ORGANIC LETTERS

2003
Vol. 5, No. 25
4787−4790

Molecular Tectonics. Dendritic Construction of Porous Hydrogen-Bonded Networks

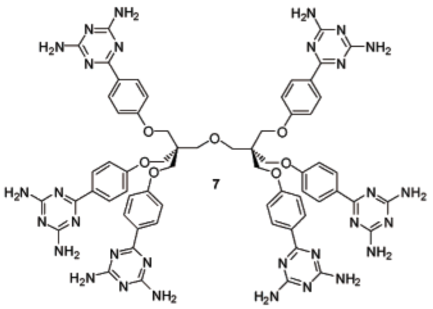
Dominic Laliberté,[†] Thierry Maris, Ariane Sirois, and James D. Wuest*

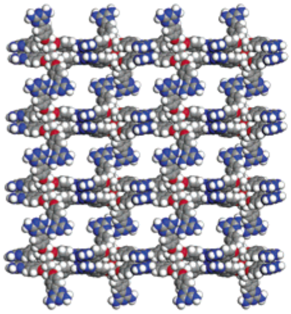
Département de Chimie, Université de Montréal, Montréal, Québec H3C 3J7, Canada

wuest@chimie.umontreal.ca

Received September 7, 2003

ABSTRACT

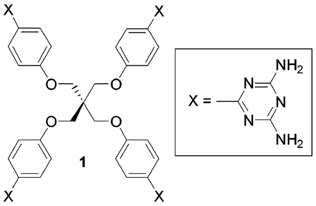




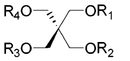
Molecules that associate to form porous networks can be made by attaching multiple hydrogen-bonding sites to suitable cores. Pentaerythrityl tetraphenyl ether, a four-armed core, is the progenitor of dendritic derivatives with more arms, including dipentaerythrityl hexaphenyl ether 7. An advantage of such dendritic derivatives is that the resulting networks are held together by larger numbers of intermolecular hydrogen bonds.

An established strategy for assembling materials by design is to build them from molecules with well-defined structures and multiple sticky sites that interact intermolecularly according to reliable motifs. In favorable cases, this approach places neighboring molecules in predetermined positions, giving ordered networks with predictable properties. Molecules of this type have been called tectons from the Greek word for builder,[1] and molecular tectonics refers to supramolecular construction directed by tectonic subunits.[1−5] This strategy promises to be a fruitful source of new ordered molecular materials with diverse architectures and properties, ranging from highly crystalline solids to liquid crystals, gels, and other less-ordered structures. Of special note is the inherent difficulty of forming ordered arrays in which tectons are closely packed at the same time that their programmed interactions are optimized; instead, tectonic association typically produces open networks that include guests.

Useful tectons can be devised by the simple expedient of attaching a suitable core to multiple sticky sites. For example, tecton **1** incorporates a four-armed core derived from pentaerythrityl tetraphenyl ether (**2**), linked to diaminotriazine groups that form multiple intermolecular hydrogen bonds according to established motifs. As planned, crystallization of tecton **1** (DMSO/dioxane) yielded an open hydrogen-bonded network with significant space for the inclusion of



1



2 ($R_1 = R_2 = R_3 = R_4 = Ph$)
3 ($R_1 = R_2 = R_3 = Ph$, $R_4 = CH_2C(CH_2OPh)_3$)
4 ($R_1 = R_2 = Ph$, $R_3 = R_4 = CH_2C(CH_2OPh)_3$)
5 ($R_1 = Ph$, $R_2 = R_3 = R_4 = CH_2C(CH_2OPh)_3$)
6 ($R_1 = R_2 = R_3 = R_4 = CH_2C(CH_2OPh)_3$)
8 ($R_1 = R_2 = R_3 = OTs$, $R_4 = CH_2C(CH_2OTs)_3$)

[†] Boehringer-Ingelheim Fellow, 2001-2002.

(1) Simard, M.; Su, D.; Wuest, J. D. *J. Am. Chem. Soc.* **1991**, *113*, 4696.

(2) Fournier, J.-H.; Maris, T.; Wuest, J. D.; Guo, W.; Galoppini, E. *J. Am. Chem. Soc.* **2003**, *125*, 1002.

