH_3$ and $n = 3$, X = $CH_2OH$ or COOH. *(3,4,5Pr-(3,5Pr)*$^2$)12G3-$CO_2CH_3$ self-assembles in a supramolecular sphere that generates the $P4_2/mnm$ tetragonal lattice.[11a]

All other dendrons self-assemble into various columnar and smectic structures. This trend is in agreement with that observed in the case of the benzyl ether library.[8b] However, the diversity of column shapes, sizes, and lattices resulting from the phenylpropyl dendrons is much larger than the diversity that resulted from the benzyl ether dendrons. For example, in the case of the phenylpropyl dendrons $p6mm$ hexagonal columnar ($\Phi_h$), $p2mm$ simple rectangular columnar ($\Phi_{r-s}$), and $c2mm$ centered rectangular columnar ($\Phi_{r-c}$), periodic arrays were obtained, while in the case of benzyl ether dendrons only the $\Phi_h$ lattice was observed.[8b] In addition, the dimensions of the current supramolecular columns can be up to 140 Å larger (*(4Pr-3,4Pr-3,5Pr)*12G2-$CO_2CH_3$) than that of the corresponding benzyl ether dendron.[8b] An additional characteristic that must be mentioned is the faster dynamics of self-assembly mediated by the more flexible phenylpropyl dendrons when compared with the corresponding benzyl ether dendrons. This dynamics facilitates the assembly of higher-order structures with phenylpropyl dendrons.

***Scheme 7.*** Retrostructural Analysis of Supramolecular Dendrimers Self-Assembled from $AB_2$ 3,5-Disubstituted Dendrons



**Dimensions of Supramolecular Dendrimers and Their Solid Angle.** Previously, we have reported that the dimensions of the columnar and spherical supramolecular dendrimers correlate with the solid angle ($\alpha$) or the projection of the solid angle ($\alpha'$) of the self-assembling dendron.[7g] The solid angle determines the shape of the dendron and the number of the dendrons ($\mu$) that self-assemble to generate a supramolecular sphere or the 4.7 Å cross section of a supramolecular column.[8b,9] Both $\alpha$ and $\mu$ change as a function of generation number of the dendron and at the same generation as a function of dendron architecture. The values of $\alpha$ and $\mu$ are obtained by the retrostructural analysis of the supramolecular dendrimers and are reported in Schemes 5−7. Recently, it has been demonstrated that, in porous supramolecular columns self-assembled from dendritic dipeptides,[15b,23] $\alpha$ and $\mu$ correlate the dendron architecture with the pore diameter. When the generation number, $n$, increases, $\alpha$ increases and $\mu$ decreases until ultimately $\mu$ becomes equal to 1. When $\mu = 1$, the dendron is equal to a sphere, and therefore, the dendron becomes a dendrimer.[7h] Therefore, the control of the solid angle of the dendron represents one of the most challenging architectural design principles that must be elucidated to advance the complexity

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(23) (a) Percec, V.; Dulcey, A. E.; Peterca, M.; Ilies, M.; Ladislaw, J.; Rosen, B. M.; Edlund, U.; Heiney, P. A. *Angew. Chem., Int. Ed.* **2005**, *44*, 6516−6521. (b) Percec, V.; Dulcey, A.; Peterca, M.; Ilies, M.; Miura, Y.; Edlund, U.; Heiney, P. A. *Aust. J. Chem.* **2005**, *58*, 472−482. (c) Percec, V.; Dulcey, A. E.; Peterca, M.; Ilies, M.; Sienkowska, M. J.; Heiney, P. A. *J. Am. Chem. Soc.* **2005**, *127*, 17902−17909. (d) Percec, V.; Dulcey, A. E.; Peterca, M.; Ilies, M.; Nummelin, S.; Sienkowska, M. J.; Heiney, P. A. *Proc. Natl. Acad. Sci. U.S.A.* **2006**, *103*, 2518−2523.

