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# Covalent Connection of Individualized, Neutral, Dendronized Polymers on a Solid Substrate Using a Scanning Force Microscope

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**Abstract:** The synthesis of a neutral, high-molar-mass, acrylamide-based, third-generation dendronized polymer (denpol) with a defined number of azide groups at its periphery is reported. An attach-to route is used in which a first-generation denpol is reacted with second-generation (G2) dendrons. The degree of structure perfection of the resulting denpol is quantified as 99.8%. This value was obtained after the introduction of a fluorescence label at the sites that remained unaffected by the dendronization. The high coverage was independently confirmed for the dendronization of another first-generation polymer and a closely related G2 dendron. The third-generation denpol resulting from the first dendronization experiment was spin-coated as a sub-monolayer onto highly oriented graphite precoated with an ultrathin layer of $C_{12}H_{25}NH_2$, which was introduced to provide a well-defined substrate for denpol adsorption and manipulation. Scanning force microscopy revealed single denpols, which could be moved across the surface and "welded" by covalent cross-linking induced by photochemical decomposition of the azides into highly reactive nitrenes. The successful formation of covalent bonds between two denpols was confirmed by mechanically challenging the link with the scanning force microscope (SFM) tip. This is the second reported case of a move–connect–prove sequence using polymers and the SFM, which for the first time employs noncharged denpols, thus widening the applicability of this method significantly.

**Keywords:** dendrons · fluorescence spectroscopy · polymers · scanning force microscopy · single-molecule studies

## Introduction

In a recent experiment, two strands of dendronized polymers (denpols)[1] were covalently "welded" together by photochemical treatment after they had been brought into tight contact on an atomically flat, solid substrate by dragging one of them to the other and pushing them into tight contact with a scanning force microscope (SFM) tip.[2] The actual welding was then achieved by peripheral azide groups that decomposed to nitrenes upon UV irradiation. Because of the extremely high reactivity of the nitrenes, they underwent nonselective intra- and intermolecular bond-forming reactions, the latter leading to covalent cross-linking between the strands. The connection was proved by mechanically challenging the welding point. A critical issue for such move–connect–prove sequences is the preparation of the individual chains on the substrate under conditions in which the adsorption energy has just the right size. On the one hand it should not be too high, so that the molecules can be moved about with the SFM tip without tearing them apart. On the other hand it should not be too low, because otherwise the molecules diffuse on the surface until they find each other and form islands to reduce line tension. This subtle balance between opposing factors was achieved by depositing the positively charged denpols on a highly oriented pyrolytic graphite (HOPG) surface from organic solution. The fact that these experiments can be carried out under ambient conditions is considered a key advantage of this approach, compared to the ultrahigh vacuum techniques required for related connection experiments with the scanning tunneling microscope (STM).[3] It must be pointed out, however, that the preparation of single macromolecules of such high molar mass from solution suffers from an intrinsic problem, namely the presence of impurities. According to

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our current view, these impurities play an important role in immobilizing denpols on HOPG, since they can form a soft adsorbate layer that may slow down the diffusion of the adsorbed denpols.[4] It was therefore decided to develop procedures to reduce the sensitivity of the experiment toward this problem by 1) employing a chemistry which avoids the simultaneous presence of side products as in the previous case,[2] and 2) precoating the solid substrate with a soft organic monolayer that guarantees the immobilization of single adsorbed denpols and still allows their manipulation.[5] We foresee a considerable future impact of SFM experiments of the kind described for the bottom-up approach to nanosized functional devices on solid surfaces whenever molecular objects of whatever sort need to be stabilized in certain geometries. To create a broader basis for move–connect–prove sequences, a neutral, azide-decorated denpol was synthesized.

Herein, we describe the synthesis of a noncharged, third-generation (G3) denpol of high molar mass, 25% of the peripheral amine groups of which carry azide functions for cross-linking, the remaining 75% being benzyloxycarbonyl (Cbz)-protected. The synthesis uses the attach-to procedure,[1] in which appropriately functionalized G2 dendrons are bound to the two amine anchor groups that a high-molar-mass G1 denpol presents per repeat unit. Since this protocol involves hundreds of such coupling steps per macromolecule, the degree to which the entire conversion could be achieved was determined quantitatively. For this purpose, residual amine groups in the former G1 denpol that had not reacted with a G2 dendron were amplified by treating them with 5-dimethylaminonaphthalene-1-sulfonyl (dansyl) chloride, a potent fluorescence label commonly used in biochemistry.[6] The degree to which the dansyl group was covalently incorporated into the polymer structure was determined by fluorescence intensity measurements, the results of which were confirmed in an independent, structurally different system.

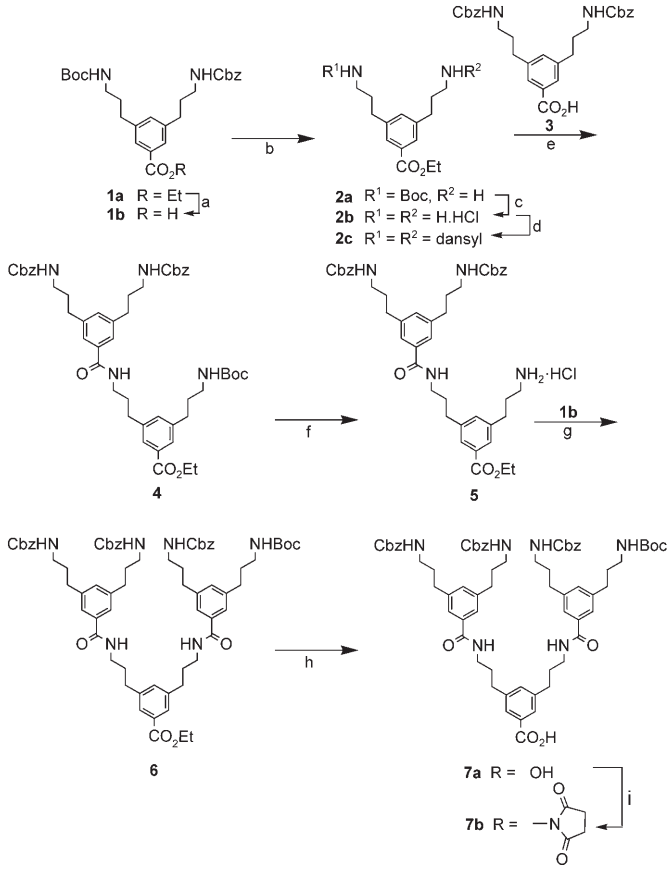
This characterized G3 denpol was prepared by spin coating the denpol from chloroform onto a quasi-2D network on HOPG, to give a sub-monolayer of mostly individual denpols on HOPG precoated with a layer of $C_{12}H_{25}COOH$. Single denpols were manipulated with the SFM tip in contact mode for a new move–connect–prove sequence. A blind experiment was also carried out to prove that irradiation is an essential prerequisite for the connection to be irreversible, and that it therefore has a truly covalent nature.