(3) Sauriat-Dorizon, H.; Maris, T.; Wuest, J. D.; Enright, G. D. *J. Org. Chem.* **2003**, *68*, 240.

(4) Laliberté, D.; Maris, T.; Wuest, J. D. *J. Org. Chem.*, accepted for publication.

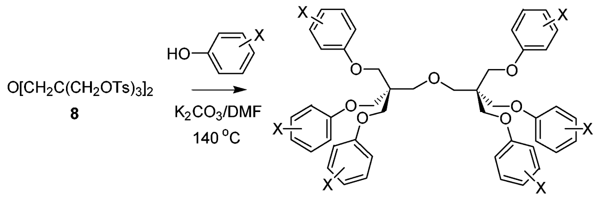
(5) For references to related work, see: Fournier, J.-H.; Maris, T.; Wuest, J. D. *J. Org. Chem.*, in press. Fournier, J.-H.; Maris, T.; Simard, M.; Wuest, J. D. *Cryst. Growth Des.* **2003**, *3*, 535.

10.1021/ol035712j CCC: $25.00

other molecules.[4] In this structure, 66% of the volume is accessible to guests,[6,7] which occupy interconnected channels with cross sections up to 9 × 5 Å^2 in diameter.[8] The high porosity of the network is noteworthy because the pentaerythrityl tetraphenyl ether core is flexible and can adopt various nontetrahedral geometries, yet a close-packed guest-free structure is not favored.

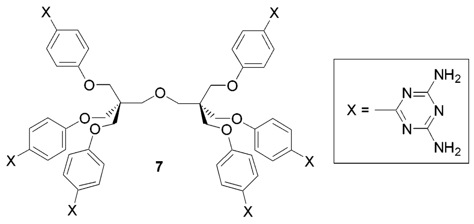
Tecton **1** can be considered to be the progenitor of a family of self-associating dendrimers derived from the pentaerythrityl tetraphenyl ether core.[9,10] Further dendritic growth offers promising new multiarmed cores for supramolecular construction, including hexaphenyl ether **3** (derived from dipentaerythritol), octaphenyl ether **4** (derived from tripentaerythritol), decaphenyl ether **5** (derived from tetrapentaerythritol), and dodecaphenyl ether **6** (derived from pentapentaerythritol).[11−13] Dendritic tectons with such cores are exciting targets for synthesis for the following reasons: (1) The number of sticky sites per tecton will increase with each generation, thereby increasing the number of intermolecular interactions and strengthening the resulting networks. (2) The density of sticky sites on the periphery of each tecton is expected to increase with each generation,[9,10] thereby reducing the number of neighboring tectons not held in positions imposed by directional forces. (3) The porosity of materials built from dendritic tectons should be enhanced because it will have dual origins, one corresponding to intertectonic spaces (as in normal tectonic networks) and the other corresponding to intratectonic spaces (due to the characteristically low density of the dendritic cores of the tectons themselves).[9,10,14] (4) The crystallinity of progenitor **1** suggests that dendritic derivatives of higher generations may also yield single crystals suitable for X-ray diffraction, whereas conventional dendrimers without strong intermolecular interactions normally resist crystallization because they are conformationally flexible and globular.[15,16]

Table 1. Reactions of Dipentaerythrityl Hexatosylate (**8**) with Phenols



entry	phenol	product	yield (%)
1	X = 4-Br	**9**	79
2	X = 3-Br	**10**	72
3	X = 2-Br	**11**	68
4	X = 4-NO$_2$	**12**	85
5	X = 4-CN	**13**	86
6	X = 3-CN	**14**	76
7	X = 4-CHO	**15**	75

To permit an initial test of these hypotheses, we synthesized diverse hexasubstituted derivatives of dipentaerythrityl hexaphenyl ether (**3**), including tecton **7**, in which diaminotriazine groups are attached to all six arms of the core. Our syntheses are similar to those used previously to make analogous derivatives of pentaerythrityl tetraphenyl ether (**2**).[4] Base-induced reactions of phenols with the known dipentaerythrityl hexatosylate (**8**)[11,17] (K_2CO_3/DMF/Δ) provided previously unknown derivatives **9**−**15** in good yields (Table 1). In this way, various substituted six-armed cores of potential utility in molecular and supramolecular construction can be obtained conveniently in a single step.



7

---

(6) The percentage of volume accessible to guests was estimated by the PLATON program,[7] using standard parameters.[2−5]

(7) Spek, A. L. *PLATON, A Multipurpose Crystallographic Tool*; Utrecht University: Utrecht, The Netherlands, 2001. van der Sluis, P.; Spek, A. L. *Acta Crystallogr.* **1990**, *A46*, 194.

(8) The dimensions of a channel in a particular direction correspond to the cross section of an imaginary cylinder that could be passed through the hypothetical open network in the given direction in contact with the van der Waals surface. Such values are inherently conservative because (1) they measure the cross section at the most narrow constriction, and (2) they systematically underestimate the sizes of channels that are not uniform and linear.

(9) Newkome, G. R.; Moorefield, C. N.; Vögtle, F. *Dendrimers and Dendrons: Concepts, Syntheses, Applications*; VCH: Weinheim, Germany, 2001.

(10) For other recent reviews of the subject of dendrimers, see: Grayson, S. M.; Fréchet, J. M. J. *Chem. Rev.* **2001**, *101*, 3819. Chow, H.-F.; Leung, C.-F.; Wang, G.-X.; Zhang, J. *Top. Curr. Chem.* **2001**, *217*, 1. Zimmerman, S. C.; Lawless, L. J. *Top. Curr. Chem.* **2001**, *217*, 95. Vögtle, F.; Gestermann, S.; Hesse, R.; Schwierz, H.; Windisch, B. *Prog. Polym. Sci.* **2000**, *25*, 987.

(11) For recent use of derivatives of dipentaerythritol in materials science, see: Shukla, A. A.; Bae, S. S.; Moore, J. A.; Barnthouse, K. A.; Cramer, S. M. *Ind. Eng. Chem. Res.* **1998**, *37*, 4090.

(12) For other recent uses of derivatives of dipentaerythritol in materials science, see: Biela, T.; Duda, A.; Rode, K.; Pasch, H. *Polymer* **2003**, *44*, 1851. Gigant, K.; Posset, U.; Schottner, G.; Baia, L.; Kiefer, W.; Popp, J. *J. Sol-Gel Sci. Technol.* **2003**, *26*, 369. Mayadunne, R. T. A.; Moad, G.; Rizzardo, E. *Tetrahedron Lett.* **2002**, *43*, 6811. Rohr, T.; Knaus, S.; Gruber, H.; Sherrington, D. C. *Macromolecules* **2002**, *35*, 97. Kader, M. A.; Bhowmick, A. K.; Inoue, T.; Chiba, T. *J. Mater. Sci.* **2002**, *37*, 1503. Kaczmarek, H.; Ołdak, D.; Szalla, A. *J. Appl. Polym. Sci.* **2002**, *86*, 3725. Huang, H.; Zhang, J.-Z.; Shi, W.-F. *J. Appl. Polym. Sci.* **2001**, *80*, 499. Joziasse, C. A. P.; Grablowitz, H.; Pennings, A. J. *Macromol. Chem. Phys.* **2000**, *201*, 107. Bunning, T. J.; Kirkpatrick, S. M.; Natarajan, L. V.; Tondiglia, V. P.; Tomlin, D. W. *Chem. Mater.* **2000**, *12*, 2842. Menger, F. M.; Migulin, V. A. *J. Org. Chem.* **1999**, *64*, 8916.

(13) Dipentaerythritol and tripentaerythritol are commercially available and inexpensive. For preparations of tetrapentaerythritol and pentapentaerythritol, see: Padias, A. B.; Hall, H. K., Jr.; Tomalia, D. A.; McConnell, J. R. *J. Org. Chem.* **1987**, *52*, 5305. Suchanec, R. R. *Anal. Chem.* **1965**, *37*, 1361.

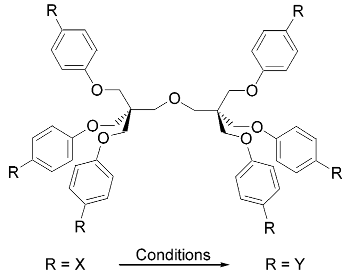
(14) For recent reviews of dendritic encapsulation, see: Gorman, C. B.; Smith, J. C. *Acc. Chem. Res.* **2001**, *34*, 60. Hecht, S.; Fréchet, J. M. J. *Angew. Chem., Int. Ed.* **2001**, *40*, 74.

(15) For structural studies of derivatives of dipentaerythritol by X-ray crystallography, see: Nättinen, K. I.; Rissanen, K. *Cryst. Growth Des.* **2003**, *3*, 339.

(16) For other recent structural studies of dendritic molecules by single-crystal X-ray diffraction, see: Bauer, R. E.; Enkelmann, V.; Wiesler, U. M.; Berresheim, A. J.; Müllen, K. *Chem. Eur. J.* **2002**, *8*, 3858. Ranganathan, D.; Kurur, S.; Gilardi, R.; Karle, I. L. *Biopolymers* **2000**, *54*, 289. Friedmann, G.; Guilbert, Y.; Wittmann, J. C. *Eur. Polym. J.* **1999**, *35*, 1097.

(17) For the structure of hexatosylate **8**, see the Supporting Information.

Table 2. Further Reactions of Hexasubstituted Derivatives of Dipentaerythrityl Hexaphenyl Ether (**3**)



entry	starting compd	conditions[a]	product	yield (%)
1	**12** (X = NO_2)	a	**16** (Y = NH_2)	99
2	**15** (X = CHO)	b	**17** (Y = CH_2OH)	82
3	**9** (X = Br)	c	**18** (Y = $B(OH)_2$)	87
4	**13** (X = CN)	d	**7** (Y = DAT[b])	79

[a] (a) H_2/Pd/C, THF; (b) $NaBH_4$, CH_3OH, −10 to 25 °C; (c) (1) BuLi, THF, −78 °C; (2) B(O-*i*Pr)$_3$, −78 to 25 °C; (3) HCl; (d) dicyandiamide, KOH, 2-methoxyethanol, reflux. [b] DAT = 4,6-diamino-1,3,5-diaminotriazin-2-yl.

Dipentaerythrityl hexaphenyl ethers **9**−**15** can then be subjected to further reactions, such as those summarized in Table 2, to produce an even broader range of substituted derivatives. In particular, reduction of hexanitro derivative **12** (Table 1, entry 4) provided the corresponding hexamine **16** (Table 2, entry 1), and reduction of hexaaldehyde **15** (Table 1, entry 7) gave hexol **17** (Table 2, entry 2). Lithiation of hexabromide **9** (Table 1, entry 1), followed by addition of B(*i*-OPr)$_3$ and then HCl, produced hexaboronic acid **18** (Table 2, entry 3). This compound can be considered to be a tecton because it incorporates multiple $B(OH)_2$ groups, which are known to self-associate by reliable patterns of hydrogen bonding.[2] Tecton **18** also promises to be a valuable intermediate for making more complex derivatives of dipentaerythrityl hexaphenyl ether by Suzuki coupling.

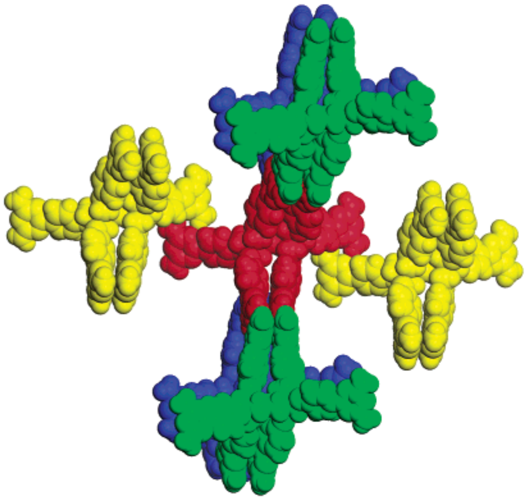


Figure 1. View of the structure of crystals of tecton **7** grown from DMSO/dioxane, showing a central tecton (red) and its six symmetry-equivalent hydrogen-bonded neighbors (colored blue, green, and yellow according to their interaction with the central tecton). All tectons adopt a characteristic ‡-shaped conformation in which two pairs of arms interact by intramolecular π-stacking.

Tecton **7** was prepared in 79% yield by the reaction of hexanitrile **13** (Table 1, entry 5) with dicyandiamide under standard conditions.[18] Single crystals suitable for X-ray diffraction could be grown by slow diffusion of dioxane into solutions of tecton **7** in DMSO. Tecton **7** crystallized in the monoclinic space group *P*2/*c* as an inclusion compound of approximate composition **7**·4 DMSO·16 dioxane.[19,20] Views of the structure appear in Figures 1−3. Like four-armed progenitor **1**, six-armed tecton **7** self-associates by extensive hydrogen bonding of its diaminotriazine groups to form an open three-dimensional network with significant volume for the inclusion of guests. Each tecton adopts a characteristic ‡-shaped conformation in which two pairs of the six arms lie parallel and interact intramolecularly by π-stacking (Figure 1).[21] Each of the four diaminotriazine groups attached to these arms forms four hydrogen bonds according to established motifs with diaminotriazine groups on equivalent π-stacked arms of four neighboring tectons (Figure 2a).[3,4] Each of the two remaining diaminotriazine groups forms two additional hydrogen bonds with two other neighbors (Figure 2b), giving a network in which each tecton forms a total of 20 hydrogen bonds with six neighboring tectons.[22] Additional

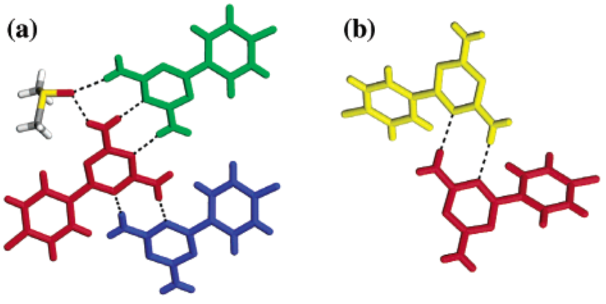


Figure 2. Hydrogen bonding in the network constructed from tecton **7**. (a) View of one of the four π-stacked arms of the central tecton (red), showing how it forms four hydrogen bonds (broken lines) with equivalent arms of the blue and green neighbors, as well as an additional hydrogen bond with a molecule of DMSO. (b) View of one of the other two arms of the central tecton (red), showing how it forms two hydrogen bonds with an equivalent arm of the yellow neighbor.

---

(18) Simons, J. K.; Saxton, M. R *Organic Syntheses*; Wiley: New York, 1963; Collect. Vol. IV, p 78.

(19) Crystal data for tecton **7**·4 DMSO·16 dioxane: $T = 223$ K, crystal size $0.22 \times 0.12 \times 0.10$ mm^3, monoclinic, space group *P*2/*c*, $a = 19.758(1)$ Å, $b = 10.865(1)$ Å, $c = 36.649(2)$ Å, $\beta = 90.759(3)°$, $V = 7866.5(8)$ Å^3, $Z = 2$, θ max = 62.36°, 63526 reflections measured, 11176 unique ($R_{int} = 0.052$). Final residual for 581 parameters and 6356 reflections with $I > 2(I)$: $R_1 = 0.0970$, w$R_2 = 0.2195$, and GoF = 1.041. Details are provided as Supporting Information.

(20) The composition was estimated by X-ray crystallography and by ^1H NMR spectroscopy of dissolved samples. The amount of any H_2O included could not be determined accurately.

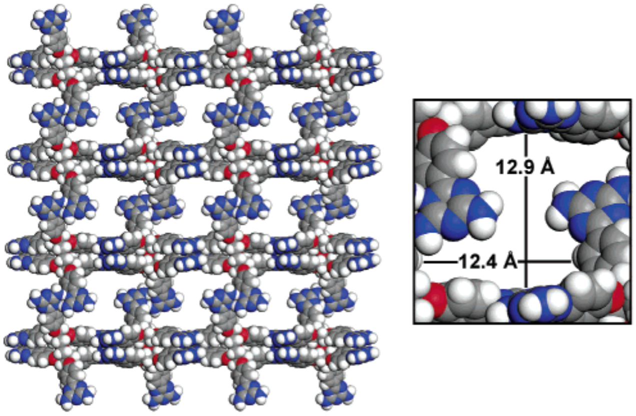


Figure 3. Views along the *b* axis of the network constructed from tecton **7**, showing a 4 × 4 × 2 array of unit cells (left) and an enlarged view of the cross section of a single channel (right). Guests are omitted, and atoms are shown as spheres of van der Waals radii.

hydrogen bonds join molecules of DMSO to the network (Figure 2a).

As planned, the network constructed from six-armed tecton **7** is held together by more intertectonic hydrogen bonds per tecton (20) than is the network built from four-armed progenitor **1** (12 per tecton).[4] This significant difference underscores the advantage of building tectons from dendritic cores.

The network constructed from six-armed tecton **7** is highly porous, and approximately 66% of the volume of the crystals is accessible to guests.[6] The guests occupy interconnected channels, which are illustrated in Figure 3. Channels lying along the *b* axis are S-shaped and have a cross section of approximately 13×12 Å^2, and those lying along the *c* axis have a cross section of approximately 11×2 Å^2.[8]

Although the porosity of the network constructed from six-armed tecton **7** is impressive, it is not greater than that of the network built from four-armed progenitor **1**, possibly because the dipentaerythrityl hexaphenyl ether core assumes a compact conformation with π-stacked arms, whereas the pentaerythrityl tetraphenyl ether core is less flexible and adopts a divergent conformation. In general, dendritic growth of the core may give networks with more hydrogen bonds per tecton, but porosity will not necessarily increase.

Our observations show that (1) the network built from tecton **7** is held together by an unusually large number of hydrogen bonds per tecton; (2) a major part of the volume is accessible to guests; and (3) large interconnected channels provide multiple routes of entry and escape. For these reasons, we expected single crystals of tecton **7** to be robust and to undergo rapid exchanges of guests without loss of crystallinity, as observed in networks built from many other tectons.[2−5] In fact, placing crystals of estimated composition **7**·4 DMSO·16 dioxane[20] in tetrahydrofuran (25 °C, 24 h) led to loss of crystallinity, whereas exchange with retention of crystallinity occurred under similar conditions in crystals of four-armed progenitor **1**. We suggest that increased intermolecular contacts in the network built from six-armed tecton **7** enhance robustness as planned but not enough to compensate for increased flexibility of the dendritic core. As a result, the network derived from six-armed tecton **7** is less able to endure stresses induced by exchange.

Our study of dendritic tectons is noteworthy because it creates new links between crystal engineering and the science of dendrimers and shows that concepts drawn from each of the two fields can be applied fruitfully to the other. In particular, dendritic growth of suitable tectonic cores can increase the number of intermolecular interactions per tecton and yield porous crystalline networks, as planned. However, dendritic cores that are too flexible will not necessarily give networks with abnormally high stability and porosity. Continued efforts to exploit the advantages of dendritic construction and minimize the disadvantages are likely to be productive.

Acknowledgment. We are grateful to the Natural Sciences and Engineering Research Council of Canada, the Ministère de l'Éducation du Québec, the Canada Foundation for Innovation, the Canada Research Chairs Program, and Merck Frosst for financial support.

Supporting Information Available: Experimental procedures for making compounds **7**, **8**, and **9**−**18**; characterization of compounds **7**, **8**, and **9**−**18**; ORTEP drawings and tables of crystallographic data, atomic coordinates, anisotropic thermal parameters, and bond lengths and angles for compounds **7** and **8** in CIF format. This material is available free of charge via the Internet at http://pubs.acs.org.

OL035712J

---

(21) Similar π-stacked conformations have been observed in other aryl-substituted derivatives of dipentaerythritol.[15]

(22) Joining the central oxygen atom of each tecton with the centers of the six neighboring tectons defines a complex noninterpenetrated six-connected network (see Supporting Information).