Dendrimer Shape Control

Transformation of a Spherical Supramolecular Dendrimer into a Pyramidal Columnar Supramolecular Dendrimer Mediated by the Fluorophobic Effect**

Virgil Percec, Martin Glodde, Gary Johansson, Venkatachalapathy S. K. Balagurusamy, and Paul A. Heiney*

Semifluorinated and perfluorinated molecules have had a large impact on the field of chemistry and their use has provided new strategies in organic,[1] supramolecular,[2,3] biomolecular, and macromolecular synthesis.[4] It is well established that perfluorinated alkanes are stiffer and less miscible than the corresponding perhydrogenated alkanes (fluorophobic effect).[4] As a consequence, the replacement of a perhydrogenated alkane with a perfluorinated alkane in the alkyl tail of a self-assembling building block enhances the thermal stability of the resulting supramolecular object and of the corresponding lattice.[2a,b,e,4c,4d] For example, the fluorophobic effect has been shown to stabilize the columnar $p6mm$ hexagonal[2a,b,e,4c,4d] as well as the $c2mm$ and $p2mm$ rectangular[2e] 2D lattices that self-organize from cylindrical semifluorinated supramolecular dendrimers. The enhanced ability of semifluorinated dendrons toward self-assembly is so strong that first generation dendrons enforce the co-assembly of a disordered polymer backbone in the center of a supramolecular cylinder through the use of covalent[4c] or only donor–acceptor interactions.[2e] Hydrogenated dendrons require higher generations to mediate self-assembly into cylindrical or spherical[5,6] supramolecular dendrimers when strong interacting groups are absent from their core.[7] To date, spherical supramolecular dendrimers have been found to self-organize into $Pm\bar{3}n$,[2b,5,6] $Im\bar{3}m$[7a,8] cubic, and $P4_{2/mnm}$ tetragonal[9] 3D lattices.

Here we report a new, completely unexpected fluorophobic effect observed during the self-assembly of dendrons that generate spherical supramolecular dendrimers in their perhydrogenated state.

---

[*] Prof. Dr. V. Percec, Dr. M. Glodde, Dr. G. Johansson,
Dr. V. S. K. Balagurusamy
Roy & Diana Vagelos Laboratories, Department of Chemistry
Laboratory for Research on the Structure of Matter
University of Pennsylvania
Philadelphia, PA 19104-6323 (USA)
Fax: (+1) 215-573-7888
E-mail: percec@sas.upenn.edu

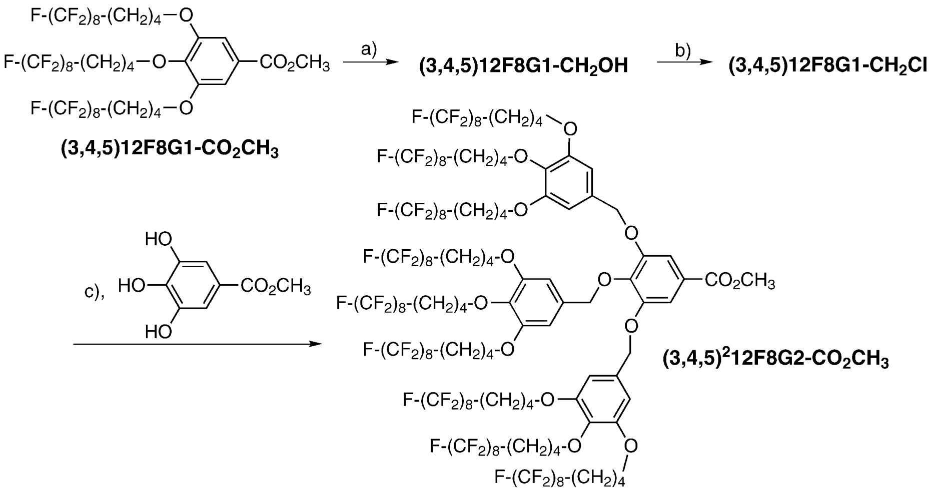
Dr. V. S. K. Balagurusamy, Prof. Dr. P. A. Heiney
Department of Physics and Astronomy
Laboratory for Research on the Structure of Matter
University of Pennsylvania
Philadelphia, PA 19104-6396 (USA)

[**] Financial support of this work by the National Science Foundation (DMR-9996288 and DMR-0102459) is gratefully acknowledged.

