From Random Coil to Extended Nanocylinder: Dendrimer Fragments Shape Polymer Chains

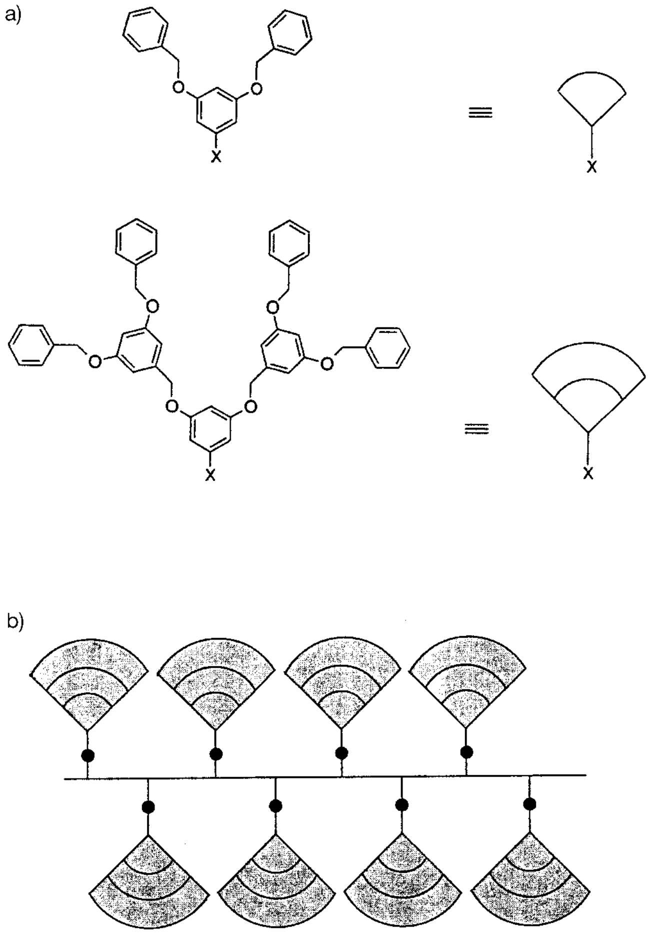
Holger Frey*

Introduction

Dendrimers—perfectly branched, highly symmetrical, treelike macromolecules—have evolved from a curiosity into an important trend in current chemistry, attracting rapidly increasing attention from an unusually broad community of scientists.[1] Various dendrimer construction strategies have been developed on the basis of classical organic and inorganic chemistry,[2] as well as on transition metal complexation.[3, 4] Based on these now well-established synthetic "algorithms", increasing research efforts are currently directed at constructing supramolecular structures and dendrimers by self-assembly processes as well as elucidating structure–property relationships.[5] For instance, flexible dendrimers with mesogenic branching points[6] or end groups[7] have been constructed that are able to induce anisotropic liquid crystalline order despite the isotropic dendrimer topology. Furthermore, self-assembly of dendrimers on surfaces to give ultrathin films with a thickness of a few nanometers has been investigated by a number of groups,[8] with the aim of developing films for application in catalysis, sensors, or chromatographic separation.[9]

For polymer chemists it is an interesting question as to how well-known linear polymers can be linked to dendritic architectures and what the supramolecular consequences of this approach might be. The combination of dendrimers and linear polymers in hybrid linear dendritic block copolymers has been employed to achieve particular self-assembly effects. Block copolymers with a linear polyethylene oxide block and a dendritic polybenzyl ether block form large micellar structures in solution, which depend on the size (that is, the generation) of the dendritic block.[10] Amphiphilic block copolymers have been prepared by the combination of a linear, apolar polystyrene chain with a polar, hydrophylic poly(propylene imine) dendrimer[11] as well as from polyethylene oxide with Boc-substituted poly-α,ε-L-lysine dendrimers (Boc = *tert*-butoxycarbonyl).[12] Such block copolymers form large spherical and cylindrical micelles in solution and have been described as "superamphiphiles" and "hydraamphiphiles", respectively.