***Table 1.*** XRD Data and $D_{pore}$ Values for Selected Supramolecular Porous Columns

| compound | $T$ (°C) | $d_{10}{}^{a}$ (Å) ($A_{10}{}^{b}$ au) | $d_{11}{}^{a}$ (Å) ($A_{11}{}^{b}$ au) | $d_{20}{}^{a}$ (Å) ($A_{20}{}^{b}$ au) | $d_{21}{}^{a}$ (Å) ($A_{21}{}^{b}$ au) | $a = D_{col}$ (Å) | $D_{pore}$ (Å) | $\mu$ |
|---|---|---|---|---|---|---|---|---|
| *(4Pr-(3,4Pr)$^2$)*12G2-$CO_2CH_3$ | 45 | 58.3<br>(42.6) | 33.6<br>(25.1) | 29.0<br>(20.3) | 21.9<br>(12.1) | 70.6 ± 0.4 | 12.9 ± 1.8 | 8 |
| *(4Pr-(3,4Pr)$^2$)*12G2-$CH_2OH$ | 60 | 58.1<br>(54.8) | 33.1<br>(22.8) | 28.7<br>(22.4) | – | 66.5 ± 0.4 | 8.2 ± 1.4 | 7 |
| *(4Pr-(3,4Pr)$^2$)*12G2-COOH | 60 | 57.3<br>(59.8) | 32.7<br>(19.8) | 28.5<br>(20.3) | – | 65.8 ± 0.4 | 6.6 ± 1.4 | 6 |
| *(4Pr-3,4Pr-(3,5Pr)$^2$)*12G3-$CO_2CH_3$ | 67 | 63.6<br>(51.2) | 36.6<br>(19.8) | 31.7<br>(17.8) | 24.0<br>(11.1) | 73.3 ± 0.4 | 8.2 ± 1.4 | 4 |
| *(4Pr-3,4Pr-(3,5Pr)$^2$)*12G3-$CH_2OH$ | 80 | 62.8<br>(51.7) | 36.2<br>(22.0) | 31.3<br>(19.7) | 23.7<br>(6.6) | 72.4 ± 0.4 | 7.8 ± 1.6 | 4 |
| *(4Pr-3,4Pr-(3,5Pr)$^2$)*12G3-COOH | 65 | 64.2<br>(54.9) | 36.9<br>(19.2) | 32.0<br>(17.3) | 24.2<br>(8.5) | 74.0 ± 0.4 | 7.1 ± 1.7 | 4 |
| *(4Pr-3,4Pr-3,5Pr)*12G2-$CH_2OH$ | 73 | 58.3<br>(55.9) | 33.6<br>(20.8) | 29.0<br>(19.7) | 21.9<br>(3.5) | 67.2 ± 0.4 | 7.8 ± 1.6 | 7 |
| *(4Pr-3,4Pr-3,4,5Pr)*12G3-$CH_2OH$ | 100 | 57.0<br>(55.9) | 32.8<br>(21.3) | 28.4<br>(19.2) | 21.5<br>(3.6) | 65.7 ± 0.4 | 6.8 ± 1.4 | 4 |
| *(4Pr-3,4,5Pr-(3,5Pr)$^2$)*12G3-$CO_2CH_3$ | 33 | 53.7<br>(60.2) | 30.9<br>(19.8) | 26.8<br>(16.4) | 20.3<br>(3.6) | 62.0 ± 0.4 | 4.1 ± 2.0 | 2 |
| *(4Pr-3,4,5Pr-(3,5Pr)$^2$)*12G3-$CH_2OH$ | 30 | 54.2<br>(61.3) | 31.2<br>(18.6) | 27.0<br>(14.7) | 20.5<br>(5.4) | 62.5 ± 0.4 | 4.2 ± 1.8 | 2 |
| *(3,4Pr-3,5Pr)*12G2-$CH_2OH$ | 40 | 44.6<br>(74.4) | 25.7<br>(15.9) | 22.3<br>(9.6) | – | 51.4 ± 0.4 | 2.0 ± 0.5 | 6 |

[a] *d*-Spacings of the $\Phi_h$ phase. [b] Peak amplitude scaled to the sum of the observed diffraction peaks between parentheses (au = arbitrary units).

