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Supramolecular polymer chemistry: design, synthesis, characterization, and kinetics, thermodynamics, and fidelity of formation of self-assembled dendrimers☆

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Abstract—Dendrimers **1a–d** were synthesized in 10 steps from dendrons **4–7**, bromobenzene and succinic anhydride. Tetraacids **1e** and **1f** were prepared in an analogous fashion. The aggregation of **1a–f** was studied in solution by size exclusion chromatography (SEC), vapor pressure osmometry (VPO), low angle laser light scattering (LLS), small angle neutron scattering (SANS), and by ^{1}H NMR. The data are consistent with a stable, discrete hexameric aggregate for **1b–d** in methylene chloride, non-discrete polymeric aggregates for **1a**, **1e**, and **1f**, and monomers for all compounds in tetrahydrofuran and dimethyl sulfoxide. Kinetic and thermodynamic studies and mixing experiments confirmed the highly cooperative nature of the self-assembly process.

1. Introduction

A continuing challenge in chemistry is the design of novel molecular recognition and self-assembling systems.[2] In self-assembly relatively small subunits are encoded with information that allows them to assemble into larger, well-defined structures. In contrast to the many state-of-the-art synthetic methods, relative few general strategies are available in what has been termed 'non-covalent synthesis'.[3] A broad array of scientists are actively pursuing such strategies because of the central role that self-assembly plays in biological organization and in determining the properties of materials. In the latter regard, self-assembly is considered to have significant potential to assist the manufacturing of nano- and mesoscopic materials, and thus may be integral to the development of a new generation of electronic, mechanical, and optical devices.[4]

The tobacco mosaic virus and other exquisitely complex examples of natural self-assembly systems serve as inspirations to biomimetic chemists. These systems, well optimized through evolution, are a benchmark by which abiotic self-assembly systems may be measured. Significant progress in creating discrete supramolecular structures in solution has been recorded recently.[3a,d,5] Nevertheless, with a few notable exceptions, the largest, well-characterized aggregates reported thus far have molecular dimensions and masses well below that of their naturally occurring counterparts, proteins. A simple way to create large self-assembled structures is to begin with building blocks that are already sizeable. Dendrimers have emerged as an exciting class of monodisperse polymers with hyperbranched architectures.[6] The development of a convergent synthetic approach[7a] and subsequent accelerated strategies[7b,c] has made it possible to prepare >10 kDa dendrimers in just a few steps. Thus, dendrimers are ideal building blocks for the construction of large supramolecular aggregates provided strategies can be developed for effecting inter-dendrimer recognition.

During the course of this work there were scattered reports of rational attempts to engineer specific contacts between linear and hyperbranched polymers, and even dendrimers.[8] For example, the addition of pyridine-containing compounds to a linear polymer with benzoic acid pedant groups promoted the self-organization through hydrogen bonding interactions and induced the formation of supramolecular polymeric liquid crystals. Amphiphilic block copolymers derived from linear hydrophilic polymers and spherical hydrophobic dendrimers (or vice versa) self-assemble in aqueous solution to form micellar structures.[9] Alternatively, polymer blends in which components can interact with each other through hydrogen bonds were shown to have increasing miscibility.[10] We recently described both polymeric and discrete dendritic aggregates mediated by hydrogen-bonding interactions.[11] Herein we provide a full

☆ See Ref. 1.

Keywords: dendrimers; tetraacids; vapor pressure.

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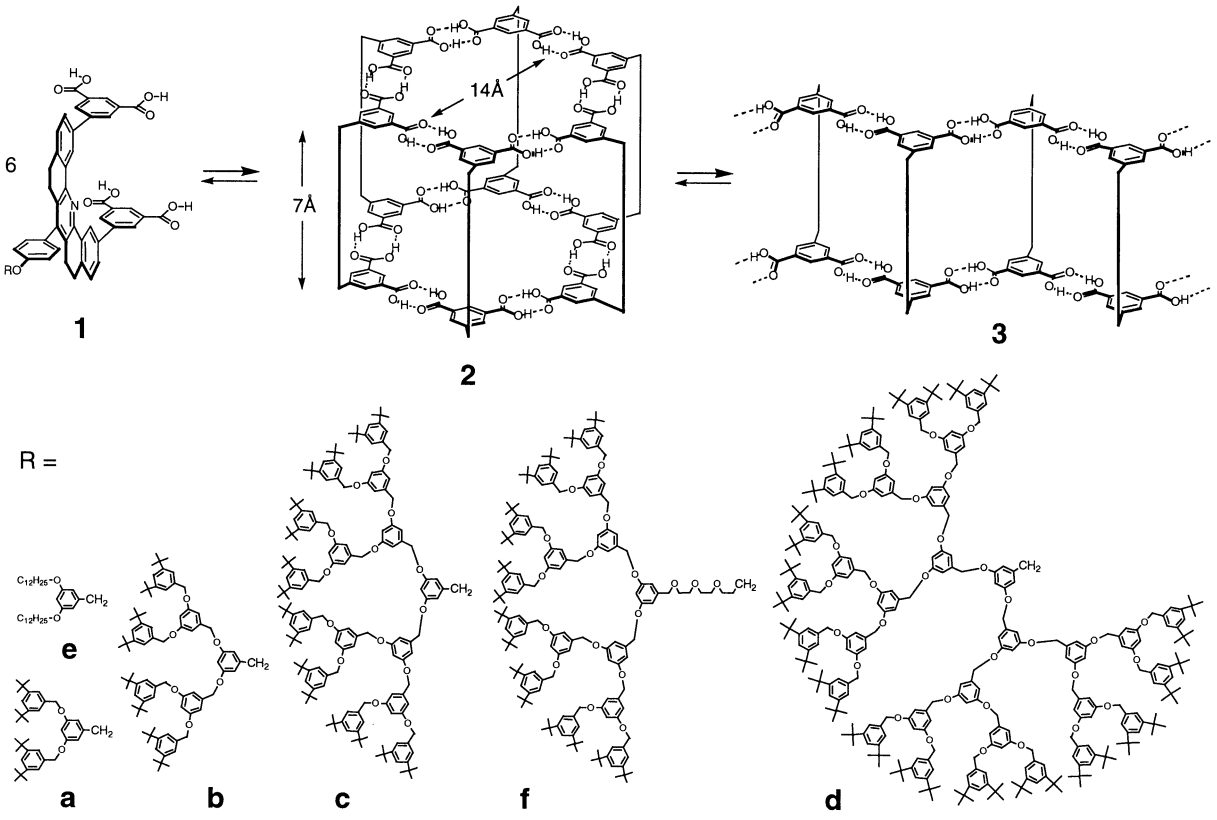


Scheme 1.

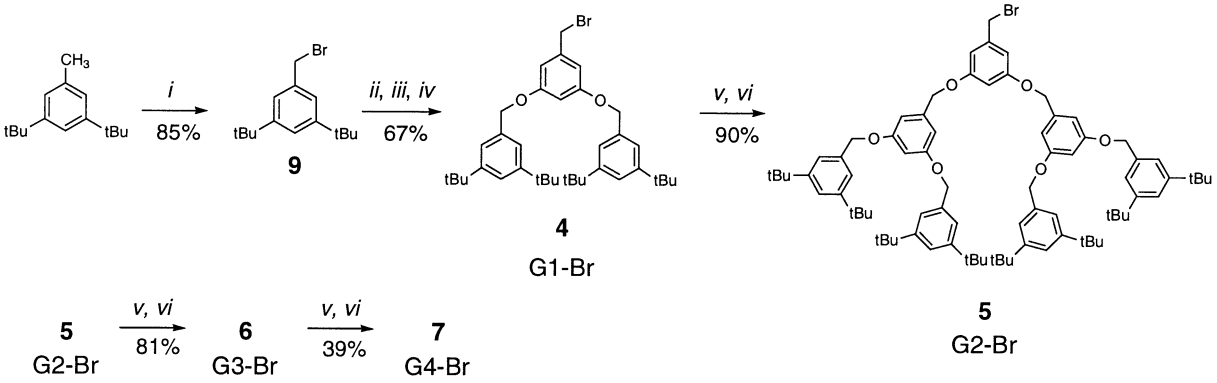
account of this work including the first kinetic and thermodynamic studies on these structures.

Tetraacids **1** were designed to hold two isophthalic acid units in a syn-arrangement using a rigid spacer previously used to construct molecular tweezers.[12] To the spacer unit of compounds **1** are attached first- through fourth-generation Fréchet-type dendrimers (see **a**–**d**, Scheme 1).[7a] By normal pairing of carboxylic acids into hydrogen-bonding dimers, these molecules were designed to self-assemble into cyclic hexamer **2** with large internal cavity (Scheme 1).[13] However, a series of polymeric aggregates (e.g. **3**) is also possible. Herein, we detail the syntheses, characterization, and self-assembly studies of dendrimers **1a**–**f**.

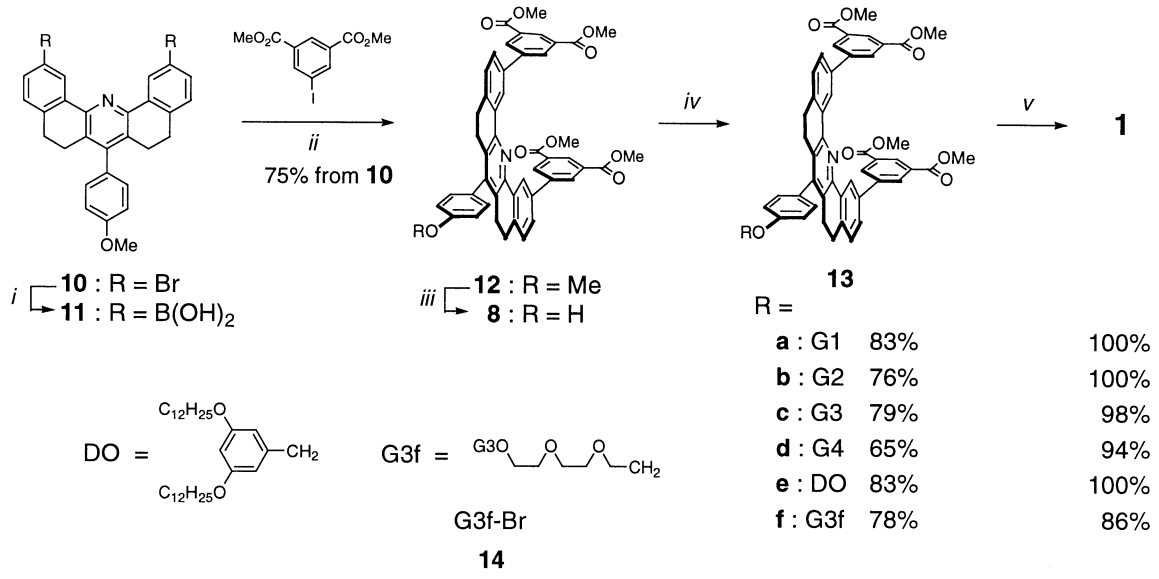
2. Result and discussions

2.1. Synthesis of dendritic tetraacids 1

The synthesis of target molecules **1** was achieved in a convergent fashion using dendritic bromides **4**–**7** and phenol **8**. Dendritic bromides **4**–**7** were synthesized using Fréchet's convergent dendrimer synthetic strategy.[7a] Thus, NBS bromination of 3,5-di(*tert*-butyl)toluene gave monobromide **9** in 85% yield along with some residual starting material and dibrominated product (Scheme 2). Reaction of **9** with methyl 3,5-dihydroxybenzoate followed by reduction and treatment with phosphorus tribromide afforded the first generation dendritic bromide **4**. The higher generation



Scheme 2. (i) NBS/hυ; (ii) methyl 3,5-dihydroxybenzoate, K_2CO_3, 18-cr-6, acetone (87%); (iii) LAH/THF; (iv) PBr_3/Et_2O; (v) 3,5-dihydoxybenzyl alcohol, K_2CO_3, 18-cr-6; (vi) CBr_4, PPh_3.



Scheme 3. (i) (1) BuLi, $B(OMe)_3$ (51%), (2) KOH, EtOH (89%); (ii) $Pd(PPh_3)_4$, PhMe, K_2CO_3(aq), reflux; (iii) BBr_3, CH_2Cl_2 (84%); (iv) Gn-Br, 18-cr-6, K_2CO_3, acetone, Bu_4NI; (v) KOH, H_2O, THF, MeOH.

bromides **5**–**7** were synthesized in an iterative procedure involving reaction of 3,5-dihydroxybenzyl alcohol with the appropriate dendron bromide (**4**–**6**) followed by reaction of the alcohol with carbon tetrabromide and triphenylphosphine.

The synthesis of phenol **8** started from dibromide **10**, whose synthesis in five steps from bromobenzene and succinic acid was previously reported.[12] Treatment with *n*-butyllithium followed by quenching with trimethyl borate gave bisboronic acid **11** after aqueous work-up (Scheme 3). Coupling with dimethyl 5-iodophthalate under Suzuki conditions gave tetraester **12**, which was demethylated with boron tribromide to afford the key intermediate **8**. Williamson ether formation between phenol **8** and **4**–**7** afforded the corresponding dendritic tetraesters **13a**–**d**. The target dendritic tetraacids **1a**–**d** were obtained in high yields by the basic hydrolysis of the corresponding tetraesters.

Tetraesters **13a**–**d** and tetraacids **1a**–**d** were thoroughly characterized by standard spectroscopic methods. Tetraacids **1a**–**d** displayed normal ^1H NMR spectra in tetrahydrofuran-d_8 and dimethyl sulfoxide-d_6 but in chloroform-*d* ($CDCl_3$), the spectral signals for the spacer and isophthalic acid units of **1b**–**d** were broad suggesting the formation of aggregates. All these tetraesters and tetraacids were analyzed by FAB or MALDI mass spectroscopy, which gave molecular ion peaks in good agreement with the theoretical values (Table 1). No ion peaks corresponding to the aggregates were observed either by MALDI or electrospray (ES) mass spectroscopy.

2.2. Self-assembly studies

The aggregation behavior of tetraacids **1a**–**d**, was characterized by a combination of a variety of techniques including size exclusion chromatography (SEC), laser light scattering (LLS), small angle neutron scattering (SANS),

Table 1. MW measurement by FAB or MALDI mass spectrometry, SEC, LLS and VPO

Compound	Theory[a]	FAB or MALDI mass spectrometry	SEC MW		LLS		VPO
			CH_2Cl_2	THF	M_w	d*n*/d*c*	M_n
13a	1286.6	1286.5	1569	1452			
13b	1935.0	1935.5	2276	2193	2314	0.187	
13c	3232.9	3233.3	3495	3387	3514	0.192	3400
13d	5828.6	5831.9[b]	5033	5155	5793		
1a	1230.5	1230.6	7955[c]	1338			
1b	1879.0	1879.9	13,600	2129	39,532	0.189	
1c	3176.8	3200.0[b,d]	18,486	3413	49,607	0.175	15,600
1d	5768.5	–[e]	28,300[f]	4793	83,875		
19a	5251.4	5292.0[b,d]	9480		6163		
19b	9144.9	9168.5[b,d]	13,381		9314		
19c	16,932	–[e]	16,150		18,633		

[a] MWs of most abundant isotope.
[b] Determined by MALDI, all the others by FAB.
[c] Value was concentration-dependent, a 10 mM injection concentration was used.
[d] $M+Na^+$ or K^+.
[e] No signal was obtained by MALDI.
[f] Measured on HR5E column (MW range 2×10^3–4×10^6) with toluene as an eluent.

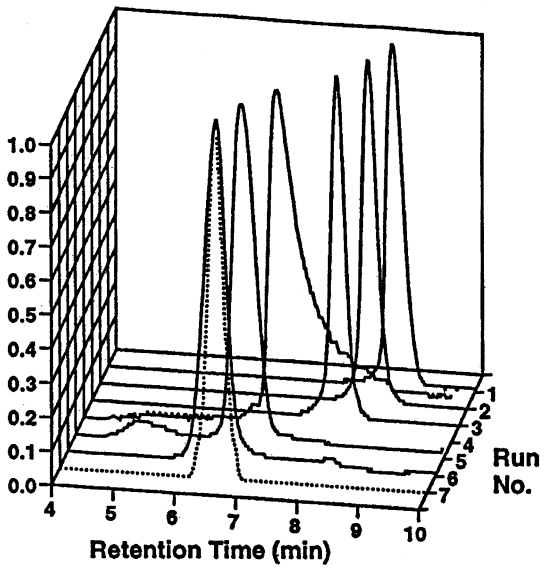


Figure 1. Stacked SEC traces of **13a–c** (run 1–3) and **1a–c** (run 4–6). Size standard **19c** (run 7, dotted line). Plots are normalized with arbitrary intensity units. All runs on Waters Ultrastyragel HR3 column (MW range 500–30,000) in CH_2Cl_2.

vapor pressure osmometry (VPO), and IR spectroscopy. Many of the studies focused on the third generation system, **1c**, rather than **1d** because it could be prepared on a larger scale.

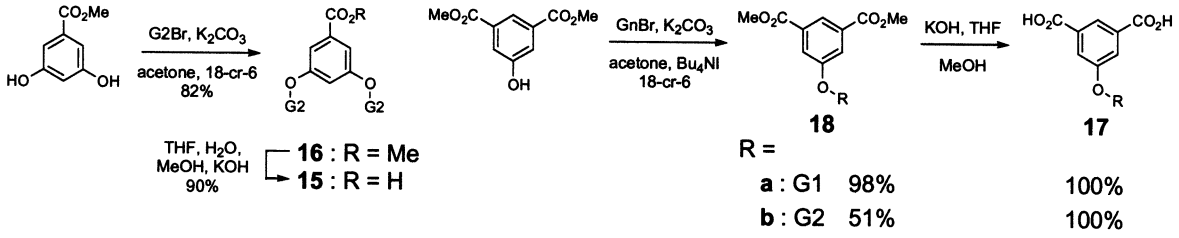
Size exclusion chromatography. SEC has emerged as a widely used technique for the study of non-covalently bonded aggregates. SEC is especially useful in the present system because of the large change in hydrodynamic radii with the generation number of tetraacids **1a–d** and between different putative *n*-mers. In addition, tetraesters **13a–d** can be used as controls because each has a size that is almost identical to its corresponding tetraacid **1a–d** yet it cannot aggregate.