In contrast to these successful efforts to link dendrimers and linear polymer chains in the manner of block copolymers, only very recently a breakthrough has been achieved in the synthesis of linear polymers with dendritic side groups (Scheme 1). This will be highlighted in this contribution. Considerable synthetic effort is required to prepare suitable dendritic monomers; however, the amazing kinetic and structural features observed for such monomers and their



Scheme 1. a) Fréchet-type[13] dendritic wedges used as conical or fanlike building units; b) schematic representation of a polymer chain with dendritic side groups.[27]

---

[*] Dr. H. Frey
Freiburger Materialforschungszentrum und
Institut für Makromolekulare Chemie der Universität
Stefan-Meier-Strasse 21/31, D-79104 Freiburg (Germany)
Fax: (+49) 761-203-4709
E-mail: holfrey@fmf.uni-freiburg.de

corresponding polymers are nevertheless highly rewarding and opens up the prospect of building defined nanostructures.

Synthesis and Self-Organization of Dendrons

The term "dendron" designates a dendrimer segment possessing an AB_w-type structure, which in contrast to a perfect dendrimer is not attached to a central B_n-core unit (A and B represent the functionalities that are linked to build up the dendrimer structure). Thus, a dendron is structurally characterized by exactly one focal unit A and $w = m^g$ end groups B (m is the branching multiplicity, usually 2 or 3, and g represents the generation number). The size and number of end groups of a dendron can, of course, be varied with each generation, which gives access to a large variety of nanosize building blocks for supramolecular chemistry. The conical dendron structure may be compared to a molecular "piece of cake" (Scheme 1). In most examples where dendrons are used as supramolecular building blocks, dendritic polybenzyl ethers constructed by reactions developed by Hawker and Fréchet[13] have been employed (Scheme 1 a). Some examples of polymerizable dendrons are shown in Figure 1.

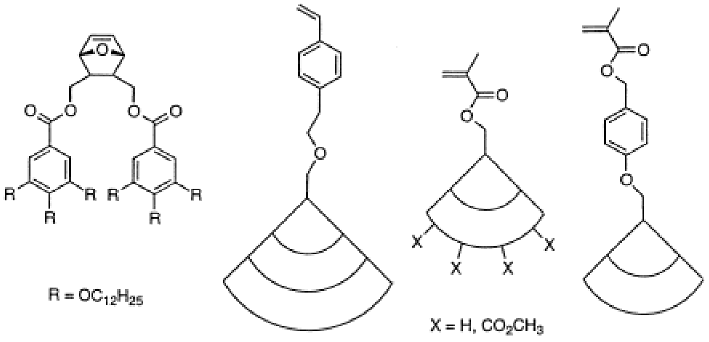
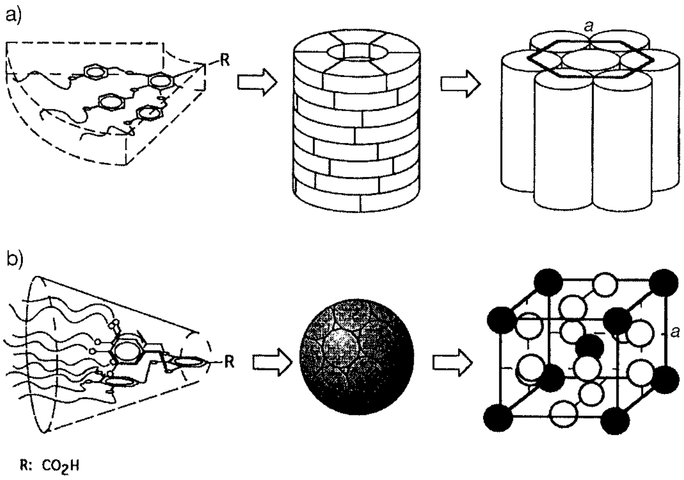


Figure 1. Examples of dendron monomers described by Percec et al., Schlüter et al., and Xi et al.

Supramolecular organization of dendrons can lead to columnar or spherical superstructures, which structure forms depends on directional and attractive interactions between such wedge-shaped molecules as well as on the size and shape of the dendrons. For instance, hydrogen-bonding interactions between diisophthalic acid moieties attached to the focal point were used by Zimmerman et al.[14] to obtain discrete self-assembled hexamers of polybenzyl ether dendrimers. Remarkably, the self-assembled structures were stable to purification by gel chromatography and the self-assembly process was solvent dependent. When small dendrons were used less stable chainlike aggregates were obtained, thus illustrating the correlation between specific recognition processes and the shape of the dendrimer wedge.