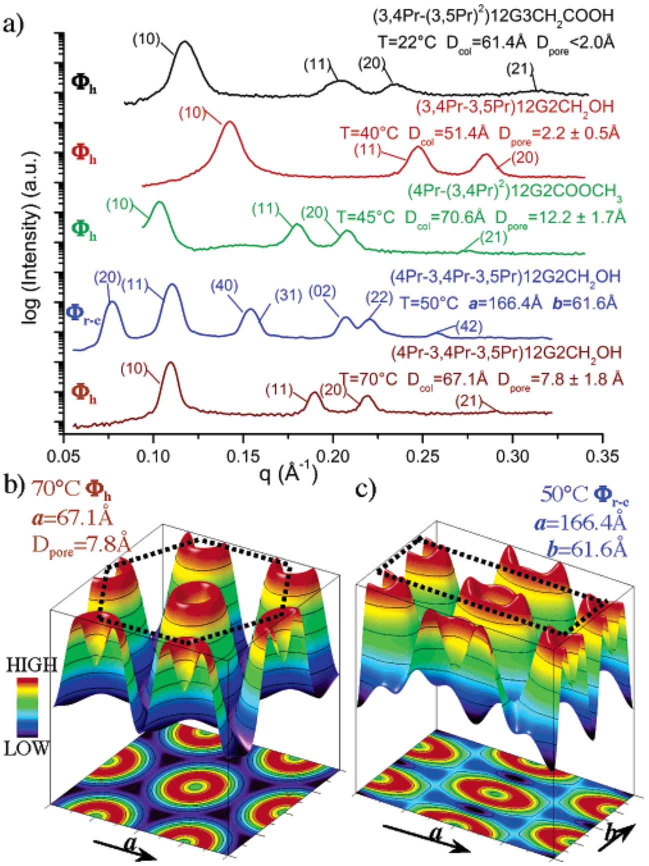

***Figure 1.*** (a) Representative small-angle XRD stack plots of supramolecular porous columns with small and large $D_{pore}$. Reconstructed electron density maps of the hollow hexagonal (b) and proposed hollow-centered rectangular phases of *(4Pr-3,4Pr-3,5Pr)*12G$_2$-$CH_2OH$ (c). *a* and *b* are lattice dimensions; $q = 4\pi \sin \theta/\lambda$; $\theta$ = X-ray diffraction angle; $\lambda = 1.54$ Å is the X-ray wavelength; and a.u. = arbitrary units.

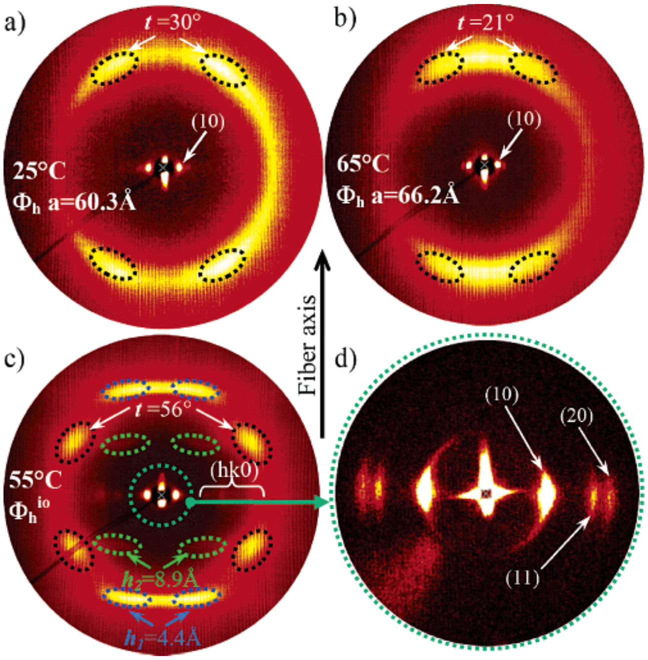

***Figure 2.*** Wide-angle XRD patterns of aligned samples. (a, b) Tilt transition and $D_{col}$ change observed for the *(4Pr-3,4Pr-3,4,5Pr)*12G2-X (X = −COOH, −$CH_2OH$, −$CO_2CH_3$) with X = COOH. (c) $\Phi_h{}^{io}$ phase of *(4Pr-(3,4Pr)$^2$)*12G2$CH_2OH$. (d) Small-angle XRD pattern indicating the fiber alignment and the first three reflections of the hexagonal phase. $t$ = dendron tilt angle; (*hk*0) = high-order reflections of the $\Phi_h{}^{io}$ phase; $h_1$ and $h_2$ = long-range helical features with estimated correlation length ∼13 layers.