When CH_2Cl_2 was used as an eluent, each tetraacid **1a–c** and its corresponding tetraester **13a–c** showed two well-separated peaks (Fig. 1). Due to the high molecular weight of the **1d** aggregate, its measurement had to be performed on a column with a higher MW range. In each case, tetraacids **1a–d** had a shorter retention time than the corresponding tetraesters **13a–d**, indicating aggregation by the former. In contrast, with THF as the eluent, the retention times of **1a–d** was nearly identical to the analogous **13a–d**. The experimental MW's of tetraacids **1a–c** and tetraesters **13a–d** were determined from their retention times both in CH_2Cl_2 and THF using polystyrene standards (PS) for calibration. As summarized in Table 1, the SEC MW of tetraesters **13** matched the theoretical monomer MW reasonably well in both solvents. The SEC MW values for tetraacids **1** in CH_2Cl_2 are within 20% of those calculated for hexameric aggregates, but close to the monomer MW in THF. This result suggests that each tetraacid self-assembles into a hexameric aggregate **2** in CH_2Cl_2 but exists as a monomer in the more competitive THF, a conclusion consistent with ^{1}H NMR studies.

One possible complication in the SEC MW determinations is the potential interaction between the polar carboxylic acid groups and the SEC column. For example, monoacid **15**, which was synthesized in two steps from **5** and methyl 3,5-dihydroxybenzoate (Scheme 4), showed a slightly broader SEC trace and a longer retention time than its precursor, ester **16**. This monoacid was not expected to dimerize at the concentrations used for the SEC experiment. To explore further the potential carboxylic acid-SEC matrix interaction, a series of dendritic isophthalic acids **17a,b** were synthesized (Scheme 4). Compounds **18a,b** contain half of the hydrogen-bonding sites of tetraacids **1a–d** and were expected to form less stable aggregates than **1a–d**. With CH_2Cl_2 as the eluent, these compounds displayed broad and poorly defined SEC peaks with extensive tailing, indicating non-specific assembly and a strong tendency to be retained by SEC column.

However, tetraacids **1b–d** (**1a** will be discussed later) showed sharp and symmetric SEC peaks (Fig. 1), with little apparent interaction with the SEC column. This observation was confirmed by two methods. First, a sample of **1c** was injected into the SEC column, the eluting volume corresponding to the peak area was collected and analyzed by UV–visible spectroscopy, which indicated complete recovery of the injected material. Second, when the polarity of the eluent was reduced from CH_2Cl_2, $E_T(30)$=40.7, to toluene, $E_T(30)$=33.9, to 40% (v/v) toluene–hexane, $E_T(30)$=31.0, the corresponding SEC retention time of **1c** changed minimally and the changes were in the same direction and of the same magnitude as seen with **13c**. A further decrease of eluent polarity to 20% (v/v) toluene–hexane resulted in the retention of both **1c** and **13c** by the SEC column. This observation indicates that the **1c** aggregate is a relatively apolar entity, consistent with the proposed cyclic structure in which the polar carboxylic acid groups are hydrogen-bonded and within the apolar dendrimer.

Although SEC calibration with PS standards is traditionally used for the MW determination of new macromolecules, the accuracy of this method is dependent on the size and shape similarity between a PS standard and the macromolecule



Scheme 4.

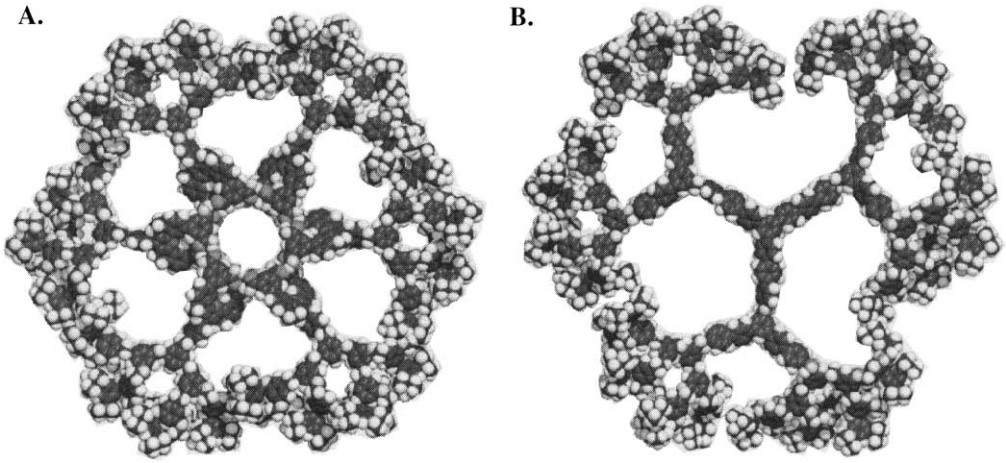
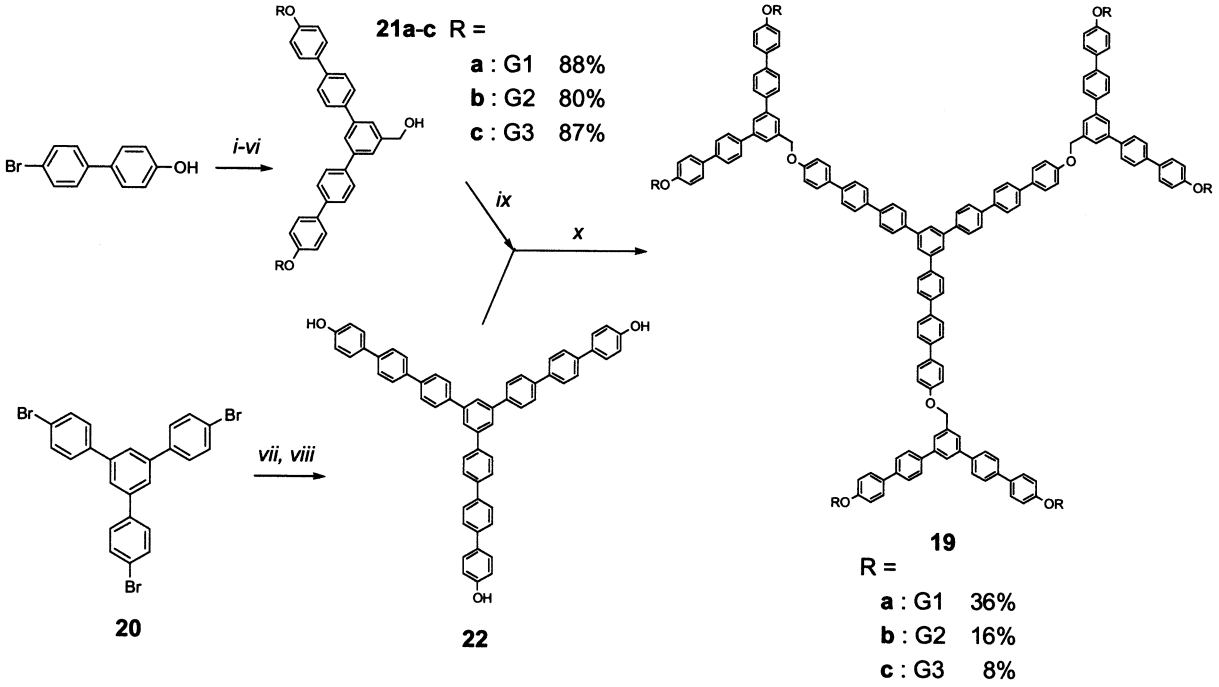


Figure 2. Molecular modeled structures showing similar sizes for: (A) $(\mathbf{1c})_6$ and (B) **19c**.

under investigation. For example, Hawker and Fréchet showed[7a] that PS is an appropriate standard for low generation dendrimers, but it underestimates the MW of high generation dendrimers due to their compactness. In the present study, tetraacids **1a–d** are still considered to be low generation dendrimers, and their proposed hexameric aggregates are not expected to be compact. Nevertheless, it would be more conclusive to have a suitable size standard for the putative hexameric aggregates.

Computer modeling studies suggested that semi-rigid dendrimers **19a–c** have sizes and shapes that are similar to the corresponding **1a–c** cyclic hexamers. Thus, they served as covalent size standards for the SEC (Fig. 2). The synthesis of **19a–c** required nine steps from the corresponding dendritic bromides **4–6**, 4-(4-bromophenyl)-phenol and tribromide **20**[14] (Scheme 5). SEC studies with CH_2Cl_2 as an eluent afforded retention times for these covalent models that were nearly identical to those of the corresponding tetraacids **1a–c**. Indeed, the SEC peaks for **1c** and **19c** have identical retention times and similar peak widths. These results strongly support the conclusion that **1c** forms a discrete, hexameric aggregate in CH_2Cl_2.

The SEC traces of tetraacid **1a** showed a broad peak with extensive tailing. This striking observation indicates that the dendritic substituents exert control over the aggregation process. It was hypothesized that **1a** might be forming non-discrete aggregates such as **3**. Computer modeling of the core tetraacid in **1** shows a 1.4 nm distance between adjacent hydroxyl groups where the dendrons are attached in aggregate **3** (Fig. 3(A)). Not only is the analogous



Scheme 5. (i) NaH, THF/MOMCl (93%); (ii) Mg, THF/$B(OMe)_3$; (iii) Methyl 3,5-dibromobenzoate, $Pd(PPh_3)_4$, PhMe, Na_2CO_3(aq), reflux (47% from benzoate); (iv) $CHCl_3$, *i*-PrOH, conc. HCl, (94%); (v) LAH, THF (95%); (vi) Gn-Br, 18-cr-6, K_2CO_3, acetone; (vii) see experimental section (47% from **20**); (viii) $CHCl_3$, *i*-PrOH, conc. HCl, (70%); (ix) CBr_4, PPh_3; (x) K_2CO_3, 18-cr-6, Bu_4NI, THF.

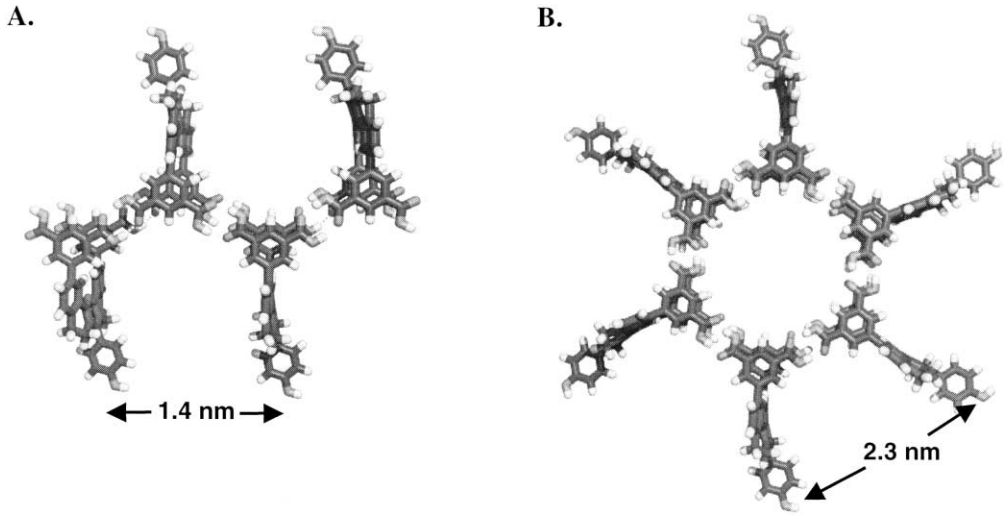


Figure 3. Molecular modeled structures showing distance between hydroxyl where dendrons are attached in: (A) linear tetramer $(\mathbf{8})_4$ modeled in aggregate structure **3**, (B) cyclic hexamer $(\mathbf{8})_6$ modeled in structure **2**.

distance (2.3 nm) greater in cyclic hexamer **2** (Fig. 3(B)), but also the dendrons diverge. Modeling shows that the first-generation dendron can be accommodated in **3**, but the second-generation dendron is already too large. Thus, **1b–d** are sterically guided in forming cyclic hexamer **2** because the larger peripheral groups cannot be accommodated in linear aggregates.[15] The extensive peak tailing for **1a** presumably originates from the interaction of uncomplexed carboxylic acid groups on the chain end with SEC column.

To further explore this hypothesized steering effect induced by the peripheral groups, two control compounds **1e**,**f**, were synthesized and compared (see Scheme 3). The 3,5-bis-(dodecyloxy)phenyl group in **1e** is smaller than the G1 dendron in **1a** and in **1f** the flexible linker is expected to be better accommodated in linear aggregate **3**. Polymeric aggregates, such as **3**, should grow as the concentration rose, whereas above a threshold concentration cyclic aggregates **2** might exhibit the constant molecular properties expected for the hexamer. Thus, a regular change in SEC derived MW values with concentration is taken as evidence for an open oligo- or polymeric aggregate. Fig. 4 shows the plot of experimental SEC MW of **1a–f** versus the natural logarithm of the injected concentration (CH_2Cl_2 eluent). Consistent with the arguments above, the SEC MW values for **1a**, **1e**, and **1f** decreased and their peaks broadened with decreasing concentration. The effect was most dramatic for **1e** containing the smallest substituent. Its SEC MW indicates monomer at high dilution and a polymer with degree of polymerization (DP)$>$10 at high concentration.

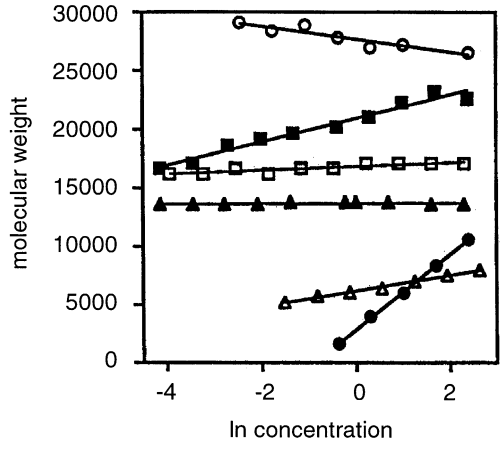


Figure 4. SEC determined molecular weights of **1a** (Δ), **1b** (▲), **1c** (□), **1d** (○) **1e** (●), **1f** (■) as a function of injection concentration. All runs in CH_2Cl_2 except **1d** (toluene). HR3 column for **1a**, **1b**, **1e**, all others on HR5E (see Table 1 for details).

For **1b** and **1c**, the SEC MW and sharpness of the peak remained essentially unchanged across a 50-fold concentration range (1 mM–0.02 mM). The SEC MW value for **1d** decreased slightly ($<$20%) as the concentration was raised and the plot showed considerable scatter. These results provide additional evidence for the formation of stable hexameric aggregates from **1b–d**.

Additional studies with **1c** were undertaken to test the stability of the hexamer in CH_2Cl_2. Hamilton has extensively studied the complexation of carboxylic acids by 2-acylamino-pyridines and shown strong association.[16] When a solution of **1c** containing up to 1500 molar ratio of 2-aminopyridine (2-NH_2Py) was analyzed by SEC, the hexamer peak remained unchanged. There are two possible reasons for this observation. One is that the hexamer is sufficiently stable that the 2-NH_2Py does not break it down. Alternatively, because 2-NH_2Py aminopyridine and **1c** are well separated on the SEC column their interaction may be prevented. When 1% (w/v) 2-NH_2Py/CH_2Cl_2 was used as an eluent two separate and sharp SEC peaks were observed in a ca. 7:1 ratio. The major peak had a retention time corresponding to the monomer, with the minor peak corresponding to the hexamer. The existence of two separated species is presumably due to a slow exchange process (vide infra). A complete breakdown of the hexamer into monomer occurred with ~5% 2-NH_2Py/CH_2Cl_2 as eluent.

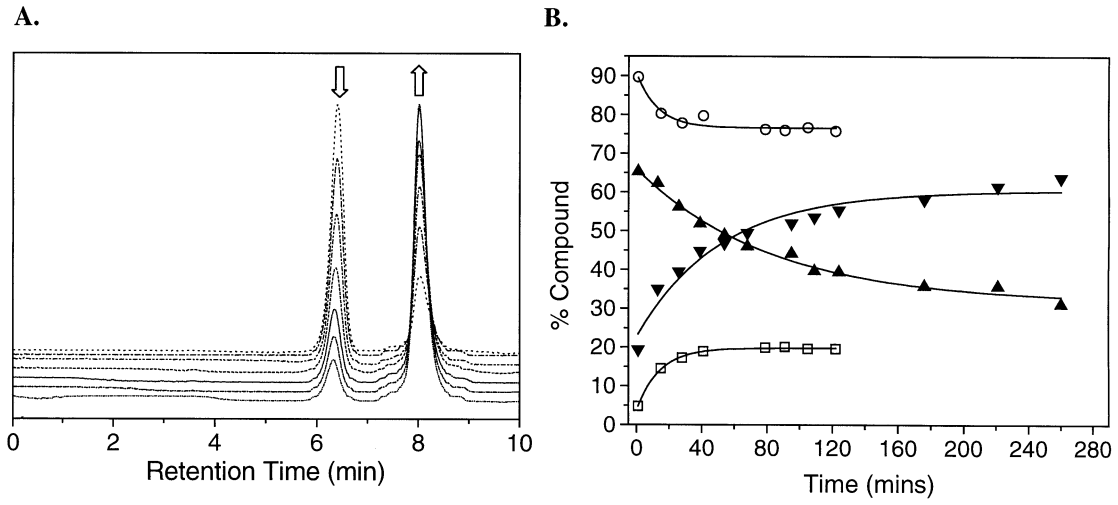


Figure 5. (A) Stacked SEC plots (CH_2Cl_2 eluent) for Compound **1c** over time following dilution of a CH_2Cl_2 solution of **1c** with an equal volume of THF. Time points: 1, 15, 27, 41, 55, 68, 81 mins. (B) Plot of dissociation and association kinetic points for Compound **1c**. Dissociation of $(\mathbf{1c})_6$ (▲) in CH_2Cl_2 solution and corresponding formation of **1c** (▼) initiated by addition of THF (see text). Formation (association) of $(\mathbf{1c})_6$ (□) in THF solution and corresponding loss of **1c** (○) initiated by addition of CH_2Cl_2.