Supporting information for this article is available on the WWW under http://www.angewandte.org or from the author.

DOI: 10.1002/ange.200351804

The synthesis, structural, and retrostructural analysis as well as the mode of self-assembly of the second generation semifluorinated dendron (Scheme 1) is similar to that of the hydrogenated analogue **(3,4,5)^{2}12G2-CO$_2$CH$_3$**.[5] Structural analysis of the hydrogenated and fluorinated supramolecular dendrimers was accomplished by a combination of differential scanning calorimetry (DSC; Table 1), thermal optical polarized microscopy (TOPM), small- and wide-angle X-ray diffraction (XRD; Table 2), and molecular-modeling experiments.[2a,e,5,6]



Scheme 1. Synthesis of **(3,4,5)^{2}12F8G2-CO$_2$Me**. a) LiAlH$_4$, Et$_2$O, 22 °C, then NaOH, H$_2$O, 88 %; b) SOCl$_2$, α,α,α-trifluorotoluene, 22 °C, 70 %; c) DMF/α,α,α-trifluorotoluene, K$_2$CO$_3$, 70 °C, then freon 113, [18]crown-6, 48 °C, 65 %.

The data in Tables 1 and 2 show that **(3,4,5)^{2}12G2-CO$_2$CH$_3$** self-assembles into a spherical supramolecular dendrimer that self-organizes into a $Pm\bar{3}n$ cubic lattice similar to that reported for other homologues from this series (Figure 1 a).[5,6] Fifteen **(3,4,5)^{2}12G2-CO$_2$Me** conical dendrons derived from *trans* conformations of the benzyl ethers self-assemble into a spherical supramolecular dendrimer with diameter D of 46.5 Å (Table 2). Based on the previous effects observed in cylindrical supramolecular dendrimers,[2a,b,e] we expected that **(3,4,5)^{2}12F8G2-CO$_2$Me** would self-assemble in a spherical supramolecular dendrimer that would self-organize into a $Pm\bar{3}n$ cubic lattice like the one observed for **(3,4,5)^{2}12G2-CO$_2$Me** (Table 1). In addition, since fluorinated alkanes are stiffer than the corresponding hydrogenated homologues, the supramolecular object generated from **(3,4,5)^{2}12F8G2-CO$_2$Me** was expected to exhibit a larger diameter than its hydrogenated homologue since, at the same temperature, its fluorinated alkyl groups would exist in a smaller number of *gauche* conformers.

Figure 2 shows the combined features of small- and wide-angle XRD patterns recorded on **(3,4,5)^{2}12F8G2-CO$_2$CH$_3$** at 50 °C and at 23 °C. The ratios of the d-spacings of the observed reflections in the small-angle region (feature a in Figure 2) establish that **(3,4,5)^{2}12F8G2-CO$_2$CH$_3$** self-assembles into supramolecular cylinders of $D = 35.8$ Å that self-organize into a 2D hexagonal columnar liquid-crystalline (LC) phase (Table 2). Unexpectedly, the XRD data show the change in supramolecular shape from a sphere to a cylinder and the decrease in diameter from 46.5 Å to 35.8 Å, respectively.

Table 1: Thermal analysis of the 3D and 2D lattices self-organized from **(3,4,5)^{2}12G2-CO$_2$Me** and **(3,4,5)^{2}12F8G2-CO$_2$Me** dendrons.

Dendron	Thermal transitions [°C] and corresponding enthalpy changes (in parenthesis) [kcal mol^{-1}][a] heating[a]	cooling
(3,4,5)^{2}12G2-CO$_2$Me	k[b]→i[c] 58.5 (40.8) k→k −1.0 (5.06); k→k 11.4 (−11.6); k→i 57.9 (29.6)	i→cub.[d] 55.6 (1.15); cub.[d]→*k* 3.84 (5.55)
(3,4,5)^{2}12F8G2-CO$_2$Me	k→k 75.4 (11.88); k→Φ_h 84.5 (0.43); Φ_h[e]→i 92.0 (1.81) k→Φ_h 22.1 (4.25); Φ_h→i 91.6 (1.85)	i→Φ_h 86.8 (1.84); Φ_h→*k* 17.6 (3.50)

[a] Data obtained from the first heating and cooling DSC scans are on the first line; data from the second heating are on the second line. [b] k = crystalline. [c] i = isotropic. [d] cub. = $Pm\bar{3}n$ cubic lattice. [e] Φ_h = $p6mm$ hexagonal columnar lattice.

Table 2: Structural and retrostructural analysis of the supramolecular dendrimers self-assembled from **(3,4,5)^{2}12G2-CO$_2$Me** and **(3,4,5)^{2}12F8G2-CO$_2$Me** dendrons from XRD experiments at 50 °C.

	Lattice	a [Å][a]	ρ_{20} [g cm^{-3}][b]	D_{exp} [Å][c]	μ[d]	α′ [°][e]
(3,4,5)^{2}12G2-CO$_2$Me	$Pm\bar{3}n$[f]	75.0	1.00	46.5	15.1	23.8
(3,4,5)^{2}12F8G2-CO$_2$Me	$p6mm$[g]	35.8	1.33	35.8	0.87 h]	360

[a] Lattice dimension. [b] ρ_{20} = experimental density at 20 °C. For **(3,4,5)^{2}12G2-CO$_2$Me**, the density was assumed to be 1 g cm^{-3}. [c] Experimentally derived column or sphere diameter; sphere diameter is calculated from $D_{exp} = 2\sqrt{3a^2/32\pi}$. [d] Number of monodendrons per column in a single stratum (Φ_h) or per spherical assembly ($Pm\bar{3}n$); Φ_h: $\mu = (\sqrt{3}\,N_A a^2 t\rho)/2\,M_r$; $Pm\bar{3}n$: $\mu = (a^3 N_A \rho)/8\,M_r$ (N_A: Avogadro's number; the average thickness of the stratum $t = 4.8$ Å, M_r = molecular weight of a monodendron). [e] Taper angle for tapered monodendrons and projection of the solid angle subtended by conical monodendrons $\alpha' = 360/\mu$ °. [f] d-spacings for the $Pm\bar{3}n$ lattice [Å]: d_{200}: 37.6, d_{210}: 33.4, d_{211}: 30.6, d_{310}: 23.4, d_{321}: 19.7, d_{410}: 18.5, d_{421}: 16.5, d_{332}: 15.9. [g] d-spacings for the $p6mm$ lattice [Å]: d_{100}: 30.7, d_{110}: 17.9, d_{200}: 15.6, d_{210}: 12.1. [h] If the large tilt is taken into account, the number of molecules that occupy the volume of a single conical stratum is 1.0; see text for discussion.

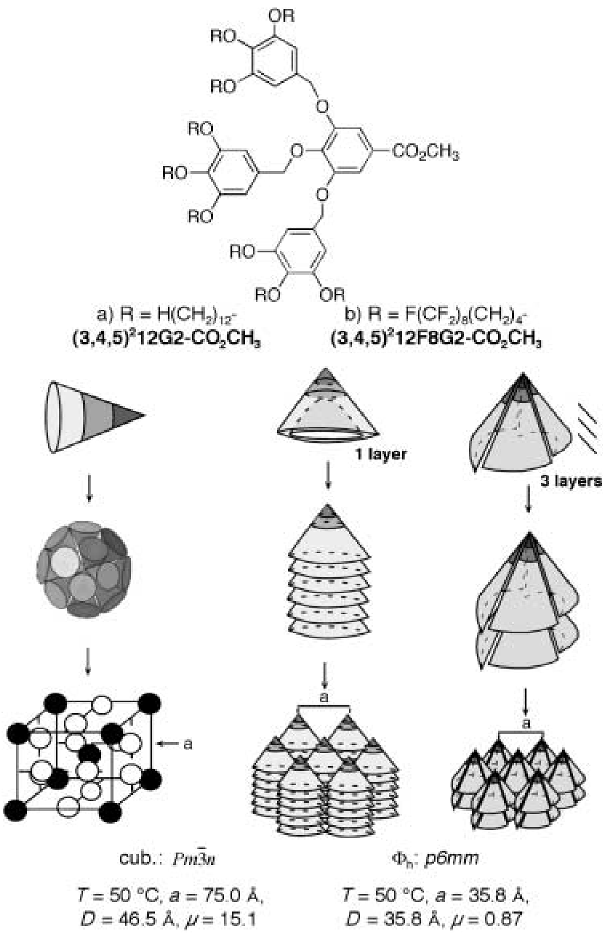


Figure 1. Structures, self-assembly, and self-organization of the second generation dendrons: a) all-*trans* cone conformation of **(3,4,5)^{2}12G2-CO$_2$Me**; b) all *gauche*-crown conformation of **(3,4,5)^{2}12F8G2-CO$_2$Me**; c) all *trans*-taper conformation of **(3,4,5)^{2}12F8G2-CO$_2$Me**.

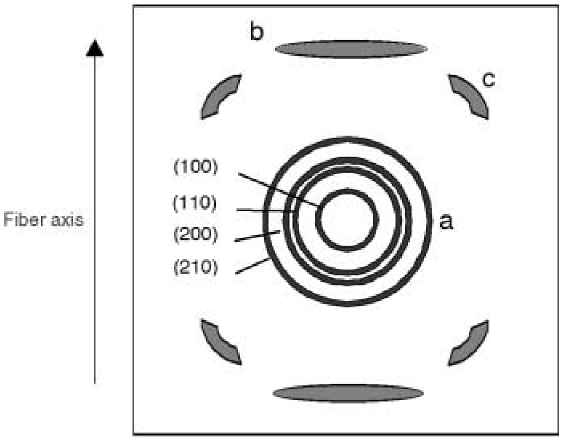


Figure 2. Combined X-ray pattern of small- and wide-angle X-ray diffractograms of **(3,4,5)^{2}12F8G2-CO$_2$CH$_3$** recorded at 50 °C and at 23 °C, respectively, on cooling from the isotropic state: a) concentric rings of the reflections, determined from the powder small-angle XRD experiment; b) π–π stacking distance along the column axis (3.9 Å); c) *d*-spacing corresponding to the average intermolecular separation along the column axis of 4.8 Å (X-like arrangement of spots, which also indicates a tilt of the molecule of 42 ± 2°).

X-ray diffraction measurements carried out on fibers from the *p6mm* LC phase at 23 °C show broad spots corresponding to π–π stacking along the column axis ($d = 3.9$ Å, feature b in Figure 2) and an X-like pattern ($d = 3.9 \pm 0.1$ Å, feature c in Figure 2). The X-like pattern implies that the molecules are tilted by 42 ± 2° from the normal to the column axis and that the intermolecular separation along the column axis is 4.8 ± 0.1 Å (see Supporting Information).

The number of untilted molecules μ that occupy a disc with the same thickness $t = 4.8$ Å as the supramolecular cylinder was calculated to be 0.87 (Table 2). However, a different calculation that considers the tilted molecules in the columns was also performed (see Supporting Information). This geometry results in a conical column stratum with an apex angle corresponding to a tilt angle of 42° and a thickness of 4.8 Å. Molecular models of two different conformations of **(3,4,5)^{2}12F8G2-CO$_2$Me** were constructed (Figure 3) to gain further insight into how the molecules pack in this unusual columnar LC phase. The two dendron conformations, which were based on predominantly all-*trans* and predominantly all-*gauche* benzyl ether conformers, had a tilt angle almost equal to the experimentally observed value of 42°, and in both cases the molecules are packed in a staggered fashion so as to fill the space, which is consistent with the observed *d*-spacings and mass density (Figure 1).

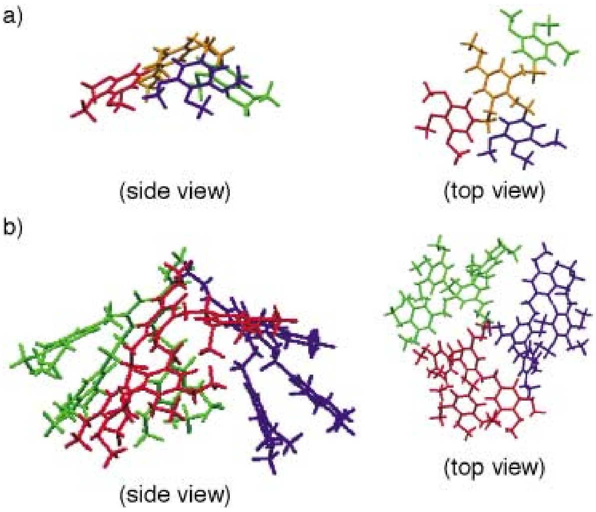


Figure 3. a) Pyramidic columnar model generated from the *gauche*-crown conformer of **(3,4,5)^{2}12F8G2-CO$_2$Me**; b) pine-tree columnar model generated from the *trans*-tapered conformer of the same dendron.

One of these two models, known as the pyramidic columnar model[10] (Figure 1 (middle column) and Figure 3 a) results from the fanning-out of all the four benzene rings of a single dendron in a nearly symmetrically arrangement from the center of the column. This model requires *gauche* conformations for all the benzyl ether groups of the dendron. The overall shape of this dendron is crownlike or conelike. This *gauche* crownlike or conelike dendron from Figure 3 a differs from the conical dendrons obtained from all-*trans* benzyl ether conformations that self-assemble into spherical supramolecular dendrimers (Figure 1, left column).[5,6] The pyramidic supramolecular column is self-assembled by the stacking of *gauche* crownlike dendrons one on top of the other, with each dendron totally occupying a single conical stratum of thickness 4.8 Å. The neighboring molecules are rotated from each other about the column axis to fill the space efficiently. The other model, known as the pine-tree columnar model, results from a helical pine-tree-like arrangement of tapered dendrons that are tilted with respect to the column axis and also rotated about the molecular long axis.[11] In this model, three dendrons with all the benzyl ethers in *trans* conformations are located nearly at the same position along the column axis to form a nonhelical pine-tree-like cone with a total vertical thickness of nearly 3 × 4.8 Å (Figure 1, Figure 3b). Density calculations show that each dendron partially occupies three neighboring conical strata of thickness 4.8 Å (see Supporting Information). Since the pine-tree model is nonhelical, from a packing point of view, both columnar models shown in Figure 1 (middle and right columns) are similar to pyramidic liquid crystals.[10]

Electron-density profiles computed from XRD data were analyzed in regard to the nanophase separation that drives the formation of these LC phases.[2b,5] The phase combinations that exhibited either slowly varying or nearly constant distributions of electron density in the regions corresponding to the aromatic, perhydrogenated aliphatic and the perfluorinated aliphatic parts were closely examined. The surface and contour plots of the electron density computed for the phase combination of "− − + +" for the reflections (100), (110), (200), and (210), respectively, is shown in Figure 4. The color-filled contour plots shown at the base represent a single supramolecular column (center) that is surrounded by six other neighboring columns. The high electron density regions in the periphery of the columns (red in Figure 4) correspond to the fluorinated alkyl chain segments whereas the low electron density regions (purple) represent the hydrogenated alkyl chain sections which are adjacent to the fluorinated alkyl chain segments. The diffraction pattern shows that the (210) peak has higher intensity than the (200) and (110) peaks. This result is consistent with the location of the fluorinated aliphatic region in the periphery of the columns, that is, the highest electron density region at the periphery. The electron density in the central region of the columns is lower than that of the fluorinated aliphatic regions, but higher than the electron density of the hydrogenated aliphatic regions that encapsulate the center of the columns. Hence, the region of intermediate electron density in the core of the columns corresponds to the aromatic part of the dendrons that form the supramolecular assembly. This observation is consistent with both our hypothesis of organization of the present *gauche* crownlike and of the *trans* tapered-like dendrons reported previously.[2a,b,e,6,7] The diameter of the aromatic region calculated from the electron-density profiles corresponding to the volume fraction of the aromatic region in the pyramidic and pine-tree models is consistent with both models of packing. The aromatic part of the *gauche*-crown or *trans*-tapered dendrons produces the core of the cylinders, with the fluorinated alkyl chain segments in the periphery and the hydrogenated alkyl chain parts in the intervening region, thus forming three distinct segregated nanophasic regions. This model is in agreement with similar structures reported from *trans*-tapered hydrogenated dendrons that self-assemble into supramolecular cylinders.[2a,6,12,13] The electron density computed from the XRD data is consistent with both the pyramidic and nonhelical pine-tree models for the packing of the dendritic molecule **(3,4,5)^{2}12F8G2-CO$_2$CH$_3$** in the columnar LC phase.

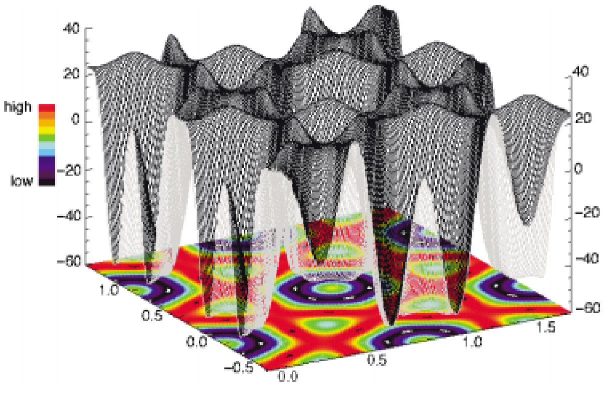


Figure 4. Electron density maps of supramolecular columns self-assembled from **(3,4,5)^{2}12F8G2-CO$_2$CH$_3$**. The profile shows the variation in the electron density in a plane perpendicular to the supramolecular columns in the LC phase. The color-filled contour maps at the base also show the variation in the electron density in the same plane.

In conclusion, we have described the first example of the transformation of the mode of self-assembly of a dendron from a spherical to a pyramidic columnar supramolecular dendrimer that is mediated by the fluorophobic effect. This change in mechanism of self-assembly is induced by the change in the dendron conformation from an all-*trans*-conical to an all-*gauche*-crown or an all-*trans*-tapered conformation. This result contrasts the role of the fluorophobic effect in the self-assembly of dendrons that form cylindrical supramolecular dendrimers when their chains are fully hydrogenated.[2a,b,e] Therefore, we conclude that the fluorophobic effect produced by the fluorinated alkyl tails of amphiphilic dendrons enhances the self-assembly into columnar supramolecular dendrimers and decreases the tendency toward self-assembly into spherical dendrimers.

Received: May 5, 2003 [Z51804]

Keywords: dendrimers · fluorophobic effect · liquid crystals · self-assembly

---

[1] For selected reviews on fluorous phases in organic synthesis, see a) I. T. Horváth, *Acc. Chem. Res.* **1998**, *31*, 641; b) D. P. Curran, *Angew. Chem.* **1998**, *110*, 1230; *Angew. Chem. Int. Ed.* **1998**, *37*, 1174; Erratum: D. P. Curran, *Angew. Chem.* **1998**, *110*, 2569; *Angew. Chem. Int. Ed.* **1998**, *37*, 2292; c) L. P. Barthel-Rosa, J. A. Gladysz, *Coord. Chem. Rev.* **1999**, *190–192*, 587; d) E. de Wolf, G. van Koten, B.-J. Deelman, *Chem. Soc. Rev.* **1999**, *28*, 37; e) C. Tschierscke, C. Markert, W. Bannwarth, S. Roller, A. Hebel, R. Haag, *Angew. Chem.* **2002**, *114*, 4136; *Angew. Chem. Int. Ed.*

2002, *41*, 3964; f) J. A. Gladysz, D. P. Curran, *Tetrahedron* **2002**, *58*, 3823 (and papers published in this special issue).

[2] For selected examples of publications on fluorinated molecules in self-assembly, see a) V. Percec, G. Johansson, G. Ungar, J. Zhou, *J. Am. Chem. Soc.* **1996**, *118*, 9855; b) S. D. Hudson, H.-T. Jung, V. Percec, W.-D. Cho, G. Johansson, G. Ungar, V. S. K. Balagurusamy, *Science* **1997**, *278*, 449; c) G. W. Coates, A. R. Dunn, L. M. Henling, D. A. Dougherty, R. H. Grubbs, *Angew. Chem.* **1997**, *109*, 290; *Angew. Chem. Int. Ed. Engl.* **1997**, *36*, 248; d) W. J. Feast, P. W. Lövenich, H. Puschmann, C. Taliani, *Chem. Commun.* **2001**, 505; e) V. Percec, M. Glodde, T. K. Bera, Y. Miura, I. Shiyanovskaya, K. D. Singer, V. S. K. Balagurusamy, P. A. Heiney, I. Schnell, A. Rapp, H.-W. Spiess, S. D. Hudson, H. Duan, *Nature* **2002**, *419*, 384.

[3] For selected examples of publications on fluorinated compounds in self-organization, see a) U. Dahn, C. Erdelen, H. Ringsdorf, R. Festag, J. H. Wendorff, P. A. Heiney, N. C. Maliszewskyj, *Liq. Cryst.* **1995**, *19*, 759; b) G. Johansson, V. Percec, G. Ungar, K. Smith, *Chem. Mater.* **1997**, *9*, 164; c) V. Percec, D. Schlueter, G. Ungar, *Macromolecules* **1997**, *30*, 645; d) F. Guittard, E. T. de Givenchy, S. Geribaldi, A. Cambon, *J. Fluorine Chem.* **1999**, *100*, 85; e) X. H. Cheng, S. Diele, C. Tschierske, *Angew. Chem.* **2000**, *112*, 605; *Angew. Chem. Int. Ed.* **2000**, *39*, 592; f) C. Rocaboy, F. Hampel, J. A. Gladysz, *J. Org. Chem.* **2002**, *67*, 6863.

[4] For several examples of fluorine in biomolecular and macromolecular chemistry, see a) B. E. Smart in *Organofluorine Chemistry. Principles and Commercial Applications* (Eds.: R. E. Banks, B. E. Stuart, J. C. Tatlow), Plenum, New York, **1994**; b) *Modern Fluoropolymers* (Ed.: J. Scheirs), Wiley, New York, **1997**; c) V. Percec, D. Schlueter, Y. K. Kwon, J. Blackwell, M. Möller, P. J. Slangen, *Macromolecules* **1995**, *28*, 8807; d) G. Johansson, V. Percec, G. Ungar, J. Zhou, *Macromolecules* **1996**, *29*, 646; e) Y. Tang, G. Ghirlanda, N. Vaidehi, J. Kua, D. T. Mainz, W. A. Goddard III, W. F. DeGrado, D. A. Tirrel, *Biochemistry* **2001**, *40*, 2790; f) S. Sheiko, E. Lermann, M. Möller, *Langmuir* **1996**, *12*, 4015.

[5] V. S. K. Balagurusamy, G. Ungar, V. Percec, G. Johansson, *J. Am. Chem. Soc.* **1997**, *119*, 1539.

[6] V. Percec, W.-D. Cho, G. Ungar, D. J. P. Yeardley, *J. Am. Chem. Soc.* **2001**, *123*, 1302, and references therein.

[7] a) V. Percec, M. N. Holerca, S. Uchida, W.-D. Cho, G. Ungar, Y. Lee, D. J. P. Yeardley, *Chem. Eur. J.* **2002**, *8*, 1106; b) V. Percec, W.-D. Cho, G. Ungar, D. J. P. Yeardley, *Chem. Eur. J.* **2002**, *8*, 2011; c) V. Percec, W.-D. Cho, P. E. Mosier, G. Ungar, D. J. P. Yeardley, *J. Am. Chem. Soc.* **1998**, *120*, 11061; d) V. Percec, C.-H. Ahn, G. Ungar, D. J. P. Yeardley, M. Möller, S. S. Sheiko, *Nature* **1998**, *391*, 161.

[8] a) D. J. P. Yeardley, G. Ungar, V. Percec, M. N. Holerca, G. Johansson, *J. Am. Chem. Soc.* **2000**, *122*, 1684; b) H. Duan, S. D. Hudson, G. Ungar, M. N. Holerca, V. Percec, *Chem. Eur. J.* **2001**, *7*, 4134.

[9] G. Ungar, Y. Liu, X. Zeng, V. Percec, W.-D. Cho, *Science* **2003**, *299*, 1208.

[10] a) H. Zimmermann, R. Poupko, Z. Luz, J. Billard, *Z. Naturforsch. A* **1985**, *40a*, 149; b) J. Malthête, A. Collet, *Nouv. J. Chim.* **1985**, *9*, 15; c) A. M. Levelut, J. Malthête, A. Collet, *J. Phys.* **1986**, *47*, 351; d) J. Malthête, A. Collet, *J. Am. Chem. Soc.* **1987**, *109*, 7544; e) R. Poupko, Z. Luz, N. Spielberg, H. Zimmermann, *J. Am. Chem. Soc.* **1989**, *111*, 6094; f) H. Zimmermann, V. Bader, R. Poupko, E. J. Wachtel, Z. Luz, *J. Am. Chem. Soc.* **2002**, *124*, 15286.

[11] Y. K. Kwon, S. Chvalun, A. I. Schneider, J. Blackwell, V. Percec, J. A. Heck, *Macromolecules* **1994**, *27*, 6129.

[12] G. Ungar, D. Abramic, V. Percec, J. A. Heck, *Liq. Cryst.* **1996**, *21*, 73.

[13] V. Percec, D. Schlueter, G. Ungar, S. Z. D. Cheng, A. Zhang, *Macromolecules* **1998**, *31*, 1745.