and control the size of hollow and nonhollow supramolecular dendrimers. An inspection of α′ and $\mu$ values from Schemes 5−7 and their comparison with the values obtained for the homologous benzyl ether dendrons reveal a substantial decrease in α′ and an increase in $\mu$ for the phenylpropyl dendrons. The outcome of this result provides a higher than expected increase in the dimension of the supramolecular dendrimer at the transition from benzyl ether to phenylpropyl ether-based supramolecular dendrimers. This result, together with the higher flexibility and lower transition temperatures, suggests architectural pathways to supramolecular dendritic architectures larger than those reported in previous publications[8b,9] and in the current report. However, in some cases mentioned during the retrostructural analysis of the libraries of phenylpropyl dendrons,

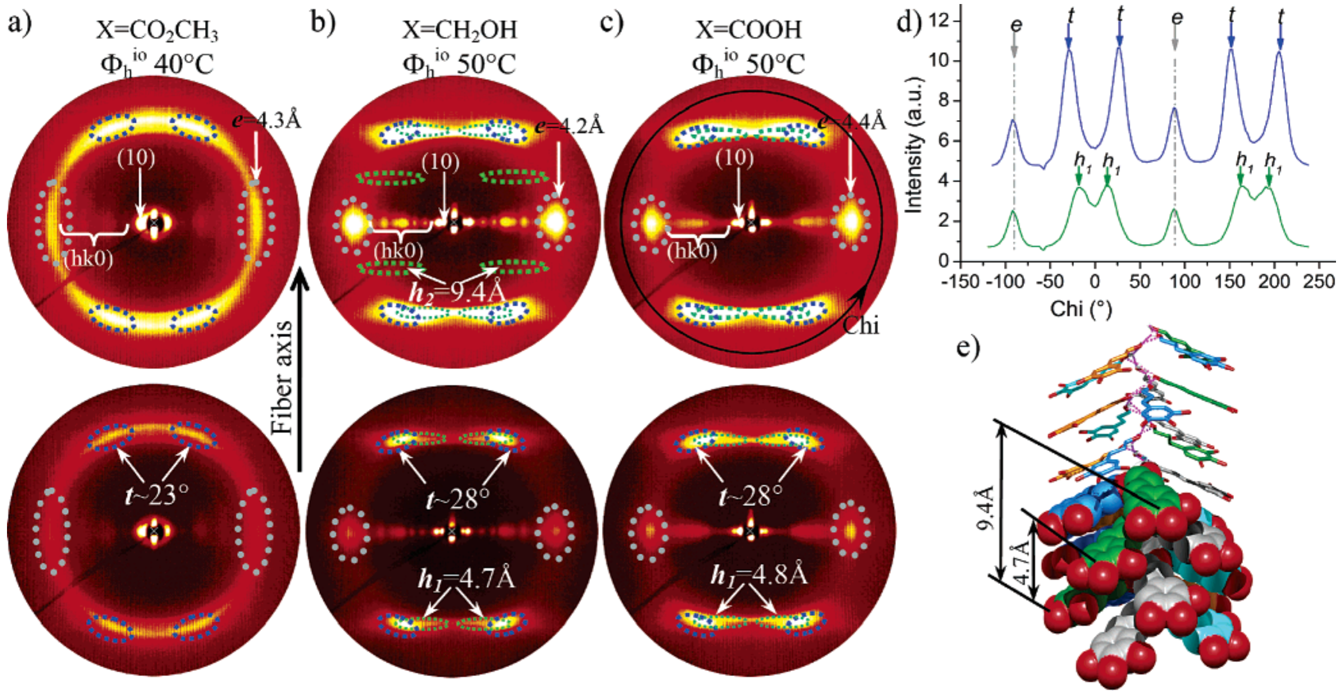

***Figure 3.*** Increased order due to H-bonding interactions observed in *(3,4Pr-3,4,5Pr)*12G2-X; wide-angle XRD patterns of aligned samples collected at the temperature indicated on the figure. (a,b,c) The bottom patterns are the same as the top ones shown with enhanced contrast. (d) For X = COOH azimuthal plots at the *t* feature *q* radius (blue) and at the $h_1$ feature *q* radius (green). (e) Supramolecular helical hexagonal columnar assembly packing of *(3,4Pr-3,4,5Pr)*12G1-$CH_2OH$. (10), (*hk*0) = reflections of the hexagonal columnar phase; Chi = azimuthal angle; *t* = dendron tilt angle; *e* = strong equatorial diffuse reflection; $h_1$, $h_2$ = long-range order helical features. The estimated correlation length is ~75 Å and corresponds to about 15 layers.