Laser light scattering and small angle neutron scattering. Weight-average MWs (M_w) of the aggregates were also determined by LLS in an on-line mode, in which a dual-angle (15 and 90°) LLS detector as well as a differential refractometer (DRI) detector was coupled to SEC. The d*n*/d*c* used for the M_w calculation was measured independently by an interferometric refractometer. Table 1 summarizes the M_w data collected. For all covalently linked dendrimers, the LLS M_w's are very close to the corresponding theoretical values. However, LLS M_w's of **1b–d** were approximately two-fold greater than the calculated hexameric MWs. The origin of the deviation is not known, but the presence of a small amount of a high MW aggregate will dramatically increase the weight-average MW determined by LLS as has been reported in other systems.[17]

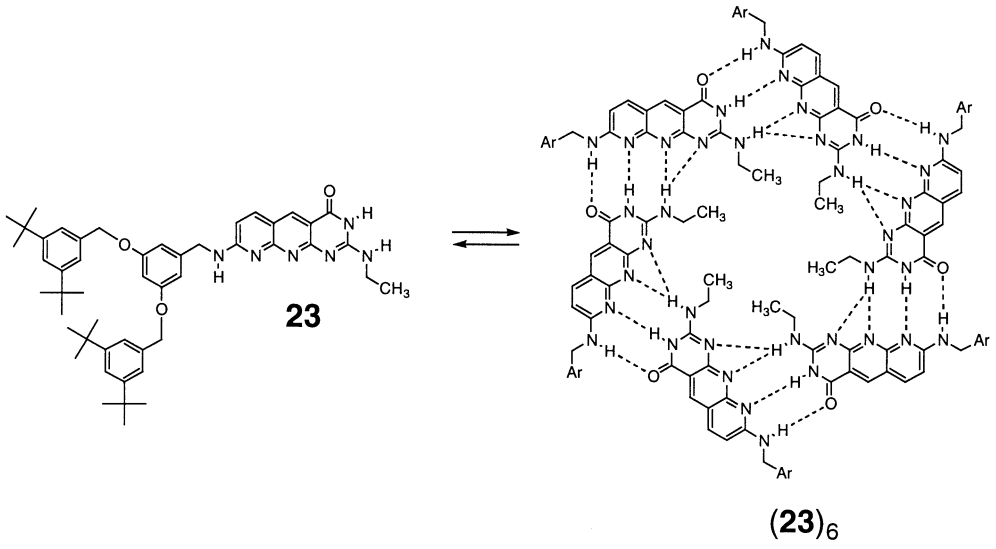
Because of the uncertainty surrounding the LLS results, tetraacids **1a–c** were investigated by using SANS. These results were previously described[18] in detail and only a brief summary will be presented here. In $CDCl_3$, the experimental SANS data of both **1b** and **1c** agreed reasonably well with simulated SANS data derived from the corresponding cyclic hexamer structural coordinates obtained by molecular modeling. Furthermore, the radii of gyration (R_g) obtained from the Guinier plots (Q region where $QR_g \sim 1.0$) were 27.1 and 30.4 Å for **1b** and **1c**, respectively, which compared well with the values of 28.6 and 33.6 Å, respectively, calculated from the modeled structure. However, the SANS data for **1a** could not be fit by a polymeric aggregate structure, modeled as **2**, whereas a hollow, cylindrical model seems to fit the data well.

Vapor pressure osmometry. VPO, a traditional technique to measure the number average MW (M_n) of a solute in a solution, has proven useful for the studies of non-covalent aggregates.[19] VPO measurements were made on several compounds including G3Br (**6**), tetraester **13c**, and tetraacid **1c** in chloroform, using benzil for calibration. The quotients of vapor pressure signal (R) over concentration (C) were plotted against C. The M_n values, inversely proportional to the intercept at [C]=0, were determined to be 1696, 3394 and 15,569 g mol^{-1} for **6**, **13c**, and **1c**, respectively (Table 1). Given the uncertainties in the method, these values matched reasonably well with the corresponding theoretical M_n.

IR spectroscopy. To gain spectroscopic evidences of the self-assembly systems, tetraacids **1a–d** were studied by IR spectroscopy. It is well known that the stretching frequency of a carbonyl group decreases upon the formation of a carboxylic acid hydrogen-bonding dimer. IR spectra of all tetraacids in $CHCl_3$ showed a broad carbonyl absorption signal with a major peak centered at ~1712 cm^{-1} and a shoulder at ~1690 cm^{-1}. These frequencies are close to the range expected for a carboxylic acid dimer. More conclusive evidence was derived from the comparison of IR spectra of tetraacid **1c** and tetraester **13c** in $CHCl_3$ and THF. For tetraester **13c**, which cannot form hydrogen bonds, the carbonyl stretching frequency ($\upsilon_{c=o}$) increased by just 4.9 cm^{-1} in moving from $CHCl_3$ to THF. In comparison, the $\upsilon_{c=o}$ of tetraacid **1c** was 12.6 cm^{-1} higher in the polar THF solvent, where the carboxylic acid group is monomeric.

2.3. Kinetics, thermodynamics, and fidelity of the self-assembly process

As discussed earlier, tetraacids **1b** and **1c** exist as hexameric aggregates in apolar solvents such as CH_2Cl_2 and $CHCl_3$ but dissociate to monomer in THF. In an effort to determine the transition point between hexamer and monomer, and thus the thermodynamic contribution of the dendritic substituents, SEC studies were performed on **1b** and **1c** using mixtures of THF–CH_2Cl_2 eluent. Strikingly, well-separated peaks for hexamer and monomer were observed, with the monomer peak increasing in intensity as the amount of THF in the eluent increased. This result is analogous to that observed with 2-NH_2Py present in the eluent (vide supra) and indicates a kinetically slow and cooperative equilibrium between monomer and hexamer. A similar observation was

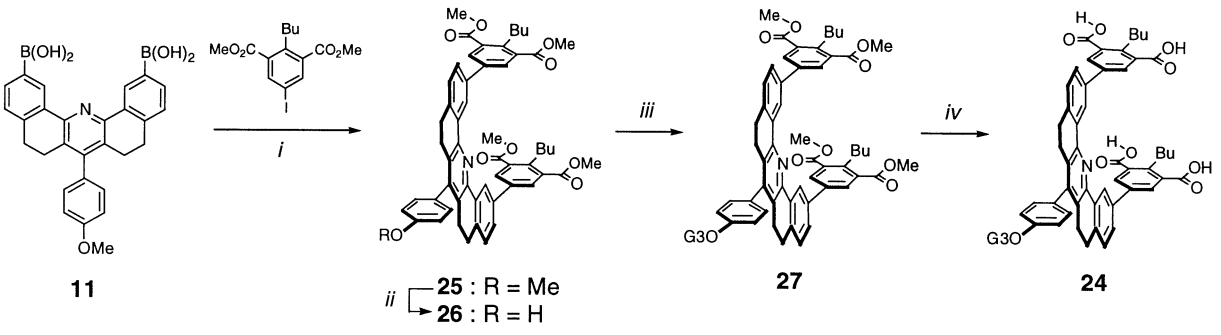


Scheme 6.

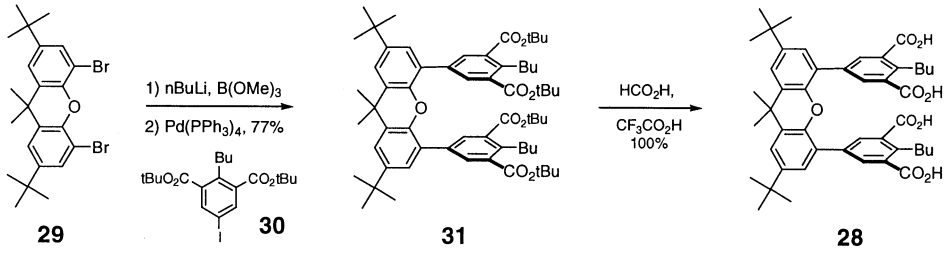
made by ^{1}H NMR studies, in which two distinct signals corresponding to *tert*-butyl peaks were detected in different ratios of THF-d_8/CD_2Cl_2.

To further elucidate the thermodynamics and kinetics of self-assembly, a variety of experiments were performed, in which the dissociation or association process was monitored by SEC or ^{1}H NMR. For example, in Fig. 5(A) is shown stacked SEC traces representing the conversion of hexamer to monomer that occurs over time after a CH_2Cl_2 solution of **1c** was diluted with an equal volume of THF. The rate of dissociation and association changed considerably from run to run, whereas the position of the equilibrium state is somewhat more reproducible. For example, in one experiment a solution of **1c** in CH_2Cl_2 diluted with an equal volume of THF reached equilibrium within 81 min whereas in another case, the dissociation process was still proceeding after 260 min. As seen in Fig. 5(B), the dissociation of $(\mathbf{1c})_6$ in CH_2Cl_2 initiated by addition of an equal volume of THF reached an equilibrium with a ca. 3:2 ratio of **1c** to $(\mathbf{1c})_6$ whereas the analogous association experiment equilibrated to a ca. 3:1 ratio of **1c** to $(\mathbf{1c})_6$. The origin of the variability is unclear and was also observed in experiments with **1b**. Qualitatively the dissociation kinetics were much slower for **1b** and its hexamer was somewhat more stable than that from **1c**. Unfortunately, definitive conclusions about the relative contribution of the dendrimers to the stability of $(\mathbf{1})_6$ could not be made.

An interesting question related to the kinetics and thermodynamics of formation is whether **1a**–**d** would form mixed aggregates or sterically sort themselves into a specific assembly and whether the assembly would maintain its integrity in the presence of other self-assembling systems. Equal molar binary mixtures of **1a** and **1d** and of **1b** and **1d** were studied by SEC as a function of mixing time. In the **1a/1d** mixture a broad peak with tailing was observed, which could be consistent with either non-specific mixed aggregates or a mixture of the $(\mathbf{1a})_n$ and $(\mathbf{1d})_6$ aggregates seen above. In the **1b/1d** mixture two well-shaped peaks were observed with the retention times of the corresponding hexamers. However, the peak separation was not sufficient to exclude the presence of mixed aggregates. We have previously described[20] a heterocyclic system (**23**) that forms a robust hexamer in a range of solvents(Scheme 6). Modeling indicates a smaller size for $(\mathbf{23})_6$ in comparison to $(\mathbf{1a})_6$. Thus, a 1:1 mixture of **1c** and **23** in toluene was studied by SEC. Two distinct peaks corresponding to the hexamer were present even after mixing for three days, although because the peaks were not base-line resolved a small amount of mixing cannot be ruled out. Thus, even though **23** contains basic sites and complementarity to **1**



Scheme 7. (i) $Pd(PPh_3)_4$, PhMe, K_2CO_3(aq), reflux; (ii) BBr_3, CH_2Cl_2; (iii) **6**, 18-cr-6, Bu_4NI, K_2CO_3, acetone (91%); (iv) KOH, H_2O, THF, MeOH (93%).



Scheme 8.

both compounds assemble with high fidelity. These results suggest the possibility of creating much more complicated self-assembling structures containing two or more complementary hydrogen bonding motifs.

2.4. Variations in the structure of the self-assembling system

To further explore the relationship between the structure and the stability of the aggregate and to pave the way toward functional hexamers, several new molecules analogous of tetraacids **1** were synthesized. The first target was compound **24**, in which a butyl group was introduced into the *ortho*-positions of carboxylic acids (Scheme 7). These butyl groups force the carboxylic acid dimer out of plane, but more importantly, they orient into the self-assembled dendrimer and could ultimately be functionalized to carry addition recognition or catalytic groups. Compound **24** was synthesized in a fashion similar to that of **1c**. Thus, diboronic acid **11** was coupled to dimethyl 2-butyl-5-iodoisophthalate. The coupling product, **25**, was demethylated to afford phenol **26**. Alkylation of **26** with G3Br **6** gave 91% yield of tetraester **27**, which was hydrolyzed to tetraacid **24** in 93%. The aggregate MW of **24** was determined to be 19478 by SEC and 36529 by LLS with toluene as an eluent. Both results were similar to those obtained from tetraacid **1c**, indicating the formation of a hexameric aggregate.

It was also of interest to explore tetraacids with spacers that provide a different distance between the isophthalic acid units. Tetraacids with shorter spacers were particularly appealing from the perspective of their greater potential for crystallinity due to their reduced internal void volume in the hexamer. For this reason, tetraacid **28** with a xanthene spacer was designed and synthesized. Dibromide **29**[21] was converted to the corresponding diboronic acid, which was coupled to di(*tert*-butyl) 2-butyl-5-iodoisophthalate (**30**) under Suzuki conditions to give tetraester **31** in 77% yield. Hydrolysis of **31** with trifluoroacetic acid and formic acid afforded the desired tetraacid **28** in quantitative yield (Scheme 8). Attempts to grow a crystal of **28** from a range of solvents including THF, ethanol, 1-propanol, 2-propanol, 1-butanol, *iso*-butanol and *tert*-butanol were unsuccessful, leading to powders or thin needles in each case.

3. Conclusions and outlook

Using a battery of techniques dendritic tetraacids **1** were shown to self-assemble in a generation-dependent manner in apolar organic solvents. Tetraacids **1a**, **1e**, and **1f** with small peripheral groups form linear, polymeric aggregates with a concentration-dependent molecular weight. These represent one of the first examples of a main-chain supramolecular polymer formed by reversible hydrogen bonding.[22] The second- to fourth-generation dendritic tetraacids, in contrast, self-assembled into discrete hexamers with high stability. To our knowledge these represent the first examples of discrete aggregates being formed from polymeric subunits.[23]

The ability to form protein-sized structures in a cooperative self-assembly process has obvious implications for the production of new nanoscopic devices. For example, one can envision covalently capturing the assembly, and with appropriate structural modifications, removing the hydrogen bonded core units to create a permanent hollow nanosphere. This type of core-shell process would produce nanospheres with capacious voids that are also highly homogeneous. In such a system molecular recognition would mediate a self-assembly process that ultimately leads to a covalent structure difficult to produce by conventional synthetic methods.

Perhaps the most important application of this type of supramolecular polymer chemistry is in creating useful new properties that take advantage of the reversibility of the assembly process. For example, the hexameric dendritic assembly **2d** would be expected to have very different materials properties in comparison to a covalent dendrimer of comparable size and analogous branching and peripheral functionality. At high temperatures it would behave more like a low molecular weight material. Likewise, physical stresses that might break bonds within a covalent structure might in the self-assembled dendrimer be dissipated by subunit dissociation. Subsequently the original structure may reform by association. Whether this type of self-healing properties will be observed in the systems described herein remains to be seen.

4. Experimental section

4.1. General methods

All solvents and reagents were of reagent grade quality, purchased commercially, and used without further purification except as noted below. The following solvents were freshly distilled prior to use: methylene chloride (CH_2Cl_2), from calcium hydride; benzene, tetrahydrofuran (THF), and diethyl ether (Et_2O) from sodium and benzophenone. Acetone was dried over 4 Å molecular sieves. Analytical thin layer chromatography (TLC) was performed on

0.2 mm silica plastic coated sheets (E. Merck) with F_{254} indicator. Flash chromatography was performed on Merck 40–63 μm silica gel. Preparative thin-layer chromatography was performed on a chromatotron (Harrison research) with a plate made from silica gel 60 PF_{254} containing gypsum. Melting points were measured on a Thomas–Hoover melting point apparatus or a Reichert hot stage apparatus and are uncorrected.

^1H and ^{13}C NMR spectra were recorded on a General Electric QE-300 or GN-500 instrument. Spectra were obtained in chloroform-*d* ($CDCl_3$) unless otherwise noted. Chemical shifts are reported in parts per million (ppm) and coupling constants are reported in Hertz (Hz). ^1H NMR spectra in chloroform-*d* were referenced to TMS as an internal reference at 0.0 ppm, or to the residual chloroform peak at 7.26 ppm. ^1H NMR spectra in dimethylsulfoxide-d_6 (DMSO-d_6) were referenced to the residual protio solvent peak at 2.49 ppm. ^{13}C NMR spectra in chloroform-*d* were referenced to the solvent peak at 77.0 ppm. ^{13}C NMR spectra in DMSO-d_6 were referenced to the solvent peak at 39.5 ppm. Infrared (IR) spectra were recorded on a Mattson Instruments FTIR (Galaxy system); absorptions are reported in wavenumbers (cm^{-1}). Mass spectra (MS) were obtained on a Finnigan-MAT-731 (EI), ZAB-SE (FAB), or TofSpec (MALDI) spectrometer. 2-(4-Hydroxyphenylazo)benzoic acid (HABA) or *trans*-3-indoleacrylic acid (IAA) were used as a matrix. Elemental analyses were performed at the University of Illinois School of Chemical Sciences.

SEC was performed on a Waters Ultrastyragel HR3 (MW range 500–30,000) or HR5E (MW range 2000–4×10^6) column coupled with Waters 410 DRI and PD2000 dual angle LLS detectors or with a Hitachi L-4000H UV detector by using Hitachi L-6000 pump. CH_2Cl_2, THF, or toluene of HPLC grade was used as an eluent as needed. HPLC was performed on an Alltech adsorbosphere HS silica column. Different ratios of ethyl acetate/methylene chloride were used as eluents. Flow rate for both SEC and HPLC was 1 mL min^{-1}. VPO experiment was performed on a UIC 070 vapor pressure osmometer. HPLC-grade chloroform was used as a solvent.

The preparation and spectra for compound **17a**,**b** and **25** are analogous to those for **13a**,**b** and **12**, respectively, and are not detailed.

4.1.1. 2,12-Bis(3,5-dicarboxyphenyl)-7-(4-(3,5-bis(3,5-di(*tert*-butyl)phenylmethoxy)phenylmethoxy)phenyl)-5,6,8,9-tetrahydrodibenz[*c*,*h*]acridine (1a). A homogeneous mixture of 60 mg (0.047 mmol) of ester **13a** in 7.5 mL of THF, 0.2 g (3 mmol) of potassium hydroxide in 1 mL of water, and 3.5 mL of methanol was refluxed overnight. The solution was cooled and concentrated under reduced pressure. The residue was diluted with water and neutralized with a 2N aqueous solution hydrogen chloride. The precipitate was filtered and washed well with water to give 51 mg (100%) of tetraacid **1a** as a white powder: ^1H NMR (90% DMSO-d_6/$CDCl_3$, 50°C) δ 13.2–12.4 (br, 4H), 8.72 (s, 2H), 8.41 (s, 2H), 8.35 (s, 4H), 7.62 (d, *J*=7.8 Hz, 2H), 7.36 (d, *J*=7.8 Hz, 2H), 7.35 (s, 2H), 7.26 (s, 4H), 7.22 (d, *J*=8.2 Hz, 2H), 7.13 (d, *J*=8.2 Hz, 2H), 6.75 (s, 2H), 6.68 (s, 1H), 5.10 (s, 2H), 5.05 (s, 4H), 2.82 (m, 4H), 2.65 (m, 4H), 1.28 (s, 36H); ^{13}C NMR δ 166.0, 160.7, 158.8, 150.6, 150.0, 147.5, 141.7, 139.7, 138.2, 137.9, 136.6, 136.2, 131.9, 131.6, 130.0, 129.6, 129.4, 128.0, 127.1, 125.0, 123.8, 122.0, 121.5, 114.9, 106.2, 101.0, 70.6, 70.0, 34.6, 31.0, 27.8, 26.0; FAB-MS calcd for $C_{80}H_{79}NO_{11}$ 1230.5 found 1230.6 (M^+). Anal. calcd for $C_{80}H_{79}NO_{11}$: C, 78.09; H, 6.47; N, 1.14. Found: C, 77.76; H, 6.54; N, 1.47.