Self-organization of tapered and dendritic—that is, fan- and cone-shaped—molecules in the solid state was reported in a series of papers by Percec et al.[15] Detailed diffraction experiments evidenced that spherical or cylindrical (columnar) superstructures are formed, which are further packed into cubic or hexagonal columnar phases (Scheme 2).



Scheme 2. Shape-directed self-assembly of wedgelike dendrons to hexagonal-columnar and cubic superstructures according to Percec et al.[15a]

Preparation of Polymers with Dendron Side-Chains

There are three approaches that can be used to prepare polymers with dendron side groups: A) divergent construction, analogous to divergent dendrimer synthesis, with a multifunctional linear polymer as a B_n-type core instead of a small "point like" core; B) attachment of prefabricated dendron building blocks onto a reactive polymer chain by a polymer-analogous reaction, similar to the final coupling step to the core in convergent dendrimer synthesis;[13] and C) polymerization of dendron monomers. The basic idea behind the first strategy was mentioned as early as 1987 by Tomalia and Kirchhoff[16a] in a patent ("comb-burst" polymers). In a recent paper, the results of this work have been published in more detail: A polyethylene imine prepared by living cationic polymerization of 2-ethyl-2-oxazoline and subsequent deprotection was used as the core for the synthesis of rod-shaped poly(amidoamine) structures.[16b] Unfortunately, little information is given by the authors concerning control of molecular weights and polydispersities of the dendronized polyethylenimine that would permit direct comparison of this concept (A) with the other strategies (B and C) discussed below.

The second strategy (B) has been investigated intensively in the last few years by Schlüter et al. with Fréchet-type polybenzyl ether wedges and hydroxy-functional poly(p-phenylene) (PPP).[17a] The key problem encountered in this case lies in the limited conversion that can be achieved in polymer-analogous reactions, particularly if higher generation dendritic wedges (G3 and higher) are employed.[17b, c] In these cases incompletely covered polymer chains are obtained; for example, only 90% of the reactive groups at the PPP backbone are linked with dendrimer fragments of a G3 dendron. This drawback of the polymer-analogous approach has motivated intense efforts along the lines of concept C, which is based on polymerizable dendrons. If a polymerizable functionality is attached to a dendron at the focal point, "dendron monomers" are obtained (Figure 1). Large polymerizable building blocks of variable size with conical topology may be prepared depending on the dendrimer generation employed. The fascinating questions for the polymer chemist are: Can such dendron monomers actually be polymerized, and if so, what are the properties of the resulting polymer chains with unusually large substituents?

A styrene-based copolymer with approximately 40 weight% (2 mol%) of repeating units carrying dendrons was reported by Hawker and Fréchet in 1992.[18] However, only in the last four years have dendrimer synthesis and related characterization methods matured sufficiently that it is now possible to study dendron (macro)monomers and to exploit their potential for the synthesis of dendron-bearing polymers. One would intuitively expect polymerization of such monomers to be troublesome, as a consequence of the sterical requirements of the large dendrimer fragments as well as the increasing shielding effect on the polymerizable moiety as the number of generations increases. These problematic aspects are well known in macromonomer chemistry[19] and are expected to be even more severe for dendron monomers. This assumption has been confirmed in the last few years by a number of authors[20] who studied the polymerization of methacrylates with various attached dendritic fragments. Indeed, a high degree of polymerization of monodendrons to macromolecules was only possible when a spacer was inserted between the polymerizable unit and the bulky dendron group, and with very long reaction times.

In contrast, recent kinetic investigations of the polymerization of spacerless G2-dendron-substituted styrene and methyl methacrylate in solution led to the unexpected conclusion that above a certain critical monomer concentration a strong increase of the rate of the free radical polymerization is observed.[21] The results can be explained by self-organization of the growing polymer chain to a spherical or columnar superstructure in solution, depending on the degree of polymerization (Figure 2). The rate constants and low initiator efficiency demonstrate that the self-assembled structure acts like a supramolecular nanoreactor that leads to a strongly enhanced local concentration of polymerizable groups. Thus, the kinetics of the polymerization is determined by self-assembly and can be viewed as "self-encapsulated" and "self-accelerated".