unexpectedly large supramolecular dendrimers have been encountered. Their size indicates that hollow supramolecular columns and even hollow spheres may be accessible without the presence of the dipeptide functionality at the dendron apex, since a combination of a decreased $\alpha$ and increased $\mu$ must correlate with an increased hollow volume or pore diameter of the supramolecular structure.[15b,23]

**Helical Porous Supramolecular Columns.** The columnar hexagonal ($\Phi_h$) lattice generated from columns containing a pore in their center can be identified by increased intensities of the higher-order 11, 20, and 21 diffraction peaks.[15b,23] A method to calculate the pore diameter of porous columns was elaborated.[15b] However, methods to calculate the pore size of the ovoidal columns that self-organize in rectangular lattices and of supramolecular spheres are not yet available. Therefore, an inspection of the powder XRD diffractograms can immediately identify hollow structures and provide the data required to calculate the pore diameter of the supramolecular columns self-organized in $\Phi_h$ lattices. A diversity of architectures whose XRD indicates self-assembly into porous columns was discovered in the libraries of phenylpropyl ether-based dendrons. Selected examples from these structures, together with their representative XRD data and their column ($D_{col}$) and pore ($D_{pore}$) diameters, are reported in Table 1 and Figure 1.

Figure 1a shows the XRD data of porous columns self-assembled from *(3,4Pr-(3,5Pr)$^2$)*12G3-$CH_2OH$, *(3,4Pr-3,5Pr)*12G2-$CH_2OH$, *(4Pr-(3,4Pr)$^2$)*12G2-$CO_2CH_3$, and *(4Pr-3,4Pr-3,5Pr)*12G2-$CH_2OH$. The $D_{pore}$ and the $D_{col}$ calculated by simulating the XRD with the electron density of the dendron are shown in the figure. Porous columns with $D_{pore}$ between 2 and 13 Å are self-assembled from phenylpropyl dendrons containing $-CO_2CH_3$, $-COOH$, and $-CH_2OH$ groups at their apex (Table 1). *(4Pr-3,4Pr-3,5Pr)*12G2-$CH_2OH$ self-assembles in both symmetric and asymmetric columns (Figure 1a and Supporting Information). The circular symmetric columns self-organize in a $\Phi_h$ lattice, while the ovoidal asymmetric columns self-organize in a $\Phi_{r-c}$ lattice. The electron density maps of both lattices were calculated and are shown in Figure 1b and c. They indicate porous structures for both lattices. However, since a calculation method for $D_{pore}$ generated from ovoidal columns is not yet available, the dimensions of ovoidal pores cannot be determined.

**Enhanced Dynamics and Order.** The high flexibility of the phenylpropyl dendrons facilitates a faster dynamics of self-assembly than that of the corresponding benzyl ether dendrons. This mediates a higher degree of order in the supramolecular assemblies generated from phenylpropyl dendrons. This dynamics is observed despite temperatures lower than those of benzyl ether dendrons and can be detected by both DSC and XRD analysis. A comparison of the enthalpy and entropy changes ($\Delta H$ and $\Delta S$) associated with the transition from ordered periodic arrays of supramolecular dendrimers to their disordered liquid state for phenylpropyl and benzyl ether based structures is available in Supporting Information Table ST10. These data demonstrate that for the same phase transition both the enthalpy and entropy changes are up to 30 times larger in the case of phenylpropyl dendrons. As a consequence of the enhanced dynamics and order, much shorter annealing is required in the case of phenylpropyl dendrons to reach equilibrium states in DSC and XRD experiments. The columnar hexagonal structures exhibited by *(3,4Pr-3,4,5Pr)*12G2-X with X = $-CO_2CH_3$, $-CH_2OH$, and $-COOH$ are used to demonstrate this concept (Figures 2, 3). The balance between flexibility, dynamics, and enhanced stiffness induced by H-bonding in the core increases the intracolumnar order at the transition from X = $-CO_2CH_3$, to $-CH_2OH$, and to $-COOH$. This trend contrasts the results obtained with the less flexible benzyl ether-based dendrons when strong interactions in the core of the dendron reduce the degree of order of the supramolecular assembly.[8b]

The effect of the increased conformational freedom of the phenylpropyl dendrimers is exemplified by the XRD results summarized in Figure 2a and b. A dendron tilt transition was observed for the first time in the supramolecular structure of this phenylpropyl-based dendron. The XRD fiber experiments of the *(4Pr-3,4Pr-3,4,5Pr)*12G2-X-based supramolecular dendrimers show that the dendron tilt angle changes from 30° at room temperature (Figure 2a) to 21° at 65 °C (Figure 2b). At both temperatures, the supramolecular assemblies are in columnar hexagonal phase. $D_{col}$ increases more than 10% between these temperatures. This is in agreement with the change observed for the dendron tilt angle. It is remarkable that this tilt transition is observed in the DSC scans as well (see Supporting Information Figure 24).

Another important effect caused by the flexibility of the phenylpropyl dendrons is illustrated by Figure 3. The comparison of the dendrimer hexagonal intracolumnar ordered phase generated from *(3,4Pr-3,4,5Pr)*12G2-X indicates that the functional group from their apex determines the degree of intracolumnar order of their supramolecular structure. The H-bonding interactions between the apex functional groups together with the increased flexibility of the dendrimers are responsible for the higher intracolumnar order. This can be seen by the increased intensities of the high-order (*hk*0) reflections, of the equatorial feature *e*, and the appearance of the $h_1$, $h_2$ helical features for the case of X = $CH_2OH$ and X = COOH in Figure 3b and c. The dendron tilt angle does not seem to be affected by the functional groups from their apex. This indicates that the overall 3D packing is not significantly changed. An additional similar example is presented in Supporting Information Figure 25.

## Conclusions

Three libraries, one of 3,4,5-trisubstituted $AB_3$ and two of constitutional isomeric 3,4- and 3,5-disubstituted $AB_2$ self-assembling phenylpropyl ether-based dendrons, were synthesized. The structural and retrostructural analysis of their supramolecular dendrimers facilitated the comparison of the self-assembly of these three libraries of phenylpropyl dendrons with those of the architecturally related benzyl ether dendrons.[8b] The more flexible and stable, under both thermal and acidic conditions, phenylpropyl ether dendrons exhibit a faster dynamics of self-assembly into larger supramolecular structures with higher order and lower transition temperatures than the corresponding benzyl ethers. In addition to the discovery of a series of novel and nonelucidated supramolecular structures, the phenylpropyl ether library self-assembles, regardless of its generation number and functional group at its apex, into all nonhollow and hollow, periodic and quasi-periodic arrays that were encountered previously with dendritic benzyl ethers[8b,11] and dendritic dipeptides.[15b,23] At the same generation number, the solid angle of the phenylpropyl ether dendrons is lower than that of the corresponding benzyl ether dendrons.[8b] This facilitated the assembly of supramolecular dendrimers with larger dimensions at the same generation number, predicted the potential synthesis of a higher number of generations of dendrons, provided the largest diversity of tapered dendrons that mediate self-assembly into helical columnar structures, and facilitated the assembly of hollow columns and spheres without the requirement of a dipeptide at the apex of the dendron.[15b,23] Self-assembling tapered dendrons are much less often encountered than conical dendrons.[8b,9] However, they are required to elucidate the structural origin of functions.[15] Therefore, this new library of self-assembling dendrons and the architectural design principles derived from it are expected to impact the field of dendritic macromolecules[1,5] and of self-organized soft complex matter[5,24] at both the fundamental and technological levels.

## Experimental Section

The synthetic methods and techniques are similar to those used conventionally in our laboratory.[8b,9,11,15] They are available in the Supporting Information.

**Acknowledgment.** Financial support by the National Science Foundation (DMR-0102459 and DMR-0548559) and the Office of Naval Research is greatly acknowledged.

**Supporting Information Available:** Experimental procedures with complete spectral, structural, and retrostructural analysis. This material is available free of charge via the Internet at http://pubs.acs.org.

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