4.1.2. 2,12-Bis(3,5-dicarboxyphenyl)-7-(4-(3,5-bis(3,5-bis(3,5-di(*tert*-butyl)phenylmethoxy)phenylmethoxy)-phenylmethoxy)phenyl)-5,6,8,9-tetrahydrodibenz[*c*,*h*]-acridine (1b). The procedure used to prepare **1a** was followed. Thus, the hydrolysis of 1.17 g (0.605 mmol) of ester **13b** in 120 mL of THF with 3.8 g (68 mmol) of potassium hydroxide in 15 mL of water and 35 mL of methanol gave 1.14 g (100%) of **1b** as a white powder: ^1H NMR δ 13.3–12.4 (br, 4H), 8.69 (s, 2H), 8.43 (s, 2H), 8.38 (s, 4H), 7.63 (d, *J*=7.6 Hz, 2H), 7.35 (d, *J*=7.6 Hz, 2H), 7.31 (s, 4H), 7.23 (s, 8H), 7.18 (d, *J*=8.4 Hz, 2H), 7.14 (d, 2H), 6.732 (d, *J*=0.9 Hz, 2H), 6.70 (d, *J*=0.9 Hz, 4H), 6.63 (t, 2H), 6.61 (t, 1H), 5.09 (s, 2H), 5.01 (s, 12H), 2.82 (m, 4H), 2.63 (m, 4H), 1.24 (s, 72H); both FAB- and MALDI-MS calcd for $C_{124}H_{135}NO_{15}$ 1879.4, found 1879.9 (M^+). Anal. calcd for $C_{124}H_{135}NO_{15}\cdot 1.8H_2O$: C, 77.90; H, 7.31; N, 0.73. Found: C, 78.13; H, 7.64; N, 0.70.

4.1.3. 2,12-Bis(3,5-dicarboxyphenyl)-7-(4-(3,5-bis(3,5-bis(3,5-bis(3,5-di(*tert*-butyl)phenylmethoxy)phenylmethoxy)phenylmethoxy)phenylmethoxy)phenyl)-5,6,8,9-tetrahydrodibenz[*c*,*h*]acridine (1c). The procedure used to prepare **1a** was followed. Thus, the hydrolysis of 0.255 g (0.079 mmol) of ester **13c** in 35 mL of THF with 0.4 g (7 mmol) of potassium hydroxide in 4 mL of water and 14 mL of methanol gave 0.247 g (98%) of **1c** as a white powder: ^1H NMR (91% DMSO-d_6/$CDCl_3$, 50°C) δ 13–12.5 (br, 4H), 8.68 (s, 2H), 8.43 (s, 2H), 8.37 (s, 4H), 7.62 (dd, *J*=6.0, 0.8 Hz, 2H), 7.33 (d, *J*=6.0 Hz, 2H), 7.28 (s, 8H), 7.20 (s, 16H), 7.16 (d, *J*=8.6 Hz, 2H), 7.08 (d, *J*=8.6 Hz, 2H), 6.71 (d, *J*=1.6 Hz, 2H), 6.68 (d, *J*=1.8 Hz, 4H), 6.67 (d, *J*=1.8 Hz, 8H), 6.62 (s, 1H), 6.60 (s, 4H), 6.58 (s, 2H), 5.03 (s, 2H), 4.97 (s, 28H), 2.79 (t, *J*=6.0 Hz, 4H), 2.62(t, *J*=6.0 Hz, 4H), 1.22 (s, 144H); MALDI-MS calcd for $C_{212}H_{247}NO_{23}$, 3177.3, found 3218 ($M+K^+$), 3200 ($M+Na^+$), 3178 (M^+). Anal. calcd for $C_{212}H_{247}NO_{23}$: C, 80.14; H, 7.84; N, 0.44. Found: C, 70.91; H, 7.82; N, 0.41.

4.1.4. 2,12-Bis(3,5-dicarboxyphenyl)-7-(4-(3,5-bis(3,5-bis-(3,5-bis(3,5-bis(3,5-di(*tert*-butyl)phenylmethoxy)phenylmethoxy)phenylmethoxy)phenylmethoxy) phenylmethoxy)phenyl)-5,6,8,9-tetrahydrodibenz[*c*,*h*]acridine (1d). The procedure used to prepare **1a** was followed. Thus, the hydrolysis of 0.27 g (0.046 mmol) of ester **13d** in 20 mL of THF with 0.3 g (5.4 mmol) of potassium hydroxide in 2 mL of water and 5 mL of methanol gave 0.25 g (94%) of **1d** as a white powder: ^1H NMR (67% DMSO-d_6/$CDCl_3$, 50°C) δ 8.60 (s, 2H), 8.42 (s, 2H), 8.17 (s, 4H), 7.48 (d, $J_{3,4}$=7.8 Hz, 2H), 7.25 (s, 16H), 7.21 (d, $J_{3,4}$=7.8 Hz, 2H), 7.11 (d, 2H), 7.05 (d, 2H), 6.69–6.62 (m, 30H), 6.59–6.52 (m, 15H), 4.91 (s, 62H), 2.74 (m, *J*=6.0 Hz, 4H), 2.59 (m, 4H), 1.21 (s, 288H).

4.1.5. 2,12-Bis(3,5-dicarboxyphenyl)-7-(4-(3,5-didodecyloxy)phenylphenyl)-5,6,8,9-tetrahydrodibenz[*c*,*h*]acridine (1e). The procedure used to prepare **1a** was followed. Thus, the hydrolysis of 53 mg (0.045 mmol) of ester **13e** in 15 mL of THF with 0.2 g (3 mmol) of potassium hydroxide in 2 mL of water and 7 mL of methanol gave 51 mg (100%) of tetra-acid **1e** as a white powder: ^{1}H NMR(DMSO-d_6, 50°C) δ 12.5–12.3 (br, 4H), 8.72 (s, 2H), 8.40 (s, 2H), 8.36 (s, 4H), 7.64 (d, J=7.6 Hz, 2H), 7.38 (d, J=7.6 Hz, 2H), 7.23 (d, J=8.4 Hz, 2H), 7.13 (d, J=8.4 Hz, 2H), 6.59 (d, J=1.6 Hz, 2H), 6.40 (t, 1H), 5.09 (s, 2H), 3.93 (t, J=6.4 Hz, 4H), 2.80 (t, J=7.2 Hz, 4H), 2.58 (t,, J=7.2 Hz, 4H), 1.67 (m, 4H), 1.39–1.16 (m, 32H), 0.80 (t, J=6.4 Hz, 6H); FAB-MS calcd for $C_{74}H_{83}NO_{11}$ 1162.5, found 1162.3 (M^+). Anal. calcd for $C_{74}H_{83}NO_{11}\cdot 0.5H_2O$: C, 75.87; H, 7.23; N, 1.20. Found: C, 75.76; H, 7.25; N, 1.35.

4.1.6. 2,12-Bis(3,5-dicarboxyphenyl)-7-(4-(3,5-bis(3,5-bis(3,5-bis(3,5-di(*tert*-butyl)phenylmethoxy)phenylmethoxy)phenylmethoxy)phenylmethoxy)ethoxyethoxyethoxyphenyl)-5,6,8,9-tetrahydrodibenz[*c*,*h*]acridine (1f). The procedure used to prepare **1a** was followed. Thus, the hydrolysis of 0.26 g (0.077 mmol) of ester **13f** in 30 mL of THF with 0.3 g (5.4 mmol) of potassium hydroxide in 3 mL of water and 15 mL of methanol gave 0.22 g (86%) of **1f** as a white powder: ^{1}H NMR (67% DMSO-d_6 /$CDCl_3$) δ 8.73 (s, 2H), 8.36 (s, 2H), 8.26 (s, 4H), 7.51 (d, 2H), 7.27 (s, 8H), 7.18 (s, 16H), 7.11 (d, 2H), 6.98 (d, 2H), 6.7–6.5 (m, 21H), 4.99–4.91 (s, 28H), 4.38 (m, 2H), 4.05 (m, 2H), other CH_2O peaks overlapped with residual water peak, 2.80 (m, 4H), 2.60 (m, 4H), 1.23 (s, 144H). FAB-MS calcd for $C_{218}H_{259}NO_{26}$: 3309.4. Found: 3310.0.

4.1.7. Methyl 3,5-bis(3,5-di(*tert*-butyl)phenylmethoxy)-benzoate. A mixture of 23.8 g (84.1 mmol) of **9**, 6.56 g (42 mmol) of methyl 3,5-dihydroxybenzoate, 16.2 g (117 mmol) of potassium carbonate, and 0.25 g (0.94 mmol) of 18-crown-6 in 280 mL of dry acetone was refluxed for 24 h or until TLC showed the disappearance of the starting materials. The solvent was removed under reduced pressure and the crude residue was dissolved in 300 mL of methylene chloride and 100 mL of water. The organic layer was separated and the aqueous layer was extracted twice with 100 mL of methylene chloride. The combined organic layers were washed with 50 mL of brine, dried with sodium sulfate, and evaporated under reduced pressure. The crude product was purified by recrystallization from petroleum ether (30–60°C) to give 21 g (87%) of white solid: mp 132–133°C; ^{1}H NMR δ 7.42 (t, J=1.5 Hz, 2H), 7.34 (d, J=2 Hz, 2H), 7.29 (d, J=1.5 Hz, 4H), 6.87 (t, J=2 Hz, 1H), 5.04 (s, 4H), 3.92 (s, 3H), 1.34 (s, 36H). Anal. calcd for $C_{38}H_{52}O_4$: C, 79.68; H, 9.15. Found: C, 79.51; H, 9.38.

4.1.8. 3,5-Bis(3,5-di(*tert*-butyl)phenylmethoxy)benzyl alcohol (G1OH). A solution of 3.3 g of methyl 3,5-bis(3,5-di(*tert*-butyl)phenylmethoxy)benzoate in 50 mL of THF was added dropwise to a mixture of 220 mg of $LiAlH_4$ in 25 mL of THF at 0°C. The mixture was allowed to warm to room temperature, stirred overnight, and carefully quenched with a 1 M aqueous solution of sodium hydroxide (ice bath cooling). The mixture was carefully filtered and the solid washed with 130 mL of THF. The organic layer was separated and the aqueous layer washed three times with 90 mL of ether. The combined organic layers were washed with brine, dried, and concentrated to give 2.9 g (92%) of a white foamy product, which was carried forward to the next step. ^{1}H NMR δ 7.42 (t, J=1.9 Hz, 2H), 7.29 (d, J=1.9 Hz, 4H), 6.68 (d, J=2.2 Hz, 2H), 6.63 (t, J=2.2 Hz, 1H), 5.02 (s, 4H), 4.67 (s, 2H), 1.40 (s, 36H).

4.1.9. 3,5-Bis(3,5-di(*tert*-butyl)phenylmethoxy)benzyl bromide (4). To a solution of 21 g (38.6 mmol) of 3,5-bis(3,5-di(*tert*-butyl)phenylmethoxy)benzyl alcohol in 250 mL of ether was added slowly a solution of 10 g (36.9 mmol) of phosphorus tribromide in 50 mL of ether at 0°C. The mixture was stirred for 2 h and was quenched slowly with 100 mL of water. The organic layer was separated and the aqueous layer was extracted twice with 100 mL of ether. The combined organic layers were washed with 80 mL of brine, dried with sodium sulfate, and concentrated under reduced pressure. The crude solid product was recrystallized from petroleum ether/hexanes to give 19 g (84%) of **4** as a white powder: mp 104°C; ^{1}H NMR δ 7.48 (t, 2H), 7.34 (d, 4H), 6.74 (d, 2H), 6.69 (t, 1H), 5.06 (s, 4H), 4.49 (s, 2H), 1.40 (s, 36H); ^{13}C NMR δ 160.3, 151.1, 139.7, 135.6, 122.4, 108.1, 102.2, 71.1, 34.9, 33.8, 31.5. Anal. calcd for $C_{37}H_{51}BrO_2$: C, 73.13; H, 8.46; Br, 13.15. Found: C, 73.34; H, 8.60; Br, 13.13.

4.1.10. 3,5-Bis(3,5-bis(3,5-di(*tert*-butyl)phenylmethoxy)-phenylmethoxy)benzyl alcohol (G2OH). A mixture of 8.56 g of **4**, 990 mg of 3,5-dihydroxybenzyl alcohol, 2.44 g of potassium carbonate, and 370 mg of 18-crown-6 in 300 mL of acetone were refluxed overnight. The solvent was removed under reduced pressure and the residue partitioned between water and methylene chloride. The water layer was washed twice with methylene chloride and the organic layers combined. The solvent was removed at reduced pressure to give 8.13 g (97%) of crude product, which was sufficiently pure to carry forward to the next step. ^{1}H NMR δ 7.44 (t, J=1.6 Hz, 4H), 7.32 (d, J=1.6 Hz, 8H), 6.77 (d, J=2.0 Hz, 4H), 6.69 (t, J=2.0 Hz, 2H), 6.67 (d, J=2.0 Hz, 2H), 6.61 (t, J=2.0 Hz, 1H), 5.04 (s, 12H), 4.67 (d, J=4.6 Hz, 2H), 1.37 (s, 72H).

4.1.11. 3,5-Bis(3,5-bis(3,5-di(*tert*-butyl)phenylmethoxy)-phenylmethoxy)benzyl bromide (5, G2Br). To the solution of 36 g (30.2 mmol) of G2OH in 200 mL of tetrahydrofuran was added 10 g (30.2 mmol) of carbon tetrabromide and 8 g (30.2 mmol) of triphenylphosphine. The mixture was stirred for 40 min and some precipitate appeared. An additional 5 g (15.1 mmol) of carbon tetrabromide and 4 g (15.1 mmol) of triphenylphosphine were added, the reaction mixture was stirred for another 1 h. The reaction was quenched with 100 mL of water and the mixture was extracted four times with 600 mL of methylene chloride. The combined organic layers were washed with 100 mL of brine, dried with sodium sulfate, and concentrated under reduced pressure. The crude residue was treated with 400 mL of 95% ethanol and cooled at the refrigerator overnight. The precipitate was filtered and purified by recrystallization from ethanol–ethyl acetate to afford 35 g (93%) of **5** as a white powder: mp 63–65°C; ^{1}H NMR δ 7.42 (t, J=1.4 Hz, 4H), 7.29 (d, J=1.4 Hz, 8H), 6.73 (d, 4H),

6.66 (m, 4H), 6.60 (t, 1H), 5.01 (s, 12H), 4.43 (s, 2H), 1.40 (s, 72H). Anal. calcd for $C_{81}H_{107}BrO_6$: C, 77.42; H, 8.58; Br, 6.36. Found: C, 77.76; H, 8.82; Br, 6.42.

4.1.12. 3,5-Bis(3,5-bis(3,5-bis(3,5-di(*tert*-butyl)phenylmethoxy)phenylmethoxy)phenylmethoxy)benzyl alcohol (G3OH). Using the same procedure for G2OH, 2 g of **5** and 112 mg of 3,5-dihydroxybenzyl alcohol was converted into crude product, which was purified by chromatography on silica (5–20% EtOAc/petroleum ether) to give 1.44 g (87%) of the desired product as a white solid, which was of sufficient purity to carry forward.

4.1.13. 3,5-Bis(3,5-bis(3,5-bis(3,5-di(*tert*-butyl)phenylmethoxy)phenylmethoxy)phenylmethoxy)benzyl bromide (6, G3Br). The procedure used to prepare **5** was followed. Thus, the reaction of 43 g (17.3 mmol) of G3-OH with 8.64 g (26 mmol) of carbon tetrabromide and 6.75 g (26 mmol) of triphenylphosphine in 200 mL of THF gave 41.1 g (93%) of **6** as a white foamy solid after purification by flash chromatography (1–10% ethyl acetate/petroleum ether): ^{1}H NMR δ 7.40 (t, 8H), 7.27 (d, 16H), 6.73 (d, 8H), 6.70 (d, 4H), 6.65–6.60 (m, 9H), 5.00–4.97(2s, 28H), 4.37(s, 2H), 1.32(s, 144H).

4.1.14. 3,5-Bis(3,5-bis(3,5-bis(3,5-bis(3,5-di(*tert*-butyl)phenylmethoxy)phenylmethoxy)phenylmethoxy)phenylmethoxy)benzyl alcohol (G4OH). Using the same procedure for G2OH, 5 g of **6** and 137 mg of 3,5-dihydroxybenzyl alcohol was converted into crude product, which was purified by chromatography on silica (5 EtOAc/petroleum ether) to give 1.51 g (47, 54% conversion) of the desired product as a white solid, which was of sufficient purity to carry forward.

4.1.15. 3,5-Bis(3,5-bis(3,5-bis(3,5-bis(3,5-di(*tert*-butyl)phenylmethoxy)phenylmethoxy)phenylmethoxy)phenylmethoxy)benzyl bromide (7, G4Br). The procedure used to prepare **5** was followed. Thus, the reaction of 1.45 g (0.3 mmol) of G4-OH with 0.298 g (1.1 mmol) of carbon tetrabromide and 0.238 g (0.9 mmol) of triphenylphosphine in 10 mL of THF gave 0.91 g (59%) of **7** as a white foamy solid after purification by flash chromatography (1–5% ethyl acetate in petroleum ether): ^{1}H NMR δ 7.41 (t, 16H), 7.29 (d, 32H), 6.76–6.73 (3d, 30H), 6.67–6.61 (4t, 15H), 5.02–4.98 (3s, 60H), 4.36 (s, 2H), 1.34 (s, 288H); ^{13}C NMR δ 160.5, 160.3, 160.2, 151.1, 140.0, 139.2, 139.1, 135.8, 122.5, 122.4, 122.2, 108.4, 106.7, 106.6, 101.8, 101.7, 71.2, 70.3, 35.0, 31.6. Anal. calcd for $C_{345}H_{443}BrO_{30}$: C, 80.46; H, 8.67; Br, 1.55. Found: C, 80.53; H, 8.85; Br, 1.89.

4.1.16. 2,12-Bis(3,5-bis(methoxycarbonyl)phenyl)-7-(4-hydroxyphenyl)-5,6,8,9-tetrahydrodibenz[*c*,*h*]-acridine (8). To a solution of 200 mg (0.26 mmol) of **12** in CH_2Cl_2 cooled to −5°C was added 0.5 mL (5.3 mmol) of boron tribromide. The reaction was stirred at <0°C for 2 h and poured onto a saturated aqueous solution of $NaHCO_3$. The mixture was acidified with 10% aqueous hydrochloric acid and extracted with ethyl ether. The organic layer was washed with water, brine, dried over magnesium sulfate and the solvent removed under reduced pressure. The crude solid was recrystallized from ether–petroleum ether to give 165 mg (84%) of **8**: ^{1}H NMR δ 8.80 (d, J=1.3 Hz, 2H), 8.49 (s, 2H), 8.44 (s, 4H), 7.48 (d, J=7.7 Hz, 2H), 7.24 (d, J=7.8 Hz, 2H), 7.09 (d, J=8.4 Hz, 2H), 7.02 (d, J=8.5 Hz, 2H), 3.73 (s, 12H), 2.84 (t, J=6.2 Hz, 4H), 2.71 (d, J=7.4 Hz, 4H); FAB-MS, (3NBA) m/z 760 (M+1, 14); HRMS calcd for $C_{47}H_{38}NO_9$: 760.2555, Found: 760.2546.

4.1.17. 2,12-(Boronic acid)-7-(4′-methoxyphenyl)-5,6,8,9-tetrahydrodibenz[*c*,*h*]acridine (11). A solution of 2.0 g (3.7 mmol) of **10** in 100 mL of THF at −75°C was treated with a 7.8 mL solution of 1.86 M *n*-butyllithium in hexane and stirred for 1 h. Keeping the internal temperature less than −60°C, 15 mL of freshly distilled trimethyl borate was added dropwise. The reaction was allowed to warm to room temperature and stir overnight. The solvent was removed and a solution of 3.75 g (36 mmol) of 2,2-dimethyl propane-1,3-diol in 150 mL of benzene was added. The solution was refluxed in a Dean–Stark apparatus for several hours (monitoring by TLC) and concentrated. The crude material (6.78 g) was purified by flash chromatography using 2% methanol–chloroform as eluent to afford 1.16 g (51%) of the bis-boronate: ^{1}H NMR δ 9.05 (s, 1H), 7.73 (d, J=7.3 Hz, 2H), 7.18 (d, J=7.4 Hz, 2H), 7.11 (d, J=8.4 Hz, 2H), 6.99 (d, J=8.6 Hz, 2H), 3.86 (s, 3H), 3.82 (s, 8H), 2.82 (t, J=6.2 Hz, 4H) 2.65 (t, J=5.0 Hz, 4H), 1.05 (s, 12H), ^{13}C NMR δ 158.5, 149.9, 146.4, 140.0, 134.3, 133.6, 130.9, 129.7, 129.5, 129.4, 128.4, 126.2, 113.5, 71.8, 54.8, 31.5, 28.1, 25.4, 21.6, 21.5. A solution of the bis-boronate in 10% ethanolic potassium hydroxide was refluxed overnight. The reaction was cooled and acidified with 10% aqueous hydrochloric acid. The yellow precipitate was filtered off and washed well with water. The crude product was recrystallized from ethanol–water to afford 1.02 g (89%) of **11** as a crystalline solid: mp >300°C. ^{1}H NMR (DMSO-d_6) δ 8.86 (s, 2H), 8.03 (br s, 4H), 7.75 (d, J=7.4 Hz, 2H), 7.21 (m, 4H), 7.06 (d, J=8.6 Hz, 2H), 3.81 (s, 3H), 2.78 (t, J=6.1 Hz, 4H), 2.59 (t, J=7.5 Hz, 4H); ^{13}C NMR (DMSO-d_6) δ 158.7 149.7, 147.0, 139.7, 134.7, 133.9, 132.8, 130.9, 130.0, 129.0, 126.8, 126.4, 114.0, 55.1, 27.6, 25.4.

4.1.18. 2,12-Bis(3,5-bis(methoxycarbonyl)phenyl)-7-(4-methoxyphenyl)-5,6,8,9-tetrahydro-dibenz[*c*,*h*]acridine (12). Compound **12** was best made with **11** prepared according to this preparation: to a solution of 2.5 g (4.5 mmol) of dibromide **10** in 125 mL of THF cooled to −78°C (acetone/dry ice) 10 mL (16 mmol) of a hexane solution of *n*-butyllithium cooled to −78°C were added dropwise. The resulting yellow solution was stirred for 10 min and quenched dropwise with a solution of 6 mL (51 mmol) of dry trimethyl borate in 10 mL THF. The resulting turbid solution was allowed to warm up to room temperature overnight, upon which time it became clear, poured into 100 mL of water and acidified dropwise with 10% w/w aqueous hydrochloric acid to pH=1. The organic layer was collected and the aqueous layer was extracted twice with 100 mL of 1:1 mixture of THF and diethyl ether each. The combined organic fractions were dried over magnesium sulfate and the solvent was removed under reduced pressure. The resulting yellow solid was used in the coupling step without further purification. Thus, a mixture of the boronic acid, 3.8 g (11.8 mmol) of dimethyl 5-iodoisophthalate, 40 mg $Pd(PPh_3)_4$, 200 mL of toluene, 2 mL of ethyl alcohol and

100 mL of 1N aqueous solution of sodium carbonate was purged with nitrogen and refluxed over 24 h at which time the layers became clear. The mixture was cooled to room temperature, diluted with 100 mL of water and 200 mL of toluene. The organic layer was collected, washed with 100 mL of brine, dried with anhydrous sodium sulfate and solvent was removed under reduced pressure. The resulting brownish residue was chromatographed over silica gel (10% petroleum ether/CH_2Cl_2 to CH_2Cl_2 to 10% ethyl acetate/CH_2Cl_2) to afford after drying in vacuo 2.6 g (75%) of **12** as a white solid: ^{1}H NMR δ 8.76 (d, J=1.4 Hz, 2H), 8.45 (br s, 2H), 8.39 (br s, 4H), 7.44 (dd, J=7.7 Hz, 1.2, 2H), 7.20 (d, J=8.2 Hz, 4H), 7.06 (d, J=8.6 Hz, 2H), 3.92 (s, 3H), 3.69 (br s, 12H), 2.81–2.83 (m, 4H), 2.65–2.79 (m, 4H),; ^{13}C NMR δ 165.6, 158.9, 148.7, 146.5, 141.9, 137.5, 137.1, 135.1, 131.8, 130.1, 130.0, 129.9, 128.4, 128.0, 127.3, 126.6, 124.8, 113.7, 55.2, 51.7, 27.1, 25.5; Anal. calcd for $C_{48}H_{39}NO_9 \cdot 0.2CH_2Cl_2$: C, 73.21; H, 5.02; N, 1.77. Found: C, 73.41; H, 5.20; N, 1.70.

4.1.19. 2,12-Bis(3,5-bis(methoxycarbonyl)phenyl)-7-(4-(3,5-bis(3,5-di(*tert*-butyl)phenylmethoxy)phenylmethoxy)-phenyl)-5,6,8,9-tetrahydrodibenz[*c*,*h*]acridine (13a). A mixture of 0.90 g (1.18 mmol) of **8**, 0.86 g (1.42 mmol) of G1-Br **4**, 0.325 g (2.36 mmol) of potassium carbonate, 30 mg (0.11 mmol) of 18-crown-6 and 0.535 g (1.45 mmol) of tetrabutylammonium iodide in 250 mL of acetone was refluxed for 26 h. The solution was concentrated under reduced pressure and the residue was dissolved in 200 mL of methylene chloride and 50 mL of water. The organic layer was separated and the aqueous layer was extracted twice with 100 mL of methylene chloride. The combined organic layers were washed with 50 mL of brine, dried with sodium sulfate, and concentrated under reduced pressure. The residue was purified by chromatography on silica (10–18% ethyl acetate/petroleum ether) to give 1.2 g (83%) of **13a** as a white foamy solid: glass transition 130–135°C; ^{1}H NMR δ 8.78 (s, 2H), 8.27 (br s, 6H), 7.46 (t, 2H), 7.35 (d, 4H), 7.31 (d, J=7.8 Hz, 2H), 7.24 (d, J=8.6 Hz, 2H), 7.18 (d, J=8.6 Hz, 2H), 7.08 (d, J=7.8 Hz, 2H), 6.85 (d, J=2 Hz, 2H), 6.46 (t, 1H), 5.17 (s, 2H), 5.08 (s, 4H), 3.55 (br s, 12H), 2.74 (m, 4H), 2.61(m, 4H), 1.38 (s, 36H); ^{13}C NMR δ 165.8, 160.5, 158.2, 151.1, 149.0, 146.7, 142.1, 139.3, 137.6, 137.3, 135.7, 135.3, 132.0, 130.3, 130.0, 128.7, 128.22, 128.21, 127.5, 126.8, 124.8, 122.4, 114.8, 106.5, 101.5, 71.1, 70.2, 51.9, 34.9, 31.5, 27.3, 25.7; FAB-MS calcd for $C_{84}H_{87}NO_{11}$ 1286.6, found 1286.5 (M^+). Anal. calcd for $C_{84}H_{87}NO_{11}$: C, 78.42; H, 6.82; N, 1.09. Found: C, 78.62; H, 6.81; N, 1.54.

4.1.20. 2,12-Bis(3,5-bis(methoxycarbonyl)phenyl)-7-(4-(3,5-bis(3,5-bis(3,5-di(*tert*-butyl)phenylmethoxy)phenyl-methoxy)phenylmethoxy)phenyl)-5,6,8,9-tetrahydro-dibenz[*c*,*h*]acridine (13b). The procedure used to prepare **13a** was followed. Thus, the reaction of 0.91 g (1.18 mmol) of **8**, 1.73 g (1.38 mmol) of G2-Br **5**, 0.414 g (3 mmol) of potassium carbonate, 20 mg (0.076 mmol) of 18-crown-6, and 0.719 g (1.95 mmol) of tetrabutylammonium iodide in 200 mL of acetone gave 1.73 g (76%) of **13b** as a white foamy solid: glass transition 114–118°C; ^{1}H NMR δ 8.80 (s, 2H), 8.51 (br s, 2H), 8.44 (br s, 4H), 7.48 (d, J=7.8 Hz, 2H), 7.42 (t, J=1.5 Hz, 4H), 7.30 (d, J=1.5 Hz, 8H), 7.23 (d, J=7.8 Hz, 2H), 7.19 (d, J=8.8 Hz, 2H), 7.14 (d, J=8.6 Hz, 2H), 6.79-6.77 (m, 6H), 6.68–6.66 (m, 3H), 5.11 (s, 2H), 5.05 (s 4H), 5.03 (s, 8H), 3.74 (br s, 12H), 2.82 (m, 4H), 2.68 (m, 4H), 1.34 (s, 72H); ^{13}C NMR δ 165.8, 160.4, 160.2, 158.1, 151.0, 149.0, 146.8, 142.0, 139.3, 138.9, 137.6, 137.3, 135.6, 135.3, 132.0, 130.3, 130.2, 130.0, 128.7, 128.2, 127.5, 126.8, 124.7, 122.3, 114.7, 106.4, 101.5, 71.0, 70.2, 70.1, 51.9, 34.8, 31.4, 27.3, 25.7; FAB-MS calcd for $C_{128}H_{143}NO_{15}$ 1935.5, found 1935.5 (M^+). Anal. calcd for $C_{128}H_{143}NO_{15:}$ C, 79.43; H, 7.45; N, 0.72. Found: C, 79.08; H, 7.50; N, 0.95.

4.1.21. 2,12-Bis(3,5-bis(methoxycarbonyl)phenyl)-7-(4-(3,5-bis(3,5-bis(3,5-bis(3,5-di(*tert*-butyl)phenylmethoxy)-phenylmethoxy)phenylmethoxy)phenylmethoxy) phenyl-5,6,8,9-tetrahydrodibenz[*c*,*h*]acridine (13c). The procedure used to prepare **13a** was followed but using THF as the solvent. Thus, the reaction of 500 mg (0.66 mmol) of **8**, 1.85 g (0.72 mmol) of G3-Br **6**, 0.100 g (0.73 mmol) of potassium carbonate, 93 mg (0.346 mmol) of 18-crown-6, and 0.369 g (1 mmol) of tetrabutylammonium iodide in 90 mL of tetrahydrofuran gave 1.67 g (79%) of **13c** as a white foam: glass transition 92–96°C; ^{1}H NMR δ 8.85 (d, 2H), 8.62 (br s, 2H), 8.54 (s, 4H), 7.58 (d, J=7.8 Hz, 2H), 7.41 (t, J=1.5 Hz, 8H), 7.29 (d, J=1.5 Hz, 18H), 7.17 (d, J=8.6 Hz, 2H), 7.13 (d, J=8.6 Hz, 2H), 6.78–6.73 (m, 14H), 6.68–6.52 (m, 7H), 5.08 (s, 2H), 5.03 (s, 28H), 3.75 (br s, 12H), 2.88 (m, 4H), 2.73 (m, 4H), 1.37 (s, 144H); FAB-MS calcd for $C_{216}H_{255}NO_{23}$ 3233.4, found 3233.3 (M^+). Anal. calcd for $C_{216}H_{255}NO_{23}$: C, 80.24; H, 7.95; N, 0.43. Found: C, 80.26; H, 8.01; N, 0.59.

4.1.22. 2,12-Bis(3,5-bis(methoxycarbonyl)phenyl)-7-(4-(3,5-bis(3,5-bis(3,5-bis(3,5-bis(3,5-di(*tert*-butyl)phenyl-methoxy)phenylmethoxy)phenylmethoxy)phenyl meth-oxy)phenyl-methoxy)phenyl-5,6,8,9-tetrahydrodibenz-[*c*,*h*]acridine (13d). The procedure used to prepare **13a** was followed but using THF as the solvent. Thus, the reaction of 99.3 mg (0.13 mmol) of **8**, 0.66 g (0.13 mmol) of G4-Br **7**, 0.100 g (0.73 mmol) of potassium carbonate, 75 mg (0.28 mmol) of 18-crown-6, and 99.8 mg (0.2 mmol) of tetrabutylammonium iodide in 40 mL of tetrahydrofuran gave 0.50 g (65%) of **13d** as a white foam: ^{1}H NMR (50°C) δ 8.86 (br s, 2H), 8.66 (br s, 2H), 8.56 (s, 4H), 7.58 (br, J=7.8 Hz, 2H), 7.39 (s, 16H), 7.26 (d, J=1.3 Hz, 32H), 7.24 (d, J=7.8 Hz, 2H), 7.14 (d, 2H), 7.12(d, 2H), 6.78–6.73 (3d, 30H), 6.68–6.62 (3t, 15H), 5.05–5.00 (3s, 62H), 3.86 (br s, 12H), 2.86 (m, 4H), 2.72(m, 4H), 1.35 (s, 288H); ^{13}C NMR δ 166.1, 160.7, 160.6, 160.5, 158.5, 151.5, 151.3, 151.1, 151.0, 142.4, 139.4, 139.3, 137.9, 137.9, 136.0, 135.7, 132.3, 132.3, 130.6, 130.4, 127.7, 125.2, 122.8, 122.6, 122.5, 122.4, 122.3, 115.0, 106.9, 106.7, 106.5, 101.9, 101.8, 101.7, 71.3, 70.4, 52.1, 35.2, 31.8, 27.5, 26.0; MALDI-MS calcd for $C_{392}H_{479}NO_{39}$ 5829.1, found 5853.3 ($M+Na^+$), 5831.9 (M^+). Anal. calcd for $C_{216}H_{255}NO_{23}$: C, 80.77; H, 8.28; N, 0.24. Found: C, 80.77; H, 8.40; N, 0.29.

4.1.23. 2,12-Bis(3,5-bis(methoxycarbonyl)phenyl)-7-(4-(3,5-didodecyloxy)phenylphenyl)-5,6,8,9-tetrahydrodi-benz[*c*,*h*]acridine (13e). The procedure used to prepare **13a** was followed. Thus, the reaction of 0.9 g (1.18 mmol) of **8**, 0.762 g (1.42 mmol) of 3,5-didodecyloxybenzyl bromide, 0.414 g (3 mmol) of potassium carbonate, 30 mg (0.11

mmol) of 18-crown-6, and 0.72 g (1.95 mmol) of tetrabutylammonium iodide in 250 mL of acetone over 24 h gave 1.2 g (83%) of **13e** as a white foam: glass transition 75–80°C; ^{1}H NMR δ 8.76 (s, 2H), 8.22 (s, 6H), 7.27 (dd, J=7.8 Hz, 0.9, 2H), 7.22 (d, J=8.6 Hz, 2H), 7.15 (d, J=8.6 Hz, 2H), 7.05 (d, J=7.8 Hz, 2H), 6.66 (d, J=2 Hz, 2H), 6.46 (t, J=2 Hz, 1H), 5.11 (s, 2H), 4.00 (t, J=6.4 Hz, 4H), 3.50 (br s, 12H), 2.71 (m, 4H), 2.58 (m, 4H), 1.82 (m, 4H,), 1.49–1.28 (m, 32H), 0.88 (t, J=6.3 Hz, 6H); ^{13}C NMR δ 165.7, 160.6, 158.2, 148.9, 146.6, 142.0, 139.1, 137.6, 137.2, 135.2, 131.9, 130.3, 130.2, 130.0, 128.5, 128.1, 127.4, 126.7, 124.9, 114.7, 105.8, 100.8, 70.2, 68.1, 51.8, 31.9, 29.7, 29.66, 29.64, 29.45, 29.38, 29.32, 27.22, 26.1, 25.7, 22.7, 14.2. Anal. calcd for $C_{78}H_{91}NO_{11}$: C, 76.88; H, 7.53; N, 1.15. Found: C, 76.89; H, 7.74; N, 1.12.

4.1.24. 3,5-Bis(3,5-bis(3,5-bis(3,5-di(*tert*-butyl)phenylmethoxy)phenylmethoxy)phenylmethoxy)phenylmethoxyethoxyethoxyethanol. To a suspension of 0.19 g (7.8 mmol) of sodium hydride in 70 mL of tetrahydrofuran was added 2.36 g (15.7 mmol) of triethylene glycol slowly. The mixture was stirred for 30 min and 2 g (0.78 mmol) of G3Br **7** was added. The mixture was refluxed for 3 h, quenched with 30 mL of water, and extracted three times with 200 mL of chloroform. The combined organic layers were washed with 30 mL of brine, dried over anhydrous sodium sulfate, and concentrated under reduced pressure. The residue was purified by chromatography to give 1.24 g (60%) of G3$(OCH_2CH_2)_3OH$ as a white foam: ^{1}H NMR δ 7.43 (t, J=1.6 Hz, 8H), 7.31 (d, J=1.6 Hz, 16H), 6.77 (d, J=8 Hz, 8H), 6.75 (d, J=2 Hz, 4H), 6.68 (t, J=2 Hz, 4H), 6.65 (d, J=2 Hz, 2H), 6.64 (t, 2H), 6.62 (t, 1H), 5.03–5.01 (2s, 28H), 4.54 (s, 1H), 3.72–3.58 (m, 12H), 1.36 (s, 144H); ^{13}C NMR δ 160.7, 160.4, 160.2, 151.2, 141.0, 139.5, 139.2, 135.9, 122.6, 122.5, 106.8, 106.7, 101.8, 101.4, 73.3, 72.7, 71.3, 70.9, 70.88, 70.6, 70.4, 70.3, 69.6, 62.0, 35.1, 31.7. Anal. calcd for $C_{175}H_{232}O_{18}$: C, 80.11; H, 8.91. Found: C, 80.37; H, 8.90.

4.1.25. 10-(3,5-Bis(3,5-bis(3,5-bis(3,5-di(*tert*-butyl)phenylmethoxy)phenylmethoxy)phenylmethoxy)phenyl)-3,6,9-trioxydecyl bromide (14). The procedure used to prepare **5** was followed. Thus, the reaction of 0.55 g (0.21 mmol) of G3$(OCH_2CH_2)_3OH$, 207 mg (0.63 mmol) of carbon tetrabromide, 165 mg (0.63 mmol) of triphenylphosphine afforded 0.52 (92%) of **14** as a white foam after purification by chromatography (5–15% ethyl acetate/petroleum ether): ^{1}H NMR δ 7.41 (t, J=1.7 Hz, 8H), 7.29 (d, J=1.7 Hz, 16H), 6.75 (d, J=2.1 Hz, 8H), 6.73 (d, J=2.1 Hz, 4H), 6.66 (t, J=2.1 Hz, 4H), 6.63 (m, 4H), 6.58 (t, 1H), 5.01–4.97 (2s, 28H), 4.52 (s, 2H), 3.77 (t, J=6.3 Hz, 2H), 3.68–3.61 (m, 8H), 3.42 (t, J=6.3 Hz, 2H), 1.34 (s, 144H); ^{13}C NMR δ 160.8, 160.5, 160.4, 151.3, 141.2, 139.7, 139.5, 136.1, 122.7, 122.6, 106.9, 106.8, 101.9, 101.5, 73.4, 71.5, 71.4, 71.1, 71.0, 70.9, 70.5, 70.3, 69.8, 35.2, 31.9, 30.7. Anal. calcd for $C_{175}H_{231}BrO_{17}$: C, 78.24; H, 8.67; Br, 2.97. Found: C, 78.25; H, 8.89; Br, 3.30.

4.1.26. 2,12-Bis(3,5-bis(methoxycarbonyl)phenyl)-7-(4-(3,5-bis(3,5-bis(3,5-bis(3,5-di(*tert*-butyl)phenylmethoxy)-phenylmethoxy)phenylmethoxy)phenylmethoxy)ethoxyethoxyethoxyphenyl)-5,6,8,9-tetrahydrodibenz[*c*,*h*]acridine (13f). The procedure used to prepare **13a** was followed. Thus, the reaction of 0.113 g (0.15 mmol) of **8**, 0.40 g (0.15 mmol) of **14**, 0.12 g (0.87 mmol) of potassium carbonate, 27 mg (0.12 mmol) of 18-crown-6, and 0.14 g (0.38 mmol) of tetrabutylammonium iodide in 50 mL of acetone gave 0.39 g (78%) of **13f** as a white foam after purification by chromatography (10–30% ethyl acetate/petroleum ether): ^{1}H NMR δ 8.79 (s, 2H), 8.42 (s, 2H), 8.39 (s, 4H), 7.41 (s, 8H), 7.29 (s, 16H), 7.17 (d, 4H), 7.08 (d, J=8.4 Hz, 2H), 6.75–6.63 (m, 21H), 5.02 (s, 28H), 4.55 (s, 2H), 4.22 (t, 2H), 3.94 (t, 2H), 3.80 (m, 4H), 3.65 (br m, 18H), 2.80 (m, 4H), 2.65 (m, 4H), 1.35 (s, 144H); ^{13}C NMR δ 166.1, 160.4, 160.2, 160.1, 158.4, 151.5, 149.3, 147.0, 142.3, 141.2, 139.7, 139.5, 137.9, 137.5, 136.1, 135.7, 132.2, 130.7, 130.6, 130.4, 129.1, 128.4, 127.7, 127.0, 125.2, 122.4, 114.8, 106.8, 106.6, 101.9, 101.4, 71.4, 71.3, 71.0, 70.6, 70.4, 70.1, 69.7, 67.7, 52.0, 35.1, 31.8, 27.5, 25.9. FAB-MS calcd for $C_{222}H_{267}NO_{26}$: 3365.6. Found: 3366.1. Anal. calcd for $C_{222}H_{267}NO_{26}\cdot 0.3CH_2Cl_2$: C, 78.74; H, 7.95; N, 0.41. Found: C, 78.64; H, 7.92; N, 0.29.

4.1.27. 3,5-Bis(3,5-bis(3,5-bis(3,5-di(*tert*-butyl)phenylmethoxy)phenylmethoxy)phenylmethoxy)benzoic acid (15). The procedure used to prepare **1a** was followed. Thus, the hydrolysis of 0.20 g (0.079 mmol) of ester **16** in 17 mL of THF with 0.2 g (3.6 mmol) of potassium hydroxide in 2 mL of water and 7 mL of methanol gave 0.18 g (90%) of **15** as a white foam after purification by chromatography (0.8–1% methanol/methylene chloride): ^{1}H NMR 7.40 (t, 8H), 7.34 (d, 2H), 7.27 (d, 16H), 6.88 (t, 1H), 6.73 (d, 8H), 6.71 (d, 4H), 6.65 (t, J=2 Hz, 4H), 6.62 (t, J=2 Hz, 2H), 5.00 (s, 28H), 1.33 (s, 144H); MALDI-MS calcd for $C_{169}H_{218}O_{16}$, 2505.6, found 2528.9 ($M+Na^+$). Anal. calcd for $C_{169}H_{218}O_{16}$: C, 81.01; H, 8.77. Found: C, 81.01; H, 8.82.

4.1.28. Methyl 3,5-bis(3,5-bis(3,5-bis(3,5-di(*tert*-butyl)-phenylmethoxy)phenylmethoxy)phenylmethoxy)benzoate (16). The procedure used to prepare **13a** was followed. Thus, the reaction of 0.53 g (0.43 mmol) of G2-Br **5**, 34 mg (0.20 mmol) of methyl 3,5-dihydroxybenzoate, 0.138 g (1 mmol) of potassium carbonate, and 13 mg (0.05 mmol) of 18-crown-6 in 25 mL of acetone gave 0.42 g (82%) of **16** as a white foam: ^{1}H NMR 7.43 (t, J=2 Hz, 8H), 7.33 (d, J=2 Hz, 2H), 7.29 (d, J=2 Hz, 16H), 6.86 (t, J=2 Hz, 1H), 6.76 (d, J=2 Hz, 8H), 6.73 (d, 4H), 6.67 (t, J=2 Hz, 4H), 6.63 (t, J=2 Hz, 2H), 5.02 (s, 28H), 3.91 (s, 3H), 1.36 (s, 144H); ^{13}C NMR δ 166.9, 160.7, 160.4, 160.0, 151.3, 139.2, 139.1, 135.9, 132.3, 122.6, 122.5, 108.7, 107.3, 106.7, 102.0, 101.8, 71.3, 70.5, 70.4, 52.5, 35.1, 31.8. Anal. calcd for $C_{170}H_{220}O_{16}$: C, 81.04; H, 8.80. Found: C, 81.22; H, 8.81.

4.1.29. Dimethyl 5-(3,5-bis(3,5-di(*tert*-butyl)phenylmethoxy)phenylmethoxy)isophthalate (18a). The procedure used to prepare **13a** was followed. Thus, the reaction of 0.159 g (0.26 mmol) of G1-Br **4**, 50 mg (0.24 mmol) of dimethyl 5-hydroxyisophthalate, 65.6 mg (0.48 mmol) of potassium carbonate, 15 mg (0.06 mmol) of 18-crown-6, and 0.72 g (1.95 mmol) of tetrabutylammonium iodide in 30 mL of acetone gave 0.17 g (98%) of **18a** as a white foam: ^{1}H NMR δ 8.31 (t, 1H), 7.85 (d, J=1.5 Hz, 2H), 7.42 (t, J=2 Hz, 2H), 7.29 (d, J=2 Hz, 4H), 6.74 (d, J=2 Hz, 2H), 6.71 (t, 1H), 5.11 (s, 2H), 5.02 (s, 4H),

3.95 (s, 6H), 1.34 (s, 36H); ^{13}C NMR δ 166.1, 160.5, 158.8, 151.1, 138.4, 135.7. 131.9, 123.3, 122.3, 120.2, 106.5, 101.8.

4.1.30. Dimethyl 5-(3,5-bis(3,5-bis(3,5-di(*tert*-butyl)-phenylmethoxy)phenylmethoxy)phenylmethoxy)isophthalate (18b). The procedure used to prepare **13a** was followed. Thus, the reaction of 0.418 g (0.33 mmol) of G2-Br **5**, 70 mg (0.33 mmol) of dimethyl 5-hydroxyisophthalate, 92 mg (0.67 mmol) of potassium carbonate, 50 mg (0.19 mmol) of 18-crown-6, and 0.123 g (0.33 mmol) of tetrabutylammonium iodide in 41 mL of acetone gave 0.228 g (51%) of **18b** as a white foam: ^{1}H NMR δ 8.30 (t, 1H, H-2), 7.84 (d, J=1 Hz, 2H), 7.41 (s, 4H), 7.29 (s, 8H), 6.74 (d, 4H), 6.71 (d, 2H), 6.66 (s, 2H), 6.63 (s, 1H), 5.09 (s, 2H), 5.01 (s, 12H), 3.92 (s, 6H), 1.34 (s, 72H); ^{13}C NMR δ 166.1, 160.5, 160.3, 158.7, 151.1, 139.0, 138.5, 135.7. 131.9, 123.3, 122.3, 120.2, 106.5, 106.4, 101.9, 101.7. Anal. calcd for $C_{91}H_{116}O_{11}$: C, 78.86; H, 8.44. Found: C, 78.76; H, 8.47.

4.1.31. 1,3,5-Tris(4-(4-(4-(3,5-bis(4-(4-(3,5-bis(3,5-di(*tert*-butyl)phenylmethoxy)phenylmethoxy)phenyl)phenyl)-phenylmethoxy)phenyl)phenyl)phenyl)benzene (19a). The procedure used to prepare **13a** was followed but using THF as the solvent. Thus, the reaction of 0.577 g (0.37 mmol) of **21a-bromide**, 0.100 g (0.12 mmol) of **22**, 0.116 g (0.84 mmol) of potassium carbonate, 63 mg (0.24 mmol) of 18-crown-6, and 0.221 g (0.6 mmol) of tetrabutylammonium iodide in 20 mL of THF gave 0.27 g (43%) of **19a** as a white glassy solid after purification by chromatography (starting from petroleum ether, then slowly adding 10% ethyl acetate/methylene chloride as a co-eluent): ^{1}H NMR δ 7.91(s, 3H), 7.88 (t, 3H), 7.84–7.77 (ABq, 12H), 7.76–7.62 (m, 48H), 7.60 (d, J=8.7 Hz, 12H), 7.43 (t, J=1.7 Hz, 12H), 7.31 (d, J=1.7 Hz, 24H), 7.16 (d, J=8.7 Hz, 6H), 7.09 (d, J=8.7 Hz, 12H), 6.78 (d, J=1.9 Hz, 12H), 6.68 (t, J=1.9 Hz, 6H), 5.26 (br s, 6H), 5.10 (s, 12H), 5.03 (s, 24H), 1.36 (s, 216H); UV–visible λ 306, 251, 231; MALDI calcd for $C_{375}H_{408}O_{21}$: 5251.4, found: 5292.0 ($M+K^+$). Anal. calcd for $C_{375}H_{408}O_{21}$: C, 85.77; H, 7.83. Found: C, 85.47; H, 7.70.

4.1.32. 1,3,5-Tris(4-(4-(4-(3,5-bis(4-(4-(3,5-bis(3,5-bis(3,5-di(*tert*-butyl)phenylmethoxy)phenylmethoxy)phenyl-methoxy)phenyl)phenyl)phenylmethoxy)phenyl) phenyl)-phenyl)benzene (19b). The procedure used to prepare **13a** was followed but using THF as the solvent. Thus, the reaction of 635 mg (0.222 mmol) of **21b-bromide**, 60 mg (0.074 mmol) of **22**, 51 mg (0.37 mmol) of potassium carbonate, 20 mg (0.076 mmol) of 18-crown-6, and 0.109 g (0.296 mmol) of tetrabutylammonium iodide in 20 mL of THF gave 0.12 g (18%) of **19b** as a white glassy solid after purification by chromatography (starting from petroleum ether, then slowly adding 10% ethyl acetate/methylene chloride as a co-eluent): ^{1}H NMR δ 7.94 (s, 3H), 7.88 (t, 3H), 7.84–7.77 (ABq, 12H), 7.77–7.63 (m, 48H), 7.60 (d, J=8.7 Hz, 12H), 7.42 (t, J=1.7 Hz, 24H), 7.29 (d, J=1.7 Hz, 48H), 7.17 (d, J=8.7, 6H), 7.08 (d, J=8.7 Hz, 12H), 6.76 (d, 36H), 6.75 (t, 12H), 6.63 (t, 6H), 5.28 (br s, 6H), 5.10–5.00 (3s, 84H), 1.35 (s, 432H); MALDI calcd for $C_{639}H_{744}O_{54}$: 9144.9, found: 9168.5 ($M+Na^+$).

4.1.33. 1,3,5-Tris(4-(4-(4-(3,5-bis(4-(4-(3,5-bis(3,5-bis(3,5-bis(3,5-di(*tert*-butyl)phenylmethoxy)phenylmethoxy)-phenylmethoxy)phenylmethoxy)phenyl)phenyl)phenyl-methoxy)phenyl)phenyl)phenyl)benzene (19c). The procedure used to prepare **13a** was followed but using THF as the solvent. Thus, the reaction of 625 mg (0.114 mmol) of **21c-bromide**, 30 mg (0.037 mmol) of **22**, 90 mg (0.65 mmol) of potassium carbonate, 40 mg (0.15 mmol) of 18-crown-6, and 0.150 g (0.41 mmol) of tetrabutylammonium iodide in 60 mL of THF gave 62.6 mg (10%) of **19c** as a white glassy solid after purification by chromatography (starting from petroleum ether, then slowly adding 3% ethyl acetate/methylene chloride as a co-eluent): ^{1}H NMR δ 7.82 (s, 3H), 7.76 (d, 9H), 7.71 (d, 6H), 7.66–7.62 (m, 24H), 7.60 (d, 6H), 7.57–7.53 (d, 18H), 7.48–7.45 (d, 12H), 7.42 (s, 48H), 7.17 (s, 96H), 7.15 (d, 6H), 6.96 (d, 12H), 6.64 (m, 84H), 6.55–6.51 (s, 42H), 5.18 (br s, 6H), 5.03 (s, 180H), 1.34 (s, 864H). Anal. calcd for $C_{1167}H_{1416}O_{93}$: C, 82.78; H, 8.43. Found: C, 82.83; H, 8.18.

4.1.34. 1-Methoxymethoxy-4-(4-bromophenyl)benzene. To a suspension of 7 g (60% w/w suspension in mineral oil) of sodium hydride (175 mmol), prewashed with dry petroleum ether, in 100 mL of dry THF cooled to 0°C was added dropwise a solution of 32 g (128 mmol) of 4-(4-bromophenyl)phenol in 300 mL of dry THF. The mixture was taken out of the cooling bath and stirred at room temperature for 1 h. The resulting turbid suspension was cooled to 0°C and 15 mL of MOMCl were added dropwise and the mixture was stirred at room temperature overnight. The resulting thick homogeneous mixture was evaporated as much as possible, diluted with 0.6 L of dichloromethane and cautiously poured into 1 L of water. The collected organic layer was dried with anhydrous sodium sulfate and the solvent was evaporated under reduced pressure. The resulting yellowish solid was distilled using Kugelrohr apparatus to afford 35 g (93%) of white solid. An analytically pure sample was obtained by double recrystallization from methanol to afford 1-methoxymethoxy-4-(4-bromophenyl)benzene as fluffy white plates: bp (Kugelrohr): 120–130°C/1 mm Hg, mp 90–91°C; ^{1}H NMR δ 7.54 (d, J=8.4 Hz, 2H), 7.49 (d, J=8.5 Hz, 2H), 7.42 (d, J=8.3 Hz, 2H), 7.12 (d, J=8.5 Hz, 2H, H-2, H-6), 5.22 (s, 2H, CH_2), 3.52 (s, 3H, CH_3); ^{13}C NMR δ 157.0, 139.6, 133.6, 131.8, 128.3, 127.9, 120.9, 116.6, 94.3, 56.0.

4.1.35. 1-Methoxymethoxy-4-(4-bromophenyl)phenyl boronic acid. A solution of 35 g (119 mmol) of 1-methoxymethoxy-4-(4-bromophenyl)benzene in 500 mL of dry THF was heated to reflux with 10 g (416 mmol) of magnesium turnings. The reaction was initiated by 2 mL of 1,2-dibromoethane. An exothermic reaction followed and the heating was stopped. An additional 8 mL of 1,2-dibromoethane were added over 2 h. The resulting turbid solution was refluxed overnight, cooled to room temperature and quenched with 40 mL (352 mmol) of dry trimethyl borate. The resulting milky heterogeneous mixture was refluxed for 20 min, cooled to room temperature and poured into a mixture of 0.5 L of water and 0.5 L of brine followed by 0.5 L of diethyl ether. The organic layer was separated. The aqueous layer was extracted with 500 mL of a 1/1 mixture of THF and diethyl ether and the combined organic layers evaporated under reduced pressure to afford the

crude boronic acid, which was used without further purification.

4.1.36. Methyl 3,5-bis(4-(4-methoxymethoxyphenyl)-phenyl)benzoate. A turbid mixture of the boronic acid described above, 12.5 (42.5 mmol) of methyl 3,5-dibromobenzoate in 360 mL of toluene, 150 mL of 1N aqueous solution of sodium carbonate, 5 mL of ethanol and 150 mg of $Pd(PPh_3)_4$ was refluxed for 48 h. The resulting clear biphasic reaction mixture was cooled to room temperature and diluted with 300 mL of water and 300 mL of toluene. The organic layer was collected, dried with anhydrous sodium sulfate and the solvent was evaporated under reduced pressure. The resulting yellow residue was chromatographed over silica gel (20–30% petroleum ether/dichloromethane) and recrystallized from ethyl acetate to afford 11.1 g (33% from the boronic acid, 47% from the benzoate) of the title compound as a white fluffy solid: mp 148–150°C; ^{1}H NMR δ 8.31 (br s, 2H), 8.08 (br s, 1H), 7.75 (d, J=8.2 Hz, 4H), 7.68 (d, J=8.2 Hz, 4H), 7.60 (d, J=8.5 Hz, 4H), 7.16 (d, J=8.5 Hz, 4H), 5.24 (s, 4H), 4.00 (s, 3H), 3.53 (s, 6H); ^{13}C NMR δ 167.0, 156.9, 141.6, 140.2, 138.5, 134.2, 131.3, 129.9, 128.1, 127.6, 127.2, 126.9, 116.6, 94.4, 56.0, 52.3. Anal. calcd for $C_{36}H_{22}O_6$: C, 77.12; H, 5.75. Found: C, 77.00; H, 5.69.

4.1.37. Methyl 3,5-bis(4-(4-hydroxyphenyl)phenyl)benzoate. To a clear refluxing solution of 9.8 g (17.5 mmol) of methyl 3,5-bis(4-(4-methoxymethoxyphenyl)phenyl)-benzoate in a mixture of 60 mL of chloroform and 100 mL of 2-propanol, 1 mL of concentrated aqueous hydrochloric acid was added and the reaction mixture was refluxed overnight at which time a white precipitate formed. The resulting heterogeneous mixture was cooled to 0°C and diluted with 100 mL of methanol. The filtered precipitate was dried at 140–150°C in vacuo to afford 7.8 g (94%) of analytically pure title compound as a white fluffy solid: mp 292–293°C; ^{1}H NMR (DMSO-d_6) δ 9.64 (br s, 2H), 8.17 (s, 1H), 8.14 (s, 2H), 7.79 (d, J=8.1 Hz, 4H), 7.67 (d, J=8.1 Hz, 4H), 7.54 (d, J=8.3 Hz, 4H), 6.88 (d, J=8.3 Hz, 4H), 3.90 (s, 3H); ^{13}C NMR δ 166.1, 157.4, 141.0, 139.8, 136.9, 131.0, 130.1, 129.1, 127.7, 127.4, 126.5, 125.7, 115.8, 52.3. Anal. calcd for $C_{32}H_{24}O_4$: C, 81.34; H, 5.12. Found: C, 81.35; H, 5.03.

4.1.38. 3,5-Bis(4-(4-hydroxyphenyl)phenyl)benzyl alcohol. A solution of 7.6 g (15.8 mmol) of methyl 3,5-bis(4-(4-hydroxyphenyl)phenyl)benzoate in 100 mL THF was added within 20 min to a suspension of 1.9 g (50 mmol) of $LiAlH_4$ in 50 mL THF at room temperature. The reaction mixture was stirred for 30 min at room temperature and heated to reflux for 3 h at which time the TLC indicated that the reaction was complete. The mixture was cooled to room temperature and carefully quenched with 50 mL of H_2O in an ice bath. The mixture was filtered and the mother liquor was concentrated. The resulting solid was filtered and washed with H_2O and then was recrystallized from 95% EtOH. Additional product was isolated by treating the alumina solids with 200 mL of aqueous 4N HCl. The precipitate was filtered and recrystallized from 95% EtOH. A total of 6.7 g (95%) of product was obtained as a white powder. ^{1}H NMR: δ 9.57 (s, 2H), 7.81 (s, 1H), 7.78 (d, J=8.3 Hz, 4H), 7.66 (d, J=8.4 Hz, 4H), 7.60 (s, 2H), 7.53 (d, J=8.6 Hz, 4H), 6.84 (d, J=8.6 Hz, 4H), 5.31 (t, 1H), 4.63 (d, J=5.0 Hz, 2H). ^{13}C NMR: δ 157.8, 144.6, 140.9, 139.8, 138.7, 130.9, 128.2, 127.8, 126.9, 124.2, 123.6, 116.4, 63.5.

4.1.39. 3,5-Bis(4-(4-(3,5-bis(3,5-di(*tert*-butyl)phenylmethoxy)phenylmethoxy)phenyl)phenyl)benzyl alcohol (21a). The procedure used to prepare **13a** was followed. Thus, the reaction of 4.1 g (6.8 mmol) of G1Br **4**, 1.5 g (6.8 mmol) of 3,5-bis(4-(4-hydroxyphenyl)phenyl)benzyl alcohol, 0.138 g (1 mmol) of potassium carbonate, and 13 mg (0.05 mmol) of 18-crown-6 in 100 mL of acetone gave 4.43 g (88%) of **21a** as a white powder after recrystallization from hexanes–ethyl acetate: ^{1}H NMR δ 7.84 (t, 1H), 7.75 (d, J=8.3 Hz, 4H), 7.68 (d, J=8.3 Hz, 4H), 7.65 (d, 2H), 7.61 (d, J=8.6 Hz, 4H), 7.44 (t, 4H), 7.31 (d, 8H), 7.10 (d, J=8.6 Hz, 4H), 6.79 (d, 4H), 6.69 (t, 2H), 5.11 (s, 4H), 5.04 (s, 8H), 4.87 (s, 2H) 1.41 (s, 72H); ^{13}C NMR δ 160.8, 158.4, 151.7, 142.3, 141.9, 140.2, 139.7, 139.5, 136.0, 133.7, 128.3, 127.8, 127.4, 125.2, 124.7, 122.5, 122.4, 115.7, 106.7, 101.9, 71.7, 70.3, 65.7, 35.4, 31.9. Anal. calcd for $C_{105}H_{124}O_7$: C, 84.18; H, 8.34. Found: C, 84.06; H, 8.34.

4.1.40. 3,5-Bis(4-(4-(3,5-bis(3,5-bis(3,5-di(*tert*-butyl)-phenylmethoxy)phenylmethoxy)-phenylmethoxy)phenyl)-phenyl)benzyl alcohol (21b). The procedure used to prepare **13a** was followed. Thus, the reaction of 5 g (3.99 mmol) of G2-Br **5**, 0.885 g (1.99 mmol) of 3,5-bis(4-(4-hydroxyphenyl)phenyl)benzyl alcohol, 0.824 g (6 mmol) of potassium carbonate, and 50 mg (0.19 mmol) of 18-crown-6 in 150 mL of acetone gave 4.43 g (80%) of **21b** as a white glassy solid after purification by chromatography (10–20% ethyl acetate/petroleum ether): ^{1}H NMR δ 7.84 (t, 1H), 7.77 (d, J=8.3 Hz, 4H), 7.72 (d, J=8.3 Hz, 4H), 7.69 (d, 2H), 7.64 (d, J=8.6 Hz, 4H), 7.49 (t, J=1.5 Hz, 8H), 7.36 (d, J=1.5 Hz, 16H), 7.13 (d, J=8.6 Hz, 4H), 6.83–8.81 (2d, 12H), 6.74 (t, 4H), 6.70 (t, 2H), 5.14–5.09 (3s, 28H), 4.90 (d, J=5.7 Hz, 2H), 1.90 (t, 1H), 1.41 (s, 144H); ^{13}C NMR δ 160.8, 160.5, 158.7, 151.3, 142.5, 141.9, 140.2, 139.8, 139.5, 139.4, 136.1, 133.7, 128.4, 127.9, 127.4, 125.2, 124.7, 122.7, 122.6, 115.6, 106.8, 106.7, 101.9, 71.3, 70.4, 70.3, 65.5, 35.2, 31.9. Anal. calcd for $C_{193}H_{236}O_{15}$: C, 82.91; H, 8.51 Found: C, 82.89; H, 8.56.

4.1.41. 3,5-Bis(4-(4-(3,5-bis(3,5-bis(3,5-bis(3,5-di(*tert*-butyl)phenylmethoxy)phenylmethoxy)phenylmethoxy)-phenylmethoxy)phenyl)phenyl)benzyl alcohol (21c). The procedure used to prepare **13a** was followed. Thus, the reaction of 1.25 g (0.45 mmol) of G3Br **6**, 0.11 g (0.23 mmol) of 3,5-bis(4-(4-hydroxyphenyl)phenyl)benzyl alcohol, 0.2 g (1.5 mmol) of potassium carbonate, and 40 mg (0.15 mmol) of 18-crown-6 in 90 mL of acetone gave 1.06 g (87%) of **21c** as a white glassy solid after purification by chromatography (5–20% ethyl acetate/petroleum ether): ^{1}H NMR δ 7.87 (s, 1H), 7.77 (d, J=8 Hz, 4H), 7.70 (d, J=8, 4H), 7.68 (s, 2H), 7.62 (d, J=8.5 Hz, 4H), 7.46 (s, 16H), 7.34 (d, J=1.3 Hz, 32H), 7.11 (d, J=8.6 Hz, 4H), 6.84–6.74 (m, 28H), 6.72 (m, 14H), 5.10–5.02 (s, 60H), 4.89 (br s, 2H), 1.39 (s, 288H); ^{13}C NMR δ 160.6, 160.4, 158.6, 151.2, 151.1, 142.2, 141.9, 140.2, 139.6, 139.4, 139.2, 135.9, 133.6, 128.2, 127.7, 127.2, 124.7, 124.7, 122.4, 122.4,

115.4, 106.7, 101.8, 101.7, 71.2, 70.4, 70.3, 70.2, 65.6, 35.0, 31.6. Anal. calcd for $C_{369}H_{460}O_{31}$: C, 82.20; H, 8.60. Found: C, 82.20; H, 8.73.

4.1.42. 3,5-Bis(4-(4-(3,5-bis(3,5-di(*tert*-butyl)phenylmethoxy)phenylmethoxy)phenyl)phenyl)benzyl bromide (21a-bromide). The procedure used to prepare **5** was followed. Thus, the reaction of 4.43 g (2.96 mmol) of **21a** with 2.64 g (7.97 mmol) of carbon tetrabromide and 2.1 g (7.97 mmol) of triphenylphosphine in 50 mL of THF gave 3.9 g (84%) of **21a-bromide** as a white glassy solid after purification by flash chromatography: mp 162–163°C; ^{1}H NMR δ 7.87 (s, 1H), 7.75 (d, J=8.3 Hz, 4H), 7.72 (d, J=8.3 Hz, 4H), 7.68 (d, J=1.3 Hz, 2H), 7.63 (d, J=8.6 Hz, 4H), 7.47 (t, 4H), 7.35 (d, 8H), 7.13 (d, J=8.6 Hz, 4H), 6.82 (d, 4H), 6.72 (t, 2H), 5.14 (s, 4H), 5.08 (s, 8H), 4.67 (s, 2H) 1.40 (s, 72H); ^{13}C NMR δ 160.7, 158.7, 151.3, 142.2, 140.4, 139.6, 139.1, 139.0, 136.0, 133.5, 128.3, 127.3, 126.8, 126.1, 122.6, 122.5, 115.6, 106.6, 101.7, 71.3, 35.1, 33.8, 31.8. Anal. calcd for $C_{105}H_{123}BrO_6$: C, 80.79; H, 7.94; Br, 5.12. Found: C, 80.84; H, 7.95; Br, 5.23.

4.1.43. 3,5-Bis(4-(4-(3,5-bis(3,5-bis(3,5-di(*tert*-butyl)-phenylmethoxy)phenylmethoxy)phenylmethoxy)phenyl)-phenyl)benzyl bromide (21b-bromide). The procedure used to prepare **5** was followed. Thus, the reaction of 4.4 g (1.57 mmol) of **20b** with 1.61 g (4.86 mmol) of carbon tetrabromide and 1.32 g (5.06 mmol) of triphenylphosphine in 60 mL of THF gave 4.03 g (90%) of **21b-bromide** as a white glassy solid after purification by flash chromatography (0–7% ethyl acetate/petroleum ether): glass transition 92–96°C; ^{1}H NMR δ 7.81 (s, 1H), 7.71 (d, J=8.3 Hz, 4H), 7.66 (d, J=8.3 Hz, 4H), 7.64 (d, 2H), 7.58 (d, J=8.5 Hz, 4H), 7.42 (t, 8H), 7.30 (d, 16H), 7.08 (d, J=8.5 Hz, 4H), 6.75 (m, 12H), 6.67 (t, 4H), 6.63 (t, 2H), 5.08 (s, 4H), 5.03-5.02 (2s, 24H), 4.65 (s, 2H), 1.34 (s, 144H); ^{13}C NMR δ 160.7, 160.5, 158.7, 151.3, 142.3, 140.4, 139.7, 139.3, 139.1, 139.0, 136.0, 133.6, 128.4, 127.8, 127.4, 126.8, 126.1, 122.6, 122.5, 115.5, 106.7, 106.6, 101.8, 71.3, 70.4, 70.3, 35.1, 33.7, 31.8. Anal. calcd for $C_{193}H_{235}BrO_{14}$: C, 81.08; H, 8.29; Br, 2.80. Found: C, 81.10; H, 8.51; Br, 3.02.

4.1.44. 3,5-Bis(4-(4-(3,5-bis(3,5-bis(3,5-bis(3,5-di(*tert*-butyl)phenylmethoxy)phenylmethoxy)phenylmethoxy)-phenylmethoxy)phenyl)phenyl)benzyl bromide (21c-bromide). The procedure used to prepare **5** was followed. Thus, the reaction of 0.86 g (0.16 mmol) of **21c** with 4×52.8 mg (0.64 mmol) of carbon tetrabromide and 4×42 mg (0.64 mmol) of triphenylphosphine in 30 mL of THF gave 0.78 g (90%) of **21c-bromide** as a white glassy solid after purification by flash chromatography (5–7.5% ethyl acetate/petroleum ether): ^{1}H NMR δ 7.82 (s, 1H), 7.70 (d, J=8.2 Hz, 4H), 7.65 (d, J=8.4 Hz, 4H), 7.64 (d, J=1.1 Hz, 2H), 7.58 (d, J=8.7 Hz, 4H), 7.42 (t, 16H), 7.29 (d, J=1.5 Hz, 32H), 7.07 (d, J=8.7 Hz, 4H), 6.80–6.75 (m, 28H), 6.70–6.64 (m, 14H), 5.07–4.98 (s, 60H), 4.63 (br s, 2H), 1.39 (s, 288H); ^{13}C NMR δ 160.6, 160.3, 158.6, 151.1, 142.2, 141.8, 140.3, 140.3, 139.6, 139.4, 139.2, 138.9, 138.9, 135.9, 133.5, 128.2, 127.7, 127.2, 122.4, 115.4, 106.6, 101.9, 101.8, 101.6, 71.6, 70.4, 70.2, 35.0, 31.7. Anal. calcd for $C_{369}H_{459}O_{30}Br$: C, 81.25; H, 8.48; Br, 1.46. Found: C, 81.40; H, 8.40; Br, 1.68.

4.1.45. 1,3,5-Tris(4-(4-(4-methoxymethoxyphenyl)phenyl)-phenyl)benzene. A heterogeneous mixture of 1-methoxymethoxy-4-(4-bromophenyl)phenyl boronic acid obtained from 16.4 g (56 mmol) of 1-methoxymethoxy-4-(4-bromophenyl)benzene and 5 g (208 mmol) of magnesium turnings followed by trimethyl borate quench (20 mL, 176 mmol) (see detailed procedure above), 5 g of **20** (9 mmol), 140 mL of toluene, 100 mL of 1 M aqueous solution of sodium carbonate, 3 mL of ethanol and 80 mg of $Pd(PPh_3)_4$ was evacuated and backfilled with nitrogen three times. The reaction mixture was refluxed for 48 h, cooled to room temperature and filtered using a medium porosity glass frit with a large filtering area. The filter cake was washed with 300 mL of water and left to get dry on the filter overnight under suction. The solid was collected and recrystallized twice from dioxane and dried at 140–150°C in vacuo to afford 4.5 g of the title compound (47% from **20**) as a white solid: mp 238–241°C (decomp); ^{1}H NMR δ 7.92 (s, 3H), 7.84 (AB, J=8.3 Hz, 6H), 7.78 (AB, J=8.4 Hz, 6H), 7.34 (AB, J=8.3 Hz, 6H), 7.67 (AB, J=8.2 Hz, 6H), 7.59 (AB, J=8.6 Hz, 6H), 7.15 (AB, J=8.6 Hz, 6H), 5.24 (s, 6H), 3.52 (s, 9H); HRMS (FAB): Calcd for $C_{66}H_{54}O_6$: 942.392040. Found: 942.391000.

4.1.46. 1,3,5-Tris(4-(4-(4-hydroxyphenyl)phenyl)phenyl)-benzene (22). To a refluxing suspension of 1.8 g (1.9 mmol) of 1,3,5-tris(4-(4-(4-methoxymethoxyphenyl)phenyl)phenyl)-benzene in a mixture of 140 mL of chloroform and 50 mL of 2-propanol was added 4 mL of a concentrated aqueous hydrochloric acid. The mixture was refluxed for 2 h, cooled to room temperature and sonicated for 2 h and refluxed overnight at which time more solid formed. The reaction mixture was filtered while hot and the precipitate collected was recrystallized from dioxane to yield the first crop of the product as a white solid (380 mg). The dioxane mother liquor was diluted with water to yield a second crop of the product as a white solid (410 mg). The initial filtrate was concentrated to one fourth of its volume under reduced pressure. The solid formed was recrystallized from aqueous dioxane to yield the third crop of the product as a white solid (300 mg). All the crops collected were dried in vacuo at 110–120°C and analyzed separately by ^{1}H NMR. The first crop was the most pure. Total yield of the product 1.09 g (70%): mp 260°C (decomp); ^{1}H NMR δ 9.62 (br s, 3H), 7.97 (s, 3H), 7.96 (d, J=8.1 Hz, 6H), 7.82 (d, J=8.0 Hz, 6H), 7.77 (d, J=8.0 Hz, 6H), 7.68 (d, J=8.2 Hz, 6H), 7.54 (d, J=8.6 Hz, 6H), 6.86 (d, J=8.6 Hz, 6H); HRMS (FAB): calcd for $C_{60}H_{42}O_3$: 810.3134 Found: 810.3137.

4.1.47. 2,12-Bis(3,5-dicarboxy-4-(butyl)phenyl)-7-(4-(3,5-bis(3,5-bis(3,5-bis(3,5-di(*tert*-butyl)phenylmethoxy)phenylmethoxy)phenylmethoxy)phenylmethoxy)phenyl)-5,6,8,9-tetrahydrodibenz[*c*,*h*]acridine (24). The procedure used to prepare **1a** was followed. Thus, the reaction of 0.60 g (0.18 mmol) of **27**, 0.6 g (10.7 mmol) of potassium hydroxide in 8 mL of water, 50 mL of tetrahydrofuran, and 25 mL of methanol gave 0.55 g (93%) of **24** as a white powder: ^{1}H NMR (50% DMSO-d_6/$CDCl_3$, 55°C) δ 8.55 (s, 2H), 7.91 (s, 4H), 7.43 (d, 2H), 7.26 (s, 8H), 7.22 (d, 2H), 7.16 (s, 16H), 7.09 (d, 2H), 7.04 (d, 2H), 6.7–6.5 (m, 21H), 4.93 (2s, 28H), some CH_2 signals overlapped with residual water peak, 2.77 (t, 4H), 2.61 (t, 4H), 1.52 (m, 4H), 1.35 (m, 4H), 1.23 (s, 144H), 0.85 (t, 6H). FAB-MS

calcd for $C_{220}H_{263}NO_{23}$: 3289.5. Found: 3289.8. Anal. calcd for $C_{220}H_{263}NO_{23}\cdot 2H_2O$: C, 79.46; H, 8.09; N, 0.42. Found: C, 79.24; H, 8.08; N, 0.21.

4.1.48. 2,12-Bis(3,5-bis(methoxycarbonyl)-4-butylphenyl)-7-(4-hydroxyphenyl)-5,6,8,9-tetrahydrobenz[*c*,*h*]acridine (26). Compound **26** was prepared in analogous fashion to **8**. Mp 137–140°C; ^{1}H δ NMR 8.77 (s, 2H), 8.14 (s, 4H), 7.47 (d, J=7.8 Hz, 2H), 7.25 (d, J=7.8 Hz, 2H), 7.06 (d, J=8.3 Hz, 2H), 6.95 (d, J=8.3 Hz, 2H), 5.89 (br s, 1H), 3.71 (s, 12H), 3.15 (m, 4H), 2.81–2.66 (m, 8H), 1.59–1.39 (m, 4H), 0.94 (t, J=7.1 Hz, 6H); ^{13}C NMR δ 167.8, 158.2, 150.4, 148.0, 143.8, 138.9, 138.4, 138.0, 136.9, 132.9, 132.1, 131.0, 130.3, 129.3, 128.4, 127.0, 124.8, 115.9, 51.8, 34.6, 30.3, 28.5, 26.8, 24.0, 14.1. Anal. calcd for $C_{55}H_{53}NO_9$: C, 75.75; H, 6.13, N, 1.61. Found: C, 76.02; H, 5.83, N, 2.04.

4.1.49. 2,12-Bis(3,5-bis(methoxycarbonyl)-4-butylphenyl)-7-(4-(3,5-bis(3,5-bis(3,5-bis(3,5-di(*tert*-butyl)phenylmethoxy)phenylmethoxy)phenylmethoxy)phenylmethoxy)-phenyl)-5,6,8,9-tetrahydrodibenz[*c*,*h*]acridine (27). The procedure used to prepare **13a** was followed. Thus, the reaction of 0.3 g (0.344 mmol) of **26**, 0.879 g (0.344 mmol) of G3Br **6**, 0.40 g (2.9 mmol) of potassium carbonate, 0.70 g (1.9 mmol) of tetrabutylammonium iodide, and 42 mg (0.16 mmol) of 18-crown-6 in 120 mL of acetone afforded 1.05 g (91%) of **27** as a white foam after purification with chromatography (10–25% ethyl acetate/petroleum ether): ^{1}H NMR δ 8.76 (s, 2H), 8.19 (s, 4H), 7.54 (dd, 2H), 7.41 (s, 8H), 7.29 (s, 16H), 7.17–7.11 (AB q, 4H), 6.8–6.6 (m, 21H), 5.06–4.98 (s, 28H), 3.76 (s, 12H), 3.16 (m, 4H), 2.86 (t, 4H), 2.72 (t, 4H), 1.5–1.3 (m, 8H) 1.36 (s, 144H), 0.96 (t, 6H); ^{13}C NMR δ 168.1, 160.6, 160.4, 158.5, 151.1, 151.0, 147.8, 142.9, 139.5, 139.3, 139.2, 138.6, 137.9, 137.8 136.0, 135.9, 132.8, 131.4, 130.2, 130.0, 129.8, 128.1, 127.2, 123.8, 122.2, 115.1, 106.7, 101.9, 101.7, 71.2, 70.3, 70.2, 51.9, 34.9, 34.1, 31.6, 30.0, 28.0, 26.1, 23.2, 13.9. Anal. calcd for $C_{224}H_{271}NO_{23}$: C, 80.42; H, 8.16; N, 0.42. Found: C, 80.62; H, 8.14; N, 0.73.

4.1.50. 4,5-Bis(3,5-dicarboxy-4-butyl)phenyl)-2,7-di(*tert*-butyl)-9,9-dimethyl xanthene (28). A heterogeneous solution of 1.50 g (1.52 mmol) of tetraester **31** in 60 mL of 96% formic acid and 20 mL (0.26 mol) of trifluoroacetic acid was refluxed overnight. After cooling, the white precipitate was filtered from the red reaction mixture and washed well with 200 mL of water to give 1.18 (100%) of **28** as a white solid. An analytical sample was prepared by recrystallization from 95% ethanol (fine colorless crystals): mp >350°C; ^{1}H NMR (DMSO-d_6) δ 12.3–12.1 (br, 4H), 7.67 (s, 4H), 7.53 (s, 2H), 7.09 (s, 2H), 3.11–3.08 (m, 4H), 1.71 (s, 6H), 1.49–1.33 (m, 4H), 1.30 (m, 22H), 0.88 (t, J=7.2 Hz, 3H). Anal. calcd for $C_{47}H_{54}O_9$: C, 73.99; H, 7.13. Found: C, 73.92; H, 7.09.

4.1.51. 4,5-Bis(3,5-bis(*tert*-butoxycarbonyl)-4-(*n*-butyl)-phenyl)-2,7-di(*tert*-butyl)-9,9-dimethylxanthene (31). A heterogeneous solution of 3.6 g (6.45 mmol) of diboronic acid prepared from dibromide **29**, 7.2 g (15.6 mmol) of **30**, 50 mg (0.043 mmol) of tetrakis(tri-phenylphosphine) palladium(0) in 5 mL of ethanol, 100 mL of 2 M aqueous solution of sodium carbonate, and 200 mL of toluene was refluxed for 24 h. The reaction mixture was cooled to room temperature and the organic layer was separated. The aqueous layer was extracted twice with 50 mL of toluene. The combined organic layers were washed with brine, dried over anhydrous sodium sulfate, and concentrated under reduced pressure. The residue was treated with small amount of petroleum ether. The resulting precipitate was filtered and purified by recrystallization from 95% ethanol to give 4.9 g (77%) of **31** as white fine crystals: mp 158–160°C (dec); ^{1}H NMR δ 7.71 (s, 4H), 7.46 (d, J=2.3 Hz, 2H), 7.18 (d, J=2.3 Hz, 2H), 3.16 (m, 4H), 1.79 (s, 6H), 1.52 (s, 36H), 1.37 (s, 18H), 1.6–1.4 (m, 8H), 0.96 (t, J=7.2 Hz, 6H); ^{13}C NMR δ 167.1, 145.4, 144.7, 141.9, 135.0, 133.6, 133.3, 129.4, 127.9, 126.9, 122.8, 82.0, 34.8, 34.6, 34.3, 33.7, 31.6, 30.1, 28.3, 23.7, 14.3. Anal. calcd for $C_{63}H_{86}O_9$: C, 76.64; H, 8.78. Found: C, 77.20; H, 8.64.

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References

1. Taken in part from the PhD thesis of Fanwen Zeng, University of Illinois, 1997.
2. Lehn, J.-M. *NATO ASI Ser., Ser. E* **1996**, *320*, 511–524.
3. (a) Whitesides, G. M.; Simanek, E. E.; Mathias, J. P.; Seto, C. T.; Chin, D.; Mammen, M.; Gordon, D. M. *Acc. Chem. Res.* **1995**, *28*, 37–44. (b) Prins, L. J.; Timmerman, P.; Reinhoudt, D. N. *Curr. Trends Org. Synth.* **1999**, 35–46. (c) Desiraju, G. R. *Angew. Chem., Int. Ed. Engl.* **1995**, *34*, 2311–2327. (d) Archer, E. A.; Gong, H.; Krische, M. J. *Tetrahedron* **2001**, *57*, 1139–1159.
4. Drexler, K. E. *Nanosystems: Molecular Machinery, Manufacturing, and Computation*; Wiley: New York, 1992.
5. Bong, D. T.; Clark, T. D.; Granja, J. R.; Ghadiri, M. R. *Angew. Chem., Int. Ed. Engl.* **2001**, *40*, 988–1011. Olenyuk, B.; Stang, P. J. *Chem. Rev.* **2000**, *100*, 853–907. Raymo, F. M.; Stoddart, J. F. *Chem. Rev.* **1999**, *99*, 1643–1663. Leininger, S.; Prins, L. J.; Timmerman, P.; Reinhoudt, D. N. *Pure Appl. Chem.* **1998**, *70*, 1459–1468. Reinhoudt, D. N.; Stoddart, J. F.; Ungaro, R. *Chem. Eur. J.* **1998**, *4*, 1349–1351. Conn, M. M.; Rebek Jr, J. *Chem. Rev.* **1997**, *97*, 1647–1668. Fujita, M.; Ogura, K. *Coord. Chem. Rev.* **1996**, *148*, 249–264. Fredericks, J.; Yang, J.; Geib, S. J.; Hamilton, A. D. *Proc. Indian Acad. Sci., Chem. Sci.* **1994**, *106*, 923–935.
6. Smith, D. K.; Diederich, F. *Top. Curr. Chem.* **2000**, *210*, 183–227. Beginn, U.; Moller, M. *Perspect. Supramol. Chem.* **1999**, *4*, 89–176. Hawker, C. J. *Curr. Opin. Colloid Interface Sci.* **1999**, *4*, 117–121. Newkome, G. R.; He, E.; Moorefield, C. N. *Chem. Rev. (Washington, DC)* **1999**, *99*, 1689–1746. Bosman, A. W.; Janssen, H. M.; Meijer, E. W. *Chem. Rev.* **1999**, *99*, 1665–1688. Venturi, M.; Serroni, S.; Juris, A.; Campagna, S.; Balzani, V. *Top. Curr. Chem.* **1998**, *197*, 193–228. Newkome, G. R. *Pure Appl. Chem.* **1998**, *70*, 2337–2343. Crooks, R. M.; Ricco, A. J. *Acc. Chem. Res.* **1998**, *31*, 219–227. Tomalia, D. A. *NATO ASI Ser., Ser. C* **1997**, *499*, 183–191. Zeng, F.; Zimmerman, S. C. *Chem. Rev.* **1997**, *97*, 1681–1712.

Zimmerman, S. C. *Curr. Opin. Colloid Interface Sci.* **1997**, *2*, 89–99. Newkome, G. R.; Moorefield, C. N.; Vögtle, F. *Dendritic Macromolecules: Concepts, Syntheses, Perspectives*; VCH: Weinheim, 1996. Ardoin, N.; Astruc, D. *Bull. Soc. Chim. Fr.* **1995**, *132*, 875–909.

7. (a) Hawker, C. J.; Fréchet, J. M. J. *J. Am. Chem. Soc.* **1990**, *112*, 7638–7647. (b) Kawaguchi, T.; Walker, K. L.; Wilkins, C. L.; Moore, J. S. *J. Am. Chem. Soc.* **1995**, *117*, 2159–2165. (c) Zeng, F.; Zimmerman, S. C. *J. Am. Chem. Soc.* **1996**, *118*, 5326–5327.
8. Zimmerman, N.; Moore, J. S.; Zimmerman, S. C. *Chem. Ind.* **1998**, 604–610. Kihara, H.; Kato, T.; Uryu, T.; Fréchet, J. M. J. *Chem. Mater.* **1996**, *8*, 961–968. Kato, T.; Kihara, H.; Kumar, U.; Uryu, T.; Fréchet, J. M. J. *Angew. Chem., Int. Ed. Engl.* **1994**, *33*, 1644–1645.
9. Wooley, K. L. *J. Polym. Sci., Part A: Polym. Chem.* **2000**, *38*, 1397–1407. Fréchet, J. M. J.; Gitsov, I. *Macromol. Symp.* **1995**, 441–465. van Hest, J. C. M.; Delnoye, D. A. P.; Baars, M. W. P. L.; Vangenderen, M. H. P.; Meijer, E. W. *Science* **1995**, *268*, 1592–1595. Chapman, T. M.; Hillyer, G. L.; Mahan, E. J.; Shaffer, K. A. *J. Am. Chem. Soc.* **1994**, *116*, 11195–11196. Newkome, G. R.; Baker, G. R.; Arai, S.; Saunders, M. J.; Russo, P. S.; Theriot, K. J.; Moorefield, C. N.; Rogers, L. E.; Miller, J. E.; Lieux, T. R.; Murray, M. E.; Phillips, B.; Pascal, L. *J. Am. Chem. Soc.* **1990**, *112*, 8458–8465.
10. Massa, D. J.; Shriner, K. A.; Turner, S. R.; Voit, B. I. *Macromolecules* **1995**, *28*, 3214–3220.
11. Zimmerman, S. C.; Zeng, F.; Reichert, D. E. C.; Kolotuchin, S. V. *Science* **1996**, *271*, 1095–1098.
12. Zimmerman, S. C. *Top. Curr. Chem.* **1993**, *165*, 71–102.
13. During the course of this study Hamilton and coworkers reported similar self-assembling systems: Zafar, A.; Yang, J.; Geib, S. J.; Hamilton, A. D. *Tetrahedron Lett.* **1996**, *37*, 2327–2330. Yang, J.; Marendaz, J. L.; Geib, S. J.; Hamilton, A. D. *Tetrahedron Lett.* **1994**, *35*, 3665–3668.
14. Weber, E.; Hecker, M.; Koepp, E.; Orlia, W.; Czugler, M.; Csoregh, I. *J. Chem. Soc., Perkin Trans. 2* **1988**, 1251–1257.
15. Zerkowski, J. A.; Seto, C. T.; Whitesides, G. M. *J. Am. Chem. Soc.* **1992**, *114*, 5473–5475. Mathias, J. P.; Simanek, E. E.; Whitesides, G. M. *J. Am. Chem. Soc.* **1994**, *116*, 4326–4340.
16. Zafar, A.; Geib, S. J.; Hamuro, Y.; Carr, A. J.; Hamilton, A. D. *Tetrahedron* **2000**, *56*, 8419–8427.
17. Mhatre, R.; Oian, R.; Krull, I. S.; Gadam, S.; Cramer, S. M. *Chromatographia* **1994**, *38*, 349–354. Anthonsen, M. W.; Varum, K. M.; Hermansson, A. M.; Smidsrod, O.; Brant, D. A. *Carbohydr. Polym.* **1994**, *25*, 13–23. Roger, P.; Colonna, P. *Carbohydr. Polym.* **1993**, *21*, 83–89.
18. Thiyagarajan, P.; Zeng, F.; Ku, C. Y.; Zimmerman, S. C. *J. Mater. Chem.* **1997**, *7*, 1221–1226.
19. Zimmerman, S. C.; Duerr, B. F. *J. Org. Chem.* **1997**, *57*, 2215–2217. Schrier, E. E. *J. Chem. Educ.* **1968**, *45*, 176–180.
20. Zimmerman, S. C.; Kolotuchin, S. V. *J. Am. Chem. Soc.* **1998**, *120*, 9092–9093.
21. Nowick, J. S.; Ballester, P.; Ebmeyer, F.; Rebek Jr, J. *J. Am. Chem. Soc.* **1990**, *112*, 8902–8906.
22. For other early examples of main-chain hydrogen-bonded polymers see: Castellano, R. K.; Rudkevich, D. M.; Rebek, J. *Proc. Natl. Acad. Sci. USA* **1997**, *94*, 7132–7137. Sijbesma, R. P.; Beijer, F. H.; Brunsveld, L.; Folmer, B. J. B.; Hirschberg, K.; Lange, R. F. M.; Lowe, J. K. L.; Meijer, E. W. *Science* **1997**, *278*, 1601–1604.
23. Percec and coworkers have pioneered a related approach in liquid crystalline phases: Percec, V.; Cho, W. D.; Ungar, G.; Yeardley, D. J. P. *Angew. Chem., Int. Ed. Engl.* **2000**, *39*, 1598–1602. Percec, V.; Heck, J.; Johansson, G.; Tomazos, D.; Kawasumi, M.; Chu, P.; Ungar, G. *J. Macromol. Sci., Pure Appl. Chem.* **1994**, *A31*, 1719–1758.