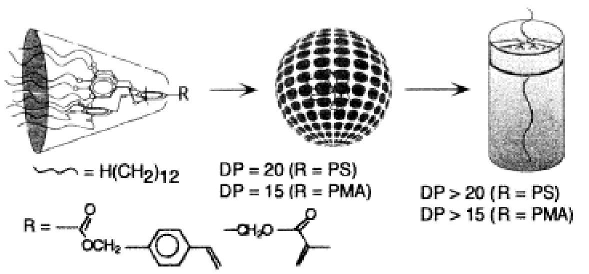


Figure 2. Dependence of the self-assembly of dendronized polymer chains on the degree of polymerization: monomers and short polymer chains assemble in spheres, whereas longer chains assemble in cylinders. This effect leads to rapid polymerization of such dendron monomers as a result of the "self-encapsulation".[21]

Polycondensation of suitable monomers represents an alternative route to dendronized polymers of high molecular weight; for example, PPP with attached dendron segments has been prepared by Suzuki cross-coupling of dendron-substituted dibromobenzenes with alkyl-chain-substituted diboronic acids in a polycondensation type of reaction.[17c] In this case, dendronized PPP of high molecular weight with a degree of polymerization exceeding 100 was obtained.

Properties and Visualization of Dendronized Polymers

When dendrimer fragments are attached to polymer chains, the conformation of the polymer chain is strongly affected by the large dendrimer wedges attached. "Dendronized" polymers can be considered as a subclass of comb polymers; that is, they are linear polymer chains densely substituted with polymeric side chains. These polymers are known to be extremely rigid in solution and exhibit Kuhn lengths of 100–200 nm, as compared to 1–2 nm for polystyrene or polymethyl methacrylate.[22] For that reason, such comb polymers are sometimes designated "cylindrical brushes".

Consequently, a cylindrical shape is also expected for polymers with large dendron side chains. Of course, biomolecules such as DNA or RNA with rigid cylindrical or wormlike shapes are well known, but in these cases the supermolecular structure (the secondary and tertiary structure) is the result of well-controlled secondary (hydrogen) bonds.

For flexible synthetic polymers the chain conformation is commonly controlled by the degree of polymerization (DP); polymers with low DP have a rather extended chain conformation, and those with high DP adopt random coil conformations in solution. Recently, Percec, Möller et al. reported extensive studies concerning the chain conformation and supramolecular structure of dendron-substituted polystyrene and polymethacrylate.[23] Remarkably, at low DP (that is, with short chains) the conical monodendrons assemble to produce a spherical superstructure with a random-coil backbone conformation (Figure 3a). On increasing the DP the self-assembly pattern of the dendrons changes, and leads to cylindrical polymers with rather extended backbones (Figure 3b). It is remarkable that this correlation between polymer conformation and the DP is opposite to that seen usually in most synthetic and natural macromolecules.

It is a fascinating consequence of the stiffness and densely covered surface of such cylindrical macromolecules that single polymer chains can be visualized. Möller et al. recently demonstrated impressively that the imaging of dendron-substituted polystyrene and polymethacrylate can be employed for an analysis of the molecular size distribution and conformation.[24] The image shown in Figure 4 was obtained by scanning force microscopy (SFM) and shows single chains of dendronized polystyrene deposited on a pyrolytic graphite substrate. The molecules exhibit short, straight segments with bends of a characteristic angle of 60° and 120° corresponding to the threefold symmetry of the graphite. In addition, the molecules in close proximity tend to align parallel, forming hairpin bends. The height of the chains is in the range of 1.6 nm and the lateral diameter of the chains is 5.3 nm (SFM, tapping mode), which illustrates that the macromolecules are collapsed on the surface. The length of each macromolecule can be approximated from the SFM images by dividing the

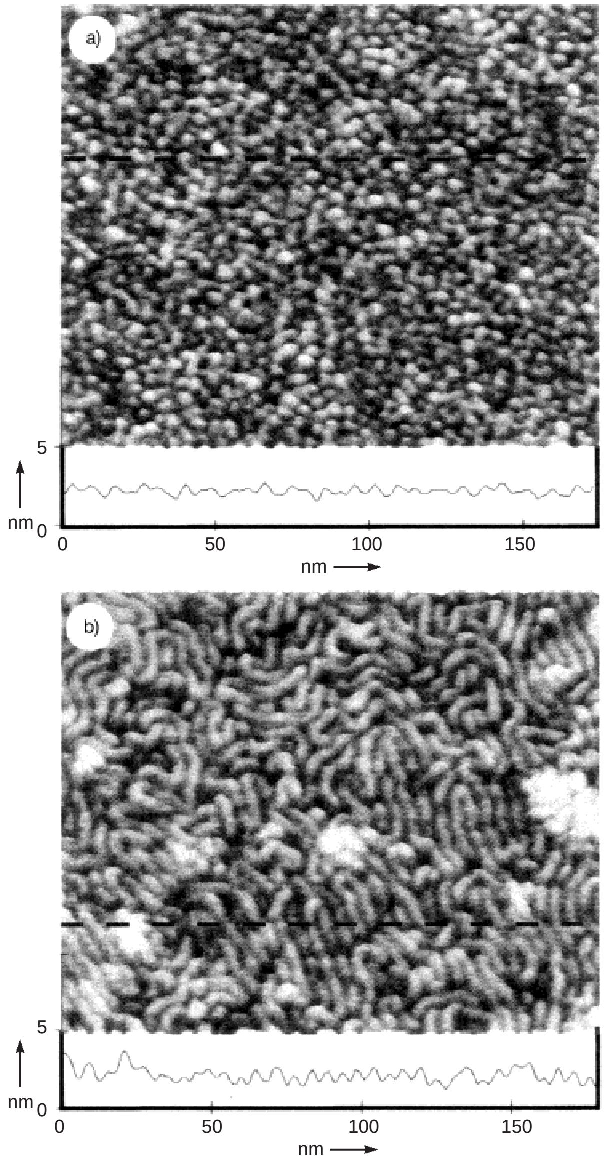


Figure 3. Topographic SFM images (tapping mode) of monomolecular films of dendron-bearing polystyrene; a) $M_n = 10800$; b) $M_n = 186500$. Spherical and cylindrical (wormlike) features are observed; cylindrical features arise from single dendronized macromolecules.[23]

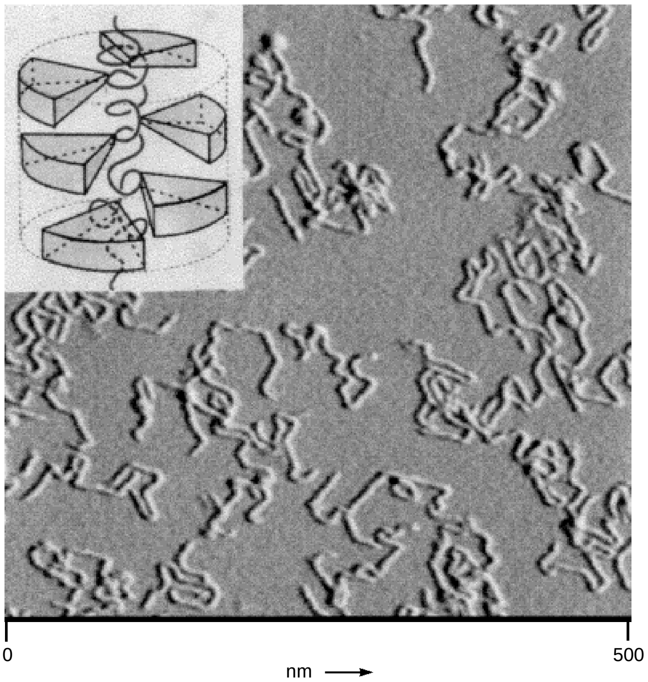


Figure 4. Single "wormlike" polymer chains of dendronized polystyrene deposited on pyrolytic graphite, imaged by topographic SFM.[24]

wormlike contours into segments of 10–20 nm, and then the distribution of the contour lengths may be calculated.

It is an intriguing question as to whether the molecular weight distribution can be determined in the solid state. Comparison of the apparent length of the macromolecules determined from the images shows that for large dendron side groups this is in good agreement with that expectated, whereas when lower generation dendrons are attached, the contour length determined from the images is considerably lower than the calculated length of the extended chains. This demonstrates that the degree of extension (uncoiling) of the chains is determined by the size of the dendrons attached.

As interaction between the surface and the substrate may affect the images, it is an interesting question as to whether the polymers actually possess cylindrical shape in solution. Small angle neutron scattering (SANS) experiments have been employed to answer this question. Figure 5 shows the scattering curve of a dendron-substituted polystyrene (G3 dendrons).[25] It is possible to describe the scattering curve by assuming that the dendron-substituted polystyrene exhibits a rod like structure. Thus, the persistence length of the molecule is of the order of the contour length, supporting the presence of stiff, cylindrical macromolecules in solution.

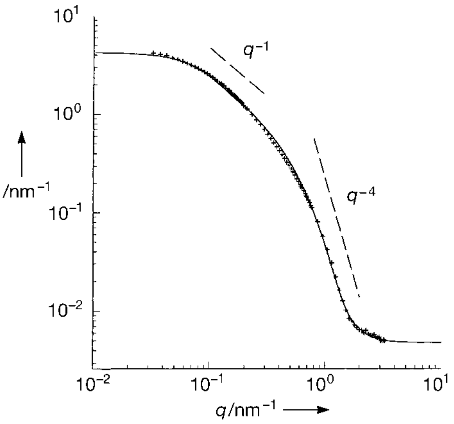


Figure 5. SANS scattering curve ($I(q)$ versus q) q = scattering vector of a G3-dendronized polystyrene, obtained by Förster, Schlüter et al.[25] The scattering curve at larger q follows the Porod q^{-4} law, and arises from the scattering at the surface of a cylinder. This observation confirms the stiff, wormlike character of the macromolecules.

Conclusion and Outlook

In summary, the attachment of dendron building blocks to common monomers leads to dramatic kinetic and structural consequences. Once more, it should be kept in mind that it is only the shape of the side groups attached that governs conformation and structure of the resulting polymer chains, not hydrogen-bonding interactions, which are ubiquitous in the self-assembly of biological macromolecules.

Based on the breakthrough achieved in the synthesis and visualization of "dendronized" polymers, it is a safe bet that this novel class of extremely stiff macromolecules will stimulate further interdisciplinary efforts to understand their physical behavior in bulk and in solution, as well as to assess their usefulness for a future nanotechnology based on "molecular objects". On the other hand, these developments may lead to libraries of shapes that can be combined to create any nanometer-sized cylindrical object with programmed length and diameter.[26] Block copolymers with one "dendronized" cylindrical block and one coiled block can also be envisaged.[27] In addition, dendrons bearing protected functionalities developed by Schlüter et al. offer further possibilities for the functionalization of such nanocylinders.[20c] Let's wait for the shape of other exciting molecular objects based on dendrimer wedges to come!

German version: *Angew. Chem.* **1998**, *110*, 2313 – 2318

Keywords: dendrimers · force microscopy · nanostructures · polymers

---

[1] a) D. A. Tomalia, A. M. Naylor, W. A. Goddard III, *Angew. Chem.* **1990**, *102*, 119 – 157*; Angew. Chem Int. Ed. Engl.* **1990**, *29*, 138 – 175; b) D. A. Tomalia, H. D. Durst, *Top. Curr. Chem.* **1993**, *165*, 193 – 313; c) G. R. Newkome, C. N. Moorefield, F. Vögtle, *Dendritic Macromolecules: Concepts, Syntheses, Perspectives*, 1st ed, VCH, Weinheim, **1996**; d) J. M. J. Fréchet, C. J. Hawker, *React. Funct. Polym.* **1995**, *26*, 127 – 150; e) B. I. Voit, *Acta Polymer.* **1995**, *46*, 87 – 99; f) H. Frey, K. Lorenz, L. Lach, *Chem. Unserer Zeit* **1996**, 75 – 85; g) O. A. Matthias, A. N. Shipway, J. F. Stoddart, *Prog. Polym. Sci.* **1998**, *23*, 1 – 56.

[2] H. Frey, C. Lach, K. Lorenz, *Adv. Mater.* **1998**, *10*, 279 – 293.

[3] C. Gorman, *Adv. Mater.* **1998**, *10*, 295 – 309.

[4] W. T. S. Huck, F. C. J. M. van Veggel, D. N. Reinhoudt, *Angew. Chem.* **1996**, *108*, 1304 – 1306; *Angew. Chem. Int. Ed. Engl.* **1996**, *35*, 1213 – 1215.

[5] a) F. Zeng, S. C. Zimmerman, *Chem. Rev.* **1997**, *97*, 1681 – 1712; b) S. C. Zimmerman, *Curr. Opin. Coll. Interf. Sci.* **1997**, *2*, 89 – 99; c) J. S. Moore, *Acc. Chem. Res.* **1997**, *30*, 402 – 413.

[6] a) V. Percec, P. W. Chu, G. Ungar, J. P. Zhou, *J. Am. Chem. Soc.* **1995**, *117*, 11 441 – 11 454; b) J. F. Li, K. A. Crandall, P. W. Chu, V. Percec, R. G. Petschek, C. Rosenblatt, *Macromolecules* **1996**, *29*, 7813 – 7819.

[7] a) K. Lorenz, D. Hölter, B. Stühn, R. Mülhaupt, H. Frey, *Adv. Mater.* **1996**, *8*, 414 – 416; b) S. A. Ponomarenko, E. A. Rebrov, A. Y. Bobrovsky, N. I. Boiko, A. M. Muzafarov, *Liq. Cryst.* **1996**, *21*, 1 – 12; c) K. Lorenz, H. Frey, R. Mülhaupt, *Macromolecules* **1997**, *30*, 6860 – 6868.

[8] a) S. Watanabe, S. L. Regen, *J. Am. Chem. Soc.* **1994**, *116*, 8855 – 8856; b) M. Wells, R. M. Crooks, *J. Am. Chem. Soc.* **1996**, *118*, 3988 – 3989; c) S. S. Sheiko, G. Eckert, G. Ignat'eva, A. M. Muzafarov, J. Spickermann, H. J. Räder, M. Möller, *Macromol. Rapid Commun.* **1996**, *17*, 283 – 297; d) M. Collaud Coen, K. Lorenz, J. Kressler, H. Frey, R. Mülhaupt, *Macromolecules* **1996**, *29*, 8069 – 8076.

[9] a) S. A. Kuzdzal, C. A. Monnig, G. R. Newkome, C. N. Moorefield, *J. Chem. Soc. Chem. Commun.* **1994**, 2139 – 2140; b) P. G. H. M. Muijselaar, H. A. Claessens, C. A. Cramers, J. F. G. A. Jansen, E. W. Meijer, E. M. de Brabender-Van den Berg, S. Vanderwal, *J. High Res. Chromat.* **1995**, *18*, 121 – 123.

[10] a) I. Gitsov, K. L. Wooley, C. J. Hawker, P. T. Ivanova, J. M. J. Fréchet, *Macromolecules* **1993**, *26*, 5621 – 5627; b) I. Gitsov, J. M. J. Fréchet, *Macromolecules* **1993**, *26*, 6536 – 6546; c) J. M. J. Fréchet, I. Gitsov, *Macromol. Symp.* **1995**, *98*, 441 – 465.

[11] a) J. C. M. van Hest, D. A. P. Delnoye, M. W. P. L. Baars, M. H. P. van Genderen, E. W. Meijer, *Science* **1995**, *268*, 1592 – 1595; b) J. C. M. van Hest, M. W. P. L. Baars, R. C. Elissenroman, M. H. P. van Genderen, E. W. Meijer, *Macromolecules* **1995**, *28*, 6689 – 6691.

[12] T. M. Chapman, G. L. Hillyer, E. J. Mahan, K. A. Shaffer, *J. Am. Chem. Soc.* **1994**, *116*, 11 195 – 11 196.

[13] C. J. Hawker, J. M. J. Fréchet, *J. Am. Chem. Soc.* **1990**, *112*, 7638 – 7647.

[14] S. C. Zimmerman, F. W. Zeng, D. E. C. Reichert, S. V. Kolotuchin, *Science* **1996**, *271*, 1095 – 1098.

[15] a) V. S. K. Balagurusamy, G. Ungar, V. Percec, G. Johansson, *J. Am. Chem. Soc.* **1997**, *119*, 1539 – 1555; b) S. D. Hudson, H.-T. Jung, V. Percec, W. D. Cho, G. Johansson, G. Ungar, V. S. K. Balagurusamy, *Science* **1997**, *278*, 449 – 452.

[16] a) D. A. Tomalia, P. M. Kirchhoff, Dow Chemical Co., US-Patent 834 993, **1987** [*Chem. Abstr.* **1998**, *108*, 56 832]; b) R. Yin, Y. Zhu, D. A. Tomalia, H. Ibuki, *J. Am. Chem. Soc.* **1998**, *120*, 2678 – 2679.

[17] a) R. Freudenberger, W. Claussen, A. D. Schlüter, H. Wallmeier, *Polymer* **1994**, *35*, 4496 – 4501; b) B. Karakaya, W. Claussen, A. Schäfer, A. Lehmann, A. D. Schlüter, *Acta Polym.* **1996**, *47*, 79 – 84; c) B. Karakaya, W. Claussen, K. Gessler, W. Saenger, A. D. Schlüter, *J. Am. Chem. Soc.* **1997**, *119*, 3296 – 3301.

[18] C. J. Hawker, J. M. J. Fréchet, *Polymer* **1992**, *33*, 1507 – 1513.

[19] *Chemistry and Industry of Macromonomers* (Ed.: Y. Yamashita), Hüthig & Wepf, Basel, **1993**.

[20] a) G. Draheim, H. Ritter, *Macromol. Chem. Phys.* **1995**, *196*, 2211 – 2222; b) Y. M. Chen, C.-F. Chen, Y.-F. Liu, Y. F. Li, F. Xi, *Macromol. Rapid Commun.* **1996**, *17*, 401 – 407; c) I. Neubert, R. Klopsch, W. Claussen, A. D. Schlüter, *Acta Polym.* **1996**, *47*, 455 – 459.

[21] V. Percec, C.-H. Ahn, B. Barboiu, *J. Am. Chem. Soc.* **1997**, *119*, 12 978 – 12 979.

[22] a) Y. Tsukahara, Y. Tsutsumi, Y. Yamashita, S. Shimada, *Macromolecules* **1990**, *23*, 5201 – 5208; b) M. Wintermantel, M. Gerle, K. Fischer, M. Schmidt, I. Wataoka, H. Urakawa, K. Kajiwara, Y. Tsukahara, *Macromolecules* **1996**, *29*, 978 – 983; c) S. S. Sheiko, M. Gerle, K. Fischer, M. Schmidt, M. Möller, *Langmuir* **1997**, *13*, 5368 – 5372; d) P. Dziezok, S. S. Sheiko, K. Fischer, M. Schmidt, M. Möller, *Angew. Chem.* **1997**, *109*, 2894 – 2897; *Angew. Chem. Int. Ed. Engl.* **1997**, *36*, 2812 – 2815.

[23] V. Percec, C.-H. Ahn, G. Ungar, D. J. P. Yeardley, M. Möller, S. S. Sheiko, *Nature* **1998**, *391*, 161 – 164.

[24] S. A. Prokhorava, S. S. Sheiko, M. Möller, C.-H. Ahn, V. Percec, *Macromol. Rapid Commun.* **1998**, in press.

[25] W. Stocker, B. L. Schürmann, J. P. Rabe, S. Förster, P. Lindner, I. Neubert, A. D. Schlüter, *Adv. Mater.* **1998**, in press.

[26] V. Percec, Makromolekulares Kolloquium Freiburg, **1998**.

[27] A. D. Schlüter, *Top. Curr. Chem.* **1998**, in press.

1433-7851/98/3716-2197 $ 17.50+.50/0