## Results and Discussion

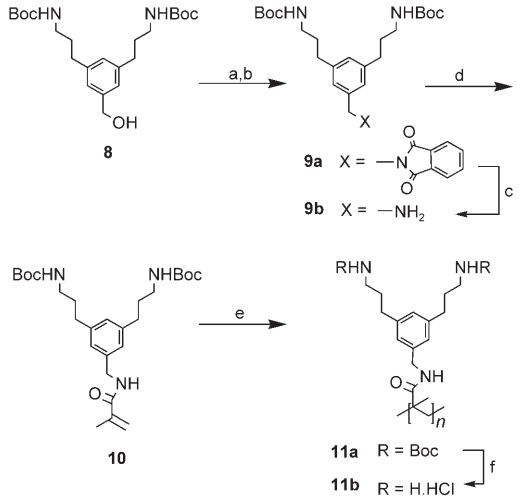
**Synthesis**: So far only denpols with identically protected peripheral amine functions have been reported.[7] Typically, all amine groups were either *tert*-butoxycarbonyl (Boc) or trimethylsilyl(ethoxy)carbonyl (Teoc) protected. In principle such denpols can be used for chemical surface modifications, for example, the decoration with azide functions required here. With such starting materials, however, the determination of the degree of coverage was expected to be complicated, specifically if higher generations were involved. The reasons for this are that the NMR spectra for the higher generation systems tend to be difficult to interpret, and also solubility problems may arise. Additionally, the coverage process would not automatically guarantee a homogeneous distribution of the newly bound moieties over the entire "surface" of the macromolecule, but rather may give rise to the formation of domains with preferred coverage. To circumvent these problems, an orthogonal synthesis strategy was devised in which denpols would become available with a predetermined ratio of orthogonally protected amines of two different kinds per repeat unit. Such a synthesis goal is rather complex and will be described in detail elsewhere.[8] The protecting group combinations chosen for this strategy were either Cbz/Boc or 2,7-di-*tert*-butyl-9-fluorenylmethoxycarbonyl (Fmoc*)/Boc. For the present work it was important to have a high-molar-mass G3 denpol with 25% of all amine groups protected with Boc and 75% with Cbz. The main thoughts behind this selection are as follows. With both the third-generation and the high molar mass, the denpol's mobility on HOPG was expected to be in a reasonable range (see Introduction and earlier work[9]). Additionally, it was known from the literature and our own work that large numbers of Boc groups can be easily cleaved off in the presence of large numbers of Cbz groups, thereby opening the way for the attachment of an aromatic azide through active ester chemistry to the denpol.

All synthetic steps finally leading to the target denpol **12c** are compiled in Schemes 1–3. As can be seen, the target denpol carries 25% azide groups and 75% Cbz-protected peripheral amines. The polymer synthesis is of the attach-to kind (Scheme 3); the G1 denpol **11b** was used as the starting material (Scheme 2) to which the G2 dendrons **7b** (Scheme 1) were attached by using well-established active ester couplings. In our laboratory, such couplings proceeded virtually quantitatively in several cases if the conditions were chosen carefully.[10] Most steps use conventional organic chemistry protocols and only a few comments will therefore be made. The starting point was the orthogonally protected dendron **1a** which had already been made available in a different context.[11] Also, the symmetrical dendron **3** of Scheme 1 could be made according to a reported procedure.[12] The selective deprotection of Cbz in **1a** with hydrogen and Pd/C went cleanly and gave dendron **2a** in quantitative yield. The amide coupling of **2a** and **3** was achieved with *N*-hydroxybenzotriazole/*N*-(3-dimethylaminopropyl)-*N'*-ethylcarbodiimide hydrochloride (HOBt/EDC) and gave **4** in a yield of 63%. Subsequent deprotection and addition of dendron **1b** furnished dendron **6**, which carries three Cbz-protected amines and one Boc group. To allow **6** to be attached to a polymer, its focal point was converted into the active ester **7b**. This dendron was prepared on the 1 g scale. Dendron **8** was synthesized according to a literature procedure.[7b] To arrive at the dendronized polyacrylic amide, the benzylic alcohol at its focal point was mesylated and then reacted with potassium phthalimide to give **9a**, which was

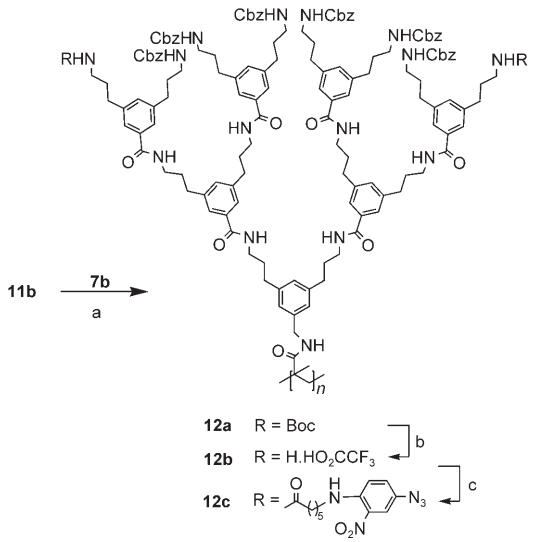
  




Scheme 1. a) KOH, THF/MeOH/$H_2O$, 6 h, 55 °C, 88 %; b) EtOAc/ethanol (1:1), Pd/C, 1,4-cyclohexadiene, $H_2$, 4 h, 97 %; c) 25 % HCl, THF, RT, 94.5 %; d) dansyl chloride, $CH_2Cl_2$, $Et_3N$, −30 °C, 20 min, 96 %; e) 1. **3**, HOBt, EDC, $CH_2Cl_2$, −30 °C, 3 h, and 2. **2a**, $Et_3N$, $CH_2Cl_2$, MeOH, −20 °C, 14 h, 63 % for both steps; f) 25 % HCl, THF, 0 °C, 3 h, 96 %; g) 1. **1b**, HOBt, EDC, $CH_2Cl_2$, −30 °C, 3 h, and 2. **5**, $Et_3N$, $CH_2Cl_2$/MeOH, −20 °C, 14 h, 78 % for both steps; h) KOH, THF/MeOH/$H_2O$, 6 h, 55 °C, 87 %; i) HOSu, $CH_2Cl_2$, DCC, RT, 14 h, 83 %. HOBt = *N*-hydroxybenzotriazole, EDC = *N*-(3-dimethylaminopropyl)-*N*′-ethylcarbodiimide hydrochloride, HOSu = *N*-hydroxysuccinimide, DCC = dicyclohexylcarbodiimide.




Scheme 2. a) **8**, MsCl, $CH_2Cl_2$, $Et_3N$, −20 °C, 2 h, and b) potassium phthalimide, DMF, 100 °C, 14 h, 91 % for both steps; c) $N_2H_4{\cdot}H_2O$, THF/EtOH, 60 °C, 6 h, 87 %; d) MAC, $CH_2Cl_2$, $Et_3N$, −20 °C, 30 min, 92 %; e) DBPO, DMF, 70 °C, 18 h, 70 %; f) 25 % HCl, THF, RT, 14 h, 96 %. MsCl = mesyl chloride, MAC = methacryloyl chloride, DBPO = dibenzoyl peroxide.




Scheme 3. a) **7b**, $CH_2Cl_2$/MeOH, $Et_3N$, RT, 60 h, 74 %; b) $CF_3COOH$, $CH_2Cl_2$, RT, 14 h, 90 %; c) *N*-succinimidyl-6-(4-azido-2-nitroanilino)hexanoate, $CH_2Cl_2$, $Et_3N$, RT, 14 h, 85 %.

then converted into the free amine with hydrazine. Compound **9b** was connected to a polymerizable unit by reacting it with freshly distilled methacrylic acid chloride. The resulting G1 macromonomer **10** was prepared on the 5 g scale.

Polymerization was carried out with dibenzoyl peroxide (DBPO, 0.15 mol %) as radical initiator precursor at 70 °C in a highly concentrated solution in DMF (30 % w/w). It was shown earlier that extremely high concentrations are a prerequisite for such polymerizations to give satisfactory molar masses.[13] After considerable optimization work on the small scale, one gram of monomer **10** was finally polymerized to give the desired polymer **11a** in 70 % yield at a molar mass of $M_w = 1.4 \times 10^6$ g mol$^{-1}$ and polydispersity index (PDI) = 2.6 (gel permeation chromatography (GPC) universal calibration).

Denpol **11a** was then deprotected with aqueous 25 % hydrochloric acid to give **11b**, which was isolated by precipitation prior to its dendronization with G2 dendron **7b**. For that purpose, polymer **11b** was dissolved in methanol which contained 4–5 equivalents of triethylamine per ammonium group of **11b**, and a solution of 1.5 equivalents of dendron **7b** per amine in methanol/methylene chloride (1:2) was added dropwise. After stirring for two days, the solvent of the still homogeneous solution was removed in a vacuum, whereupon the polymeric residue was taken up in methylene chloride with some triethylamine and a solution of another 0.25 equivalents of dendron **7b** in the same solvent was added. Stirring was continued for 12 hours, after which

conventional workup furnished polymer **12a**. For a quantitative determination of the dendronization efficiency, see below. To introduce the azide function required for the cross-linking experiments, denpol **12a** was treated with excess trifluoroacetic acid until all Boc signals in the 700 MHz $^1$H NMR spectrum had disappeared. The resulting 25 %-deprotected denpol was dissolved in chloroform and precipitated into ethyl acetate/hexane (1:1) to give **12b**. This product was finally converted into **12c** by reacting it with the commercially available *N*-succinimidyl-6-(4-azido-2-nitroanilino)hexanoate in an excess of 1.5 equivalents per amine of **12b**. The conversion of this step was not determined. There is substantial evidence that succinimidyl active esters react virtually quantitatively with amine groups of denpols.[10]

**Quantification of dendronization**: The efficiency of successive dendronization of denpols with G1 dendrons has been quantitatively determined all the way up from G2 to G4 denpols.[10] The attachment chemistry was based on the reaction between amines and succinimidyl active esters, which is known to proceed virtually quantitatively if the active ester can be employed in large excess. Amine groups that happened to remain unaffected by the dendronization process were artificially amplified by attaching the Sanger reagent to them, which is a potent UV label for primary amines. The resulting UV absorptions were measured to determine the degree to which the amines had been labeled. Assuming that all free amines had reacted with the reagent, this allowed the derivation of the dendronization efficiency. Under carefully chosen conditions efficiencies greater than 99 % were determined per growth step; this result indicates that the attach-to procedure can lead to near-perfect, high-generation denpols. The present case differs somewhat from the previous one in that the G3 denpol **12a** was synthesized by reaction of the starting polymer **11b** not with G1 dendrons, but rather with the G2 dendron active ester **7b**. Intuitively one would expect that in this case any remaining, non-dendronized amine group of **11b** would be more effectively shielded than in the previous case, because it will be surrounded by sterically more demanding G2 rather than just G1 dendrons. This will hinder the diffusion of the dansyl label to, and its reaction with, the remaining amines and thus could result in a too low fluorescence intensity and, therefore, falsely indicate a too high dendronization efficiency. It was therefore of some concern to collect evidence that the amines are still accessible by the dansylating reagent (see below).

First the model compound **2c**, which carries two dansyl groups, was prepared (Scheme 1). It served as a reference point for the fluorescence measurements, and was synthesized by reaction of the two unprotected amine groups of the corresponding G1 dendron **2b** with 1.2 equivalents of dansyl chloride per amine group at −30 °C for 15 minutes. Despite these rather mild reaction conditions, product **2c** was isolated in a yield of virtually 100 %. Its fluorescence intensity, obtained from the peak areas, was measured in the concentration range 0.0274–219 μM in chloroform (Figure 1 top, Experimental Section). A linear relationship was observed up to a concentration of 27 μM; this result indicated

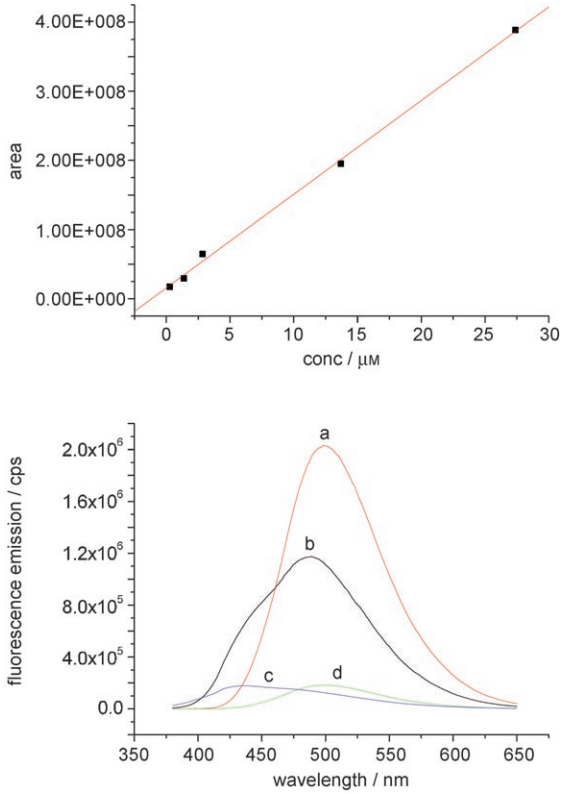



Figure 1. Top: Concentration of the dansylated model compound **2c** in chloroform [μM] versus fluorescence intensity as obtained from signal areas at room temperature. Bottom: Fluorescence curves of **2c** (a and d) and polymers c) **12a(80)** and d) **12a(100)** after reaction with dansyl chloride.

that there was no quenching. All subsequent measurements were therefore performed in this concentration range although, once incorporated into the denpol structure, the dansyl units should not easily be able to undergo both intra- and intermolecular collisional self-quenching. The latter argument holds true only for those cases in which a few amines scattered along the backbone carry dansyl labels. Otherwise the covalent fixation of labels to the same polymer chain may go so far as to render the above concentration dependence no longer applicable.

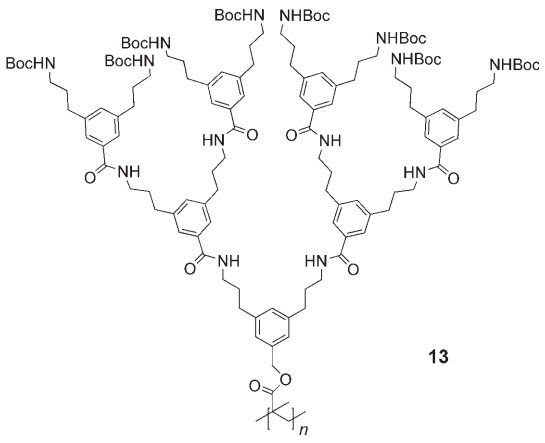
The dendronization efficiency was analyzed by dansylation of two different samples of **12a**, both of which were prepared from an identical batch of G1 denpol **11b** with $P_n = 1100$ and $P_w = 2800$. In the first sample, this starting denpol was deprotected and reacted with two equivalents of G2 dendron **7b** with the aim of complete coverage. For the second sample, a coverage of 80 % of the amines was attempted by reacting denpol **11b** with 0.8 equivalents of dendron per amine group. In the following, these samples will be referred to as **12a(100)** and **12a(80)**, respectively. Both samples were dansylated under somewhat more forceful

conditions than those used for model **2c** by employing a temperature of −10 °C[14] and a reaction time of two hours. One equivalent of dansyl chloride per amine of denpol **11b** was used for **12a(100)** and 1.5 equivalents per expected free amine group for **12a(80)**. If one assumes the presence of 1% nondendronized amines in **12a(100)**, this corresponds to a 100-fold excess of dansyl chloride, whereas the excess employed in the case of **12a(80)** was much smaller. The intention behind the more forceful reaction conditions and the huge excess of reagent for the treatment of **12a(100)** was to drive the dansylation of any free amine to completion. The excess dansyl chloride and any low-molar-mass product formed between it and an inadvertently present nucleophile were removed by repeated precipitation/dissolution cycles. After each cycle the fluorescence intensity of the polymers was measured and the process was continued until the intensity remained constant. This was typically the case after three cycles for **12a(100)** and one cycle for **12a(80)**. Additionally, the polymers were checked by thin-layer chromatography (TLC). If the fluorescence intensity had reached the final value, not even a trace of a blue-fluorescing component moved away from the polymer, irrespective of the solvents used.

Figure 1 (bottom) shows typical fluorescence curves of dansylated **12a(100)** and **12a(80)** with those of model compound **2c**. From a comparison of the signal intensities, which is described in detail in the Experimental Section, dansylation degrees of 0.15 and 18% were obtained for **12a-(100)** and **12a(80)**, respectively. These values, in turn, reflect dendron coverages of 99.8 and 82%. The very high value for **12a(100)** was confirmed twice in independent experiments. This result was even further substantiated by a closely related dendronization reaction leading to denpol **13**, for which a coverage of 99.7% was found using exactly the same procedure as described above. In this reaction denpol **13** was synthesized from a G1 polymethacrylate and a G2 dendron active ester like **7b**, except that all amine functions carried Boc groups (both not shown).[8]

Assuming that quenching of the fluorescence intensity is not occurring, this kind of analysis still has the intrinsic disadvantage of not providing any clue as to whether all nondendronized amines have actually reacted with the label. This is why, as mentioned, more forceful reaction conditions were applied[14] and a huge excess of the labeling agent was employed. There are two other arguments that should be considered in this context. First, denpol **12a(80)**, the synthesis for which the starting denpol **11b** was treated with 0.8 equivalents of G2 dendron **7b**, has a dansylation degree of 18% according to the findings above. This result confirms not only that the dendronization goes almost to completion even if the dendron, as in this case, is not in excess, but also that the dansylation clearly reaches completion, at least in this sterically less hindered case. Second, denpol **13** was obtained as a pure material in a yield of 91% after several precipitation/dissolution cycles, which were implemented to remove the last traces of the G2 dendron. The dendron had been used in an excess of two per amine group. These cycles were associated with some losses of polymer, and therefore a yield in this percentage range indicates a near-complete reaction course that does not leave much free space for interpretation. This experiment was carried out with denpol **13** rather than **12a(100)**, because the former was more abundantly available and the dendronization yield could therefore be determined with higher accuracy. Finally, a method was recently discovered for removing all dendrons of **13** by hydrolytically cutting them off exclusively at their former focal point. This will in future also enable investigation of the structural perfection of the dendrons by high-field NMR spectroscopy, a technique that cannot be reasonably applied for such a purpose to G3 denpols of molar mass above one million.

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**SFM move–connect–prove sequences**: Stable SFM imaging of **12c** was not possible for preparations from relatively low concentrations ($c = 0.05\ \mathrm{mg\,mL^{-1}}$); this result indicates that single denpols are not immobilized on the basal plane of graphite, and possible impurities do not stabilize them. At higher concentrations ($c \approx 0.5\ \mathrm{mg\,mL^{-1}}$ depending on the polymer batch), a stable quasi-2D network of denpols is formed (Figure 2a). This may be due to the inherent stability of the 2D network. Alternatively, a now increased concentration of impurities at the surface may form an organic monolayer, which causes a larger friction coefficient for the adsorbed denpols than does the bare basal plane of graphite, since the potential-energy landscape across the surface exhibits increased amplitudes. To differentiate between these cases, two strands in the network were cut in the contact-mode SFM. Figure 2b shows the resulting loose ends, with a length of about 80 nm each, immobilized on the surface. This observation, in the context of individualized denpols in the low-concentration experiment, is attributed to the increased concentration of impurities causing the immobilization. Moving two loose ends with the SFM together (Figure 2b,c) and apart again (Figure 2d) proves the reversibility of this kind of manipulation. After UV illumination of two denpol strands previously moved together (Figure 2e), the same manipulation does not allow separation of the denpols any more (Figure 2f,g). Figure 2h–j shows that the junction

  

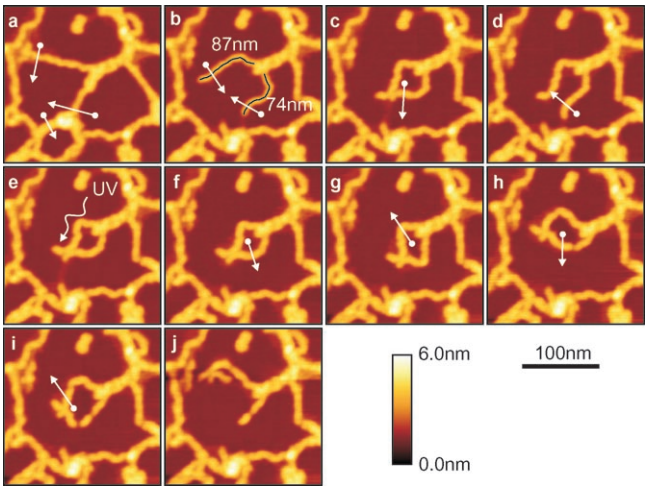


Figure 2. Move–connect–prove sequence of **12c** adsorbed on HOPG, probably with an immobilizing impurity layer. a) Initial conformation of network; b) two loose ends (87 and 74 nm) were cut out of the network; c) forming and d) opening the junction; e) denpols were moved in tight contact again and illuminated in situ with UV light (254 nm) for 5 min; f)–j) challenging the link mechanically until chain rupture.

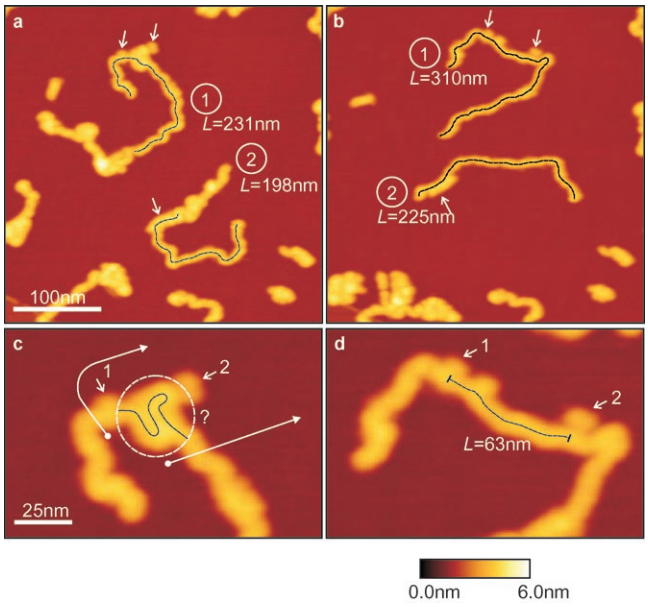


Figure 3. Compound **12c** adsorbed onto a monolayer of $C_{12}H_{25}NH_2$ on HOPG. a) Initial conformation of aggregates 1 and 2 of **12c**; b) extracted single strands 1 and 2 after several manipulation steps; c) and d) corresponding zoom of images a) and b) before and after manipulation, respectively, which display the unfolding of a claw (dashed circle) resulting in a length release of 63 nm. The white arrows in c) indicate the tip motion during contact-mode SFM manipulation.

point can be moved while the denpol breaks at a different position, thus proving the strength of the new linkage. Note that the thickness of one of the newly formed loose ends is decreased at one position; this result indicates that it may consist of a duplex.[15] Note also the twisted, higher-order supramolecular structures.

In the case described above we attribute the denpol immobilization to an ultrathin layer of organic impurities, and thus we decided to render the experiment more clear-cut by precoating HOPG with a well-defined organic layer, that is, a spin-coated monolayer of $C_{12}H_{25}NH_2$ or $C_{23}H_{47}COOH$.[5] In these cases denpols also adsorb and immobilize from low concentrations, which allows the observation of denpol aggregates and single denpol strands. Figure 3a shows **12c** adsorbed onto a monolayer of $C_{12}H_{25}NH_2$ on HOPG, in which two probable aggregates 1 and 2 are visible. SFM manipulation was used to prove the aggregation and to dissect the aggregates into their components as a starting point for a move–connect–prove sequence. Figure 3b displays two individual strands 1 and 2 with lengths of 310 and 225 nm, respectively, extracted from these aggregates by eight manipulation steps. Interestingly, intramolecular clew-shaped arrangements can also be opened by lateral manipulation (Figure 3c,d). The initial conformation shown in Figure 3c exhibits a claw (in dashed circle) with the internal structure not being evident. A probable conformation of the polymer strand is sketched as a black line. Moreover, to the left and right of the claw two small denpol fragments (white arrows 1 and 2) are adsorbed onto the strand, thus acting as an absolute position marker along the chain at a separation distance of 25 nm. After two steps of manipulation the claw was opened, as revealed by an increase in the separation of the two markers along the contour to 63 nm. These facts prove clearly that individual denpols can be immobilized on the precoated HOPG, imaged in tapping-mode SFM, and moved across the surface with high lateral accuracy in the contact mode. The process includes individualizing of denpols by dissection of denpol aggregates, which will greatly simplify manipulation experiments at the single-molecule level.

These single denpols were used for a move–connect–prove sequence (Figure 4). The linkage between two denpols can again be induced with UV light, as proven by challenging it mechanically with the SFM tip in contact mode up to chain rupture beside the induced linkage, thus indicating that the linkage between the individual strands is of truly covalent nature.

Similar results were obtained for monolayers of $C_{23}H_{47}COOH$ and indicate that there is some flexibility in the choice of the organic precoating. This finding opens up the possibility, for instance, of co-adsorbing these neutral denpols with either anionic or cationic polyelectrolytes (which require oppositely charged surfaces for their adsorption) to form heterojunctions with different macromolecules including biopolymers. With the demonstration of crosses[2] and circles (here), two fundamental 2D topologies have been realized.

  

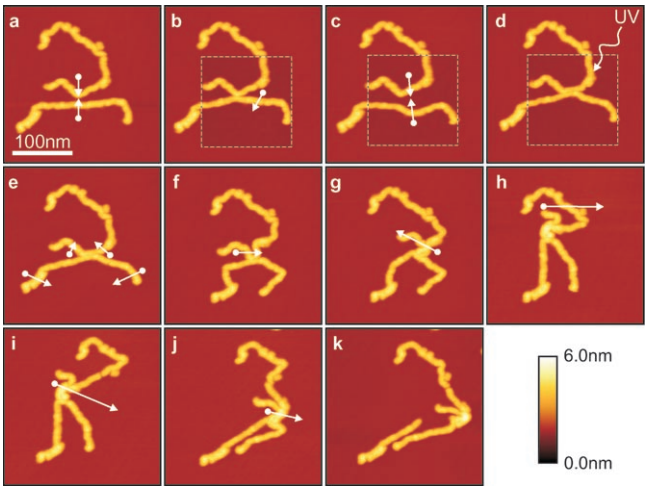


Figure 4. Move–connect–prove sequence of **12c** adsorbed onto a monolayer of $C_{12}H_{25}NH_2$ on HOPG. a) Initial conformation as shown in Figure 3b; b) a junction between the two strands is formed and c) opened; d) denpols are moved back again and illuminated in situ with UV light (254 nm) for 5 min; e)–k) challenging the link mechanically up to strand rupture close to the junction. In images b)–d), the local topography was refreshed only inside the dashed square to speed up the manipulation process. The white arrows indicate the tip movement during contact-mode SFM manipulation.

## Experimental Section

**Syntheses**: Dendrons **1a**, **1b**, **2b**, **3**, and **8** were prepared according to literature procedures.[4a,14] Reagents were purchased from Aldrich, Across, or Fluka. MAC was freshly distilled before use. THF and triethylamine were refluxed over Na with benzophenone as indicator, and dichloromethane ($CH_2Cl_2$) was dried by distillation over $CaH_2$. All other reagents and solvents were used as received. All reactions were performed under a nitrogen atmosphere. Silica gel 60 M (Macherey–Nagel, 0.04–0.063 mm, 230–400 mesh) was used as the stationary phase for column chromatography. $^1$H and $^{13}$C NMR spectra were recorded on Bruker AM 300 ($^1$H: 300 MHz, $^{13}$C: 75 MHz), AV 500 ($^1$H: 500 MHz, $^{13}$C: 125 MHz), and AV 700 ($^1$H: 700 MHz) spectrometers at room temperature (if not otherwise stated) using $CDCl_3$ or [$D_4$]MeOH as solvent. The $^{13}$C NMR spectra of polymers **12b** and **12c** were not recorded because too long accumulation times were required to obtain spectra with sufficient signal-to-noise ratios. ESI-MS analyses were performed by the MS service of the Laboratorium für Organische Chemie, ETH Zürich, on an IonSpec Ultra instrument. Elemental analyses were performed by the Mikrolabor of the Laboratorium für Organische Chemie, ETH Zürich. The samples were dried thoroughly under vacuum prior to analysis to remove strongly adhering solvent molecules. GPC measurements were carried out by using a PL-GPC 220 instrument with a 2× PL-Gel Mix-B LS column set (2× 30 cm) equipped with refractive index (RI), viscosity, and light scattering (LS; 15 and 90° angle) detectors, and LiBr (1 g$L^{-1}$) in DMF as eluent at 80 °C. Universal calibration was performed with poly(methyl methacrylate) standards in the range of $M_p$ = 2680 to 3 900 000 (Polymer Laboratories Ltd, UK).

**Fluorescence measurements**: Fluorescence measurements were performed in chloroform at room temperature using a Spex Fluorolog 2 spectrometer (Jobin Yvon, UK) with 1-cm quartz cells (see Figure 1). The intensity of the fluorescence bands was determined by measuring their area. A line shape analysis was not performed. The fluorescence intensity of the non-dansylated polymer was negligible.

In the following, the procedure is delineated according to the determination of the degrees of coverage for **12a(100)** and **12a(80)**: $A$: area of fluorescence signal; $m$: weighed-in mass of polymer; $M_{ru}$: molecular weight of repeating unit; $V$: volume of chloroform solution of labeled polymer; $C_{da}$: concentration of dansyl units in polymer; $n$: number of moles of repeating units; $n_{da}$: number of moles of dansylated repeating units; $L$: concentration of the dansylated repeat units normalized to 1 g$L^{-1}$.

**12a(100)**: Assuming no free amine groups, $M_{ru}$ = 2604 g$mol^{-1}$. For 1 g$L^{-1}$ of polymer, $n = 3.84\times10^{-4}$ mol is obtained. The values $m$ = 1.9 mg and $V$ = 2 mL from Figure 2b give $C_{da} = 4.8\times10^{-7}$ M. Normalizing this value to 1 g$L^{-1}$ ($1.9\times10^{-3}$ g/($2\times10^{-3}$), $L$ = 0.95 g$L^{-1}$), it follows that $n_{da} = 4.8\times10^{-7}$ mol$L^{-1}$/0.95 g$L^{-1}$ = $5.05\times10^{-7}$ mol. From this value the ratio of dendronized over dansylated repeating units is calculated as $n/n_{da} = 3.84\times10^{-4}/(5.05\times10^{-7}) = 760$. Since two dansyl groups will not be attached to the same repeat unit, this value corresponds to, on average, one dansyl unit at every 380th repeat unit.

**12a(80)**: Assuming that 20 % of the repeating units are dansylated gives $M_{ru}$ = 2235 g$mol^{-1}$. For 1 g$L^{-1}$ of polymer, $n = 4.47\times10^{-4}$ mol is obtained. The values $m$ = 0.25 mg and $V$ = 2 mL from Figure 2b give $C_{da} = 8.7\times10^{-6}$ M. Normalizing this value to 1 g$L^{-1}$ ($0.25\times10^{-3}$ g/($2\times10^{-3}$), $L$ = 0.125 g$L^{-1}$), it follows that $n_{da} = 8.7\times10^{-6}$ mol$L^{-1}$/0.125 g$L^{-1}$ = $6.96\times10^{-5}$ mol. From this value the ratio of dendronized over dansylated repeating units is calculated as $n/n_{da} = 4.47\times10^{-4}/(6.96\times10^{-5}) = 6.4$, which corresponds to, on average, one dansyl unit every 3.2 repeat units.

**Scanning force microscopy**: For SFM sample preparation, denpols were either directly spin-coated from chloroform onto HOPG or spin-coated onto precoated HOPG (monolayer of $C_{12}H_{25}NH_2$ or $C_{23}H_{47}COOH$). For direct deposition of denpols onto HOPG, denpols (10 μL) dissolved in chloroform (0.5 mg m$L^{-1}$) were spin-coated at 50 rps onto freshly cleaved HOPG and dried under ambient conditions for 0.5 h for subsequent SFM investigation.

For deposition of denpols onto precoated HOPG, in a first step a solution of $C_{12}H_{25}NH_2$ or $C_{23}H_{47}COOH$ (10 μL, Sigma Aldrich) in chloroform (0.1 mg m$L^{-1}$) was spin-coated at 50 rps onto freshly cleaved HOPG to yield a monolayer, and the sample was dried for 0.5 h under ambient conditions. In a second step, denpol (10 μL) dissolved in chloroform (0.04 mg m$L^{-1}$) was spin-coated at 50 rps onto the precoated HOPG. The result was an incomplete monolayer of individual strands of denpols. The sample was dried for 0.5 h before SFM imaging and manipulation.

A home-built SFM based on the multimode head and Nanoscope III controller of Digital Instruments Inc. (Santa Barbara, CA, USA) was used for SFM imaging and lateral manipulation, that is, dragging the molecules across the surface. Besides basic imaging in the tapping mode, the setup allowed movement of the SFM tip in the $x$–$y$ plane along predefined traces with additional control of the normal force,[2] in which the SFM was gently switched from tapping to contact mode.

As every step in manipulation required verification of the resulting object position and shape, that is, position and conformation of the denpol, a complete global image had to be recorded; this procedure slowed down the overall manipulation process. To bypass this problem a fast object-tracking procedure was integrated into the SFM setup, in which only the small area of interest (dashed white square in Figure 4) was scanned with lower resolution than the global image, but with the same tip velocity. A global SFM image of 512×512 pixels was recorded in several minutes, whereas local fast object-tracking with a resolution of, for example, 64×64 pixels gave the topographic result on a timescale of a few seconds, thus significantly speeding up the manipulation process.

For imaging and lateral manipulation, Olympus etched cantilevers (OMCL-AC240) with a nominal normal spring constant of 2 N$m^{-1}$ and a tip radius below 10 nm were used. Images were obtained by SFM operating in the tapping mode. During manipulation in the contact mode, the SFM tip was moved with a velocity of 500 n$ms^{-1}$, whereas the deflection was kept constant at 10 nm, which corresponds to a normal force of about 20 nN.

UV illumination was carried out with a standard spectral Ne–Hg lamp (Pen-Ray 11SC-1, UVP, Upland, CA, USA) with maximum emission at a wavelength of 254 nm.

**Ethyl-3-(3-aminopropyl)-5-(3-*tert*-butyloxycarbonylaminopropyl) benzoate (2a)**: Compound **1a** (1.55 g, 3.11 mmol) in EtOAc/EtOH (30 mL, 1:1), Pd/C (0.16 g, 10 wt %), and 1,4-cyclohexadiene (1.74 g, 22.0 mmol) were added to a hydrogenation flask. The mixture was hydrogenated

  

under $H_2$ (3 bar) at room temperature for 4 h. The solution was then filtered through celite and the solvent evaporated at room temperature to yield **2a** as a viscous oil (1.10 g, 97%). The product was used for the next step without further purification and structural analysis.

**Ethyl-3-{3,5-bis[3-(benzyloxycarbonylamino)propyl]benzoylamino}-5-[3-(*tert*-butyloxycarbonylamino)propyl] benzoate (4)**: *N*-hydroxybenzotriazole (HOBt; 0.30 g, 2.28 mmol) was added to a solution of **3** (1.10 g, 2.18 mmol) in $CH_2Cl_2$ (60 mL). After 10 min at −30 °C, *N*-(3-dimethylaminopropyl)-*N*′-ethylcarbodiimide hydrochloride (EDC; 0.46 g, 2.38 mmol) was added. The mixture was stirred until the hydrochloride had dissolved (≈3 h), then a solution of **2** (0.59 g, 1.83 mmol) and $Et_3N$ (1.03 mL, 7.33 mmol) in MeOH/$CH_2Cl_2$ (10 mL, 1:1) was added dropwise at −20 °C. The mixture was warmed to room temperature and stirred overnight. It was then washed with saturated $NaHCO_3$ (50 mL) and brine (50 mL), and dried over $MgSO_4$. Chromatographic separation (silica gel, EtOAc/hexane 2:1) yielded **4** (1.56 g, 63%) as a colorless foam. $^1$H NMR ($CDCl_3$): $\delta$ = 1.38 (t, $J$ = 7.2 Hz, 3H; $CH_3$), 1.44 (s, 9H; $CCH_3$), 1.86 (m, 6H; $CH_2$), 2.00 (m, 2H; $CH_2$), 2.64 (m, 6H; $CH_2$Ph), 2.74 (t, $J$ = 7.8 Hz, 2H; $CH_2$Ph), 3.13 (m, 6H; $CH_2$NH), 3.45 (q, $J$ = 6.0 Hz, 2H; $CH_2$NH), 4.38 (q, $J$ = 6.9 Hz, 2H; $OCH_2$), 4.75 (brs, 1H; NH), 5.06 (s, 4H; $OCH_2$Ph), 5.12 (brs, 2H; NH), 6.89 (brs, 1H; NH), 7.09 (s, 1H; ArH), 7.22 (s, 1H; ArH), 7.30 (m, 10H; ArH), 7.41 (s, 2H; ArH), 7.68 (s, 1H; ArH), 7.73 ppm (s, 1H; ArH); $^{13}$C NMR ($CDCl_3$): $\delta$ = 14.36, 28.43, 31.04, 31.14, 31.59, 32.38, 32.77, 33.20, 39.75, 40.06, 60.96, 66.63, 79.22, 124.87, 127.17, 127.18, 127.99, 128.09, 128.51, 131.65, 133.20, 134.93, 136.56, 141.68, 142.04, 142.07, 156.06, 156.58, 1.66.81, 167.91 ppm; ESI-MS: $m/z$: 873 $[M+Na]^+$; elemental analysis calcd (%) for $C_{49}H_{62}N_4O_9$ (851.04): C 69.15, H 7.34, N 6.58; found: C 69.24, H 7.49, N 6.56.

**Ethyl-3-{3,5-bis[3-(benzyloxycarbonylamino)propyl]benzoylamino}-5-(3-amino)propyl benzoate (5)**: Aqueous 25% HCl (0.75 mL, 5 equiv) in THF (3 mL) was added slowly to a solution of **4** (0.98 g, 1.15 mmol) in THF (25 mL) at 0 °C. The mixture was stirred for 3 h. The solvent was evaporated at room temperature to yield **5** as viscous oil (0.87 g, 96%). The product was used for the next step without further purification and structural analysis.

**Ethyl-3-(3-{3,5-bis[3-(benzyloxycarbonylamino)propyl]benzoylamino}-propyl)-5-(3-{3-[3-(benzyloxycarbonylamino)propyl]-5-[3-(*tert*-butyloxycarbonylamino)propyl]benzoylamino}propyl) benzoate (6)**: HOBt (90 mg, 0.66 mmol) was added to a solution of **1b** (0.30 g, 0.63 mmol) in $CH_2Cl_2$ (20 mL) at room temperature. After 10 min at −30 °C, EDC (0.13 g, 0.68 mmol) was added and the mixture stirred for 3 h. Then a solution of **5** (0.40 g, 0.51 mmol) and $Et_3N$ (0.57 mL, 4.1 mmol) in MeOH/$CH_2Cl_2$ (15 mL, 1:1) was added dropwise at −20 °C. The resulting mixture was warmed to room temperature and stirred for 14 h. It was then washed with brine (40 mL) and saturated $NaHCO_3$ (40 mL). The organic phase was dried over $MgSO_4$ and the solvent removed in vacuum. Chromatographic separation (silica gel, EtOAc/hexane 3:1) yielded **6** (0.48 g, 78%) as a colorless foam. $^1$H NMR ($CDCl_3$): $\delta$ = 1.37 (t, $J$ = 6.9 Hz, 3H; $CH_3$), 1.43 (s, 9H; $CCH_3$), 1.75 (m, 8H; $CH_2$), 1.97 (m, 4H; $CH_2$), 2.58 (m, 8H; $CH_2$Ph), 2.69 (m, 4H; $CH_2$Ph), 3.08 (q, $J$ = 6.9 Hz, 2H; $CH_2$NH), 3.13 (q, $J$ = 6.1 Hz, 6H; $CH_2$NH), 3.42 (t, $J$ = 5.8 Hz, 4H; $CH_2$NH), 4.33 (q, $J$ = 7.2 Hz,2H; $CH_2$), 5.05 (s, 6H; $OCH_2$Ph), 6.85 (brs, 2H; NH), 7.05 (s, 2H; ArH), 7.25 (s, 2H; ArH), 7.30 (m, 15H; ArH), 7.38 (s, 3H; ArH), 7.70 ppm (s, 2H; ArH); $^{13}$C NMR ($CDCl_3$): $\delta$ = 14.73, 28.43, 30.66, 31.01, 32.35, 32.95, 39.42, 40.05, 66.64, 79.24, 124.86, 125.17, 127.88, 128,04, 128.11, 128.52, 136.56, 141.65, 141.99, 156.55, 162.23, 168.77 ppm; ESI-MS: $m/z$: 1226 $[M+Na]^+$; elemental analysis calcd (%) for $C_{47}H_{60}N_4O_8$ (1203.46): C 69.86, H 7.20, N 6.98; found: C 69.66, H 7.12, N 7.02.

**3-(3-{3,5-Bis[3-(benzyloxycarbonylamino)propyl]benzoylamino}propyl)-5-(3-{3-[3-(benzyloxycarbonylamino)propyl]-5-[3-(*tert*-butyloxycarbonylamino)propyl]benzoylamino}propyl)benzoic acid (7a)**: Compound **6** (0.39 g, 0.32 mmol) was heated with KOH pellets (0.07 g, 1.24 mmol) in THF/MeOH/$H_2O$ (24 mL, 2:3:1) at 55 °C for 6 h. After the reaction was finished (TLC), water (3 mL) and then acetic acid were added until pH 5 was reached. The solvent was evaporated and the G2 acid **7a** extracted with $CH_2Cl_2$. The organic phase was dried over $MgSO_4$. After evaporation of the solvent, acid **7a** (0.33 g, 87%) was obtained as a white solid. $^1$H NMR ($CDCl_3$): $\delta$ = 1.42 (s, 9H; $CCH_3$), 1.75 (m, 8H; $CH_2$), 1.88 (m, 4H; $CH_2$), 2.57 (m, 8H; $CH_2$Ph), 2.70 (m, 4H; $CH_2$Ph), 3.07 (t, $J$ = 3.3 Hz, 2H; $CH_2$NH), 3.14 (q, $J$ = 5.1 Hz, 6H; $CH_2$NH), 3.34 (t, $J$ = 5.1 Hz, 4H; $CH_2$NH), 5.01 (s, 6H; $OCH_2$Ph), 5.15 (brs, 2H; NH), 6.83 (s, 1H; ArH), 7.04 (s, 2H; ArH), 7.27 (m, 19H; ArH), 7.73 ppm (s, 2H; ArH); $^{13}$C NMR ($CDCl_3$): $\delta$ = 28.39, 31.23, 31.29, 32.58, 33.16, 39.72, 40.14, 66.79, 125.03, 127.79, 128,15, 128.24, 128.65, 131.84, 134.55, 135.59, 136.64, 141.93, 142.96, 156.87, 175.80 ppm; ESI-MS: $m/z$: 1198 $[M+Na]^+$.

**3-(3-{3,5-Bis-[3-(benzyloxycarbonylamino)propyl]benzoylamino}propyl)-5-(3-{3-[3-(benzyloxycarbonylamino)propyl]-5-[3-(*tert*-butyloxycarbonylamino)propyl]benzoylamino}propyl)benzoic acid 2,5-dioxopyrrolidin-1-yl ester (7b)**: *N*-Hydroxysuccinimide (HOSu; 46 mg, 0.39 mmol) was added to a solution of **7a** (0.33 g, 0.27 mmol) in dry $CH_2Cl_2$ (10 mL) at room temperature. After 15 min, dicyclohexylcarbodiimide (DCC; 85 mg, 0.41 mmol) was added at −20 °C. The resulting mixture was warmed to room temperature and stirred overnight. The precipitate was isolated by filtration and the solvent was evaporated at room temperature. Chromatographic separation (silica gel, $CH_2Cl_2$/MeOH 4:1) yielded **7b** (0.29 g, 83%) as a white foam. $^1$H NMR ($CDCl_3$): $\delta$ = 1.37 (s, 9H; $CCH_3$), 1.73 (m, 8H; $CH_2$), 1.92 (m, 4H; $CH_2$), 2.58 (m, 8H; $CH_2$Ph), 2.69 (m, 4H; $CH_2$Ph), 2.85 (s, 4H; $CH_2$), 3.00 (t, $J$ = 6.3 Hz, 2H; $CH_2$NH), 3.08 (q, $J$ = 8.1 Hz, 6H; $CH_2$NH), 3.35 (t, $J$ = 6.6 Hz, 4H; $CH_2$NH), 5.01 (s, 6H; $OCH_2$Ph), 7.07 (s, 2H; ArH), 7.27 (m, 15H; ArH), 7.35 (s, 3H; ArH), 7.37 (s, 2H; ArH), 7.75 ppm (s, 2H; ArH); $^{13}$C NMR ($CDCl_3$): $\delta$ = 28.35, 30.66, 31.18, 32.47, 32.93, 39.49, 40.01, 66.57, 79.24, 124.90, 125.17, 127.88, 128.08, 128.51, 131.84, 134.55, 135.59, 141.93, 142.95, 157.11, 162.23, 168.77, 169.99 ppm; ESI-MS: $m/z$: 1295 $[M+Na]^+$; elemental analysis calcd (%) for $C_{72}H_{85}N_7O_{14}$ (1272.62): C 67.96, H 6.73, N 7.71; found: C 67.53, H 7.05, N 7.56.

**3,5-Bis(3-*tert*-butyloxycarbonylaminopropyl)benzyl phthalimide (9a)**: Mesyl chloride (1.77 mL, 22.8 mmol) in $CH_2Cl_2$ (5 mL) was added to a solution of **8** (8.4 g, 19.9 mmol) and $Et_3N$ (8.5 mL, 59.7 mmol) in $CH_2Cl_2$ (150 mL) at −30 °C. The mixture was stirred at −20 °C for 2 h and regularly checked by TLC (EtOAc/hexane 1:1) until **8** had disappeared. The reaction was then quenched with MeOH and the solution washed four times with cold water and brine. The organic phase was dried over $MgSO_4$, the solvent was evaporated at room temperature, and the product was dried under vacuum. The residue was then dissolved in DMF (100 mL), potassium phthalimide (4.05 g, 21.8 mmol) was added at room temperature, and the mixture was stirred overnight at 100 °C. The DMF was evaporated and the residue was dissolved in $CH_2Cl_2$ (70 mL), washed with 0.5 M NaOH, saturated brine, and saturated $NaHCO_3$, and finally dried over $MgSO_4$. Chromatographic separation (silica gel, EtOAc/hexane 1:1) yielded **9a** (10 g, 91%) as a pale gray solid. $^1$H NMR ($CDCl_3$): $\delta$ = 1.44 (s, 18H; $CH_3$), 1.78 (m, 4H; $CH_2$), 2.58 (t, $J$ = 7.8 Hz, 4H; $ArCH_2$), 3.14 (m, 4H; $NHCH_2$), 4.66 (brs, 2H; NH), 4.79 (s, 2H; $CH_2$), 6.92 (s, 1H; ArH), 7.08 (s, 2H; ArH), 7.72 (m, 2H; ArH), 7.85 ppm (m, 2H; ArH); $^{13}$C NMR ($CDCl_3$): $\delta$ = 28.43, 31.64, 32.88, 40.13, 41.57, 79.04, 94.71, 123.36, 126.38, 128.06, 132.14, 133.96, 136.54, 142.21, 156.00, 168.06 ppm; ESI-MS: $m/z$: 574 $[M+Na]^+$; elemental analysis calcd (%) for $C_{47}H_{60}N_4O_8$ (551.67): C 67.49, H 7.49, N 7.62; found: C 67.54, H 7.50, N 7.57.

**3,5-Bis(3-*tert*-butyloxycarbonylaminopropyl)benzylamine (9b)**: Hydrazine hydrate (2.64 mL, 54.3 mmol) was added to a solution of **9a** (10 g, 18.1 mmol) in THF/EtOH (80 mL, 1:1) and the mixture was stirred at 60 °C for 6 h. After the reaction was finished (TLC), the solvent was evaporated. The precipitate was then dissolved in $CH_2Cl_2$ and washed with 0.5 M NaOH and saturated brine. Chromatographic separation (silica gel, $CH_2Cl_2$/MeOH/$Et_3N$ 100:10:1) yielded **9b** (6.66 g, 87%) as a yellowish oil. $^1$H NMR ($CDCl_3$): $\delta$ = 1.45 (s, 18H; $CH_3$), 1.77 (m, 4H; $CH_2$), 2.60 (t, $J$ = 7.5 Hz, 4H; $ArCH_2$), 3.14 (q, $J$ = 6.6 Hz, 4H; $NHCH_2$), 3.89 (s, 2H; $CH_2NH$), 4.79 (brs, 2H; NH), 6.92 (s, 1H; ArH), 6.98 ppm (s, 2H; ArH); $^{13}$C NMR ($CDCl_3$): $\delta$ = 28.44, 31.67, 31.89, 32.96, 40.13, 46.41, 79.05, 124.83, 127.00, 141.96, 143.53, 156.00 ppm; ESI-MS: $m/z$: 422 $[M+Na]^+$.

**3,5-Bis(3-*tert*-butyloxycarbonylaminopropyl)benzylmethacrylamide (10)**: Methacryloyl chloride (2.05 mL, 21.2 mmol) in $CH_2Cl_2$ (4 mL) was added dropwise to a solution of **9b** (7.45 g, 17.7 mmol) and $Et_3N$ (3.72 mL,

  

26.5 mmol) in $CH_2Cl_2$ (60 mL) at −30 °C. The mixture was stirred at −20 °C for 30 min and monitored by TLC (EtOAc/hexane 1:1) until **9b** had disappeared. The reaction was then quenched with MeOH. The solution was washed with saturated brine and saturated $NaHCO_3$. The organic phase was dried over $MgSO_4$ and the solvent evaporated at room temperature. Chromatographic separation (silica gel, EtOAc/hexane 1:1) was carried out twice to yield **10** (7.95 g, 92 %) as a white solid. $^1$H NMR ($CDCl_3$): $\delta$ = 1.45 (s, 18H; $CH_3$), 1.77 (m, 4H; $CH_2$), 1.98 (s, 3H; $CH_2$), 2.60 (t, $J$ = 8.1 Hz, 4H; $ArCH_2$), 3.14 (q, $J$ = 6.3 Hz, 4H; $NHCH_2$), 4.45 (d, $J$ = 6.2 Hz, 2H; NH), 4.69 (br s, 2H; NH), 5.35 (s, 1H; CH), 5.75 (s, 1H; CH), 6.26 (t, $J$ = 6.1 Hz, 1H; NH), 6.93 (s, 1H; ArH), 6.94 ppm (s, 2H; ArH); $^{13}$C NMR ($CDCl_3$): $\delta$ = 18.76, 28.43, 31.62, 32.85, 40.02, 43.74, 79.09, 119.67, 125.73, 127.76, 138.45, 139.95, 142.21, 156.00, 168.24 ppm; ESI-MS: $m/z$: 512 $[M+Na]^+$; elemental analysis calcd (%) for $C_{27}H_{43}N_3O_5$ (489.65): C 66.23, H 8.85, N 8.58; found: C 65.95, H 8.87, N 8.49.

**Poly[3,5-bis(3-*tert*-butyloxycarbonylaminopropyl)benzylmethacrylamide] (11a)**: A solution of DBPO (0.47 mg, 0.16 mol %) in DMF (0.2 mL) was added to a Schlenk tube containing monomer **10** (0.60 g, 1.22 mmol). If the monomer did not completely dissolve, more DMF was added until a homogeneous solution was achieved, which was then concentrated up to approximately the initial amount of DMF by evacuation with visible inspection. An exact concentration cannot, therefore, be given. The resulting mixture was degassed several times by freeze–pump–thaw cycles, then kept at 70 °C for 18 h. After polymerization, the polymer was dissolved in $CH_2Cl_2$ and purified by column chromatography (silica gel, $CH_2Cl_2$ as eluent) to yield **11a** (0.42 g, 70 %) as a colorless foam. $^1$H NMR ($CDCl_3$): $\delta$ = 0.85 (br; $CH_3$), 1.45 (br; $CH_3$), 1.85 (br; $CH_2$), 2.55 (br; $ArCH_2$), 3.11 (br; $NHCH_2$), 4.05 (br; $CH_2CH_3$), 5.35 (br; NH), 6.94 ppm (br; ArH); $^{13}$C NMR ($CDCl_3$): $\delta$ = 28.45, 31.62, 32.85, 40.02, 41.24, 79.09, 125.73, 127.76, 138.45, 139.95, 142.21, 158.00, 168.24 ppm; elemental analysis calcd (%) for $(C_{27}H_{43}N_3O_5)_n$ $(489)_n$: C 66.23, H 8.85, N 8.58; found: C 65.63, H 9.01, N 8.33.

**Poly[3,5-bis(3-aminopropyl)benzylmethacrylamide·2 HCl] (11b)**: Aqueous 25 % HCl (0.95 mL, 6 equiv per Boc group) in THF (2 mL) at 0 °C was added dropwise to a solution of **10a** (0.30 g, 0.61 mmol) in THF (6 mL) and the mixture was stirred for 14 h. Evaporation of the solvent at room temperature yielded **11b** (0.21 g, 96 %) as a colorless solid. $^1$H NMR ($CD_3OD$): $\delta$ = 0.85 (br; $CH_3$), 1.85 (br; $CH_2$), 2.55 (br; $ArCH_2$), 3.11 (br; $NHCH_2$), 4.05 (br; $CH_2CH_3$), 6.94 ppm (br; ArH); $^{13}$C NMR ($CD_3OD$): $\delta$ = 19.18, 32.55, 39.61, 126.60, 127.61, 139.18, 141.38, 168.24 ppm.

**Poly{3,5-bis[3-(3-{3-[3,5-bis(3-{benzyloxyamino}propyl)benzoylamino]-propyl}-5-{3-[3-(3-{benzyloxyamino}propyl)-5-(3-{*tert*-butyloxyamino}propyl)benzoylamino]propyl}benzoylamino)propyl]benzylmethacrylamide} (12a)**: A solution of **7b** (0.25 g, 1.5 equiv per amine group) in $CH_2Cl_2$ (6 mL) at −20 °C was added dropwise to a solution of **11b** (20 mg, 0.055 mmol) and $Et_3N$ (0.05 mL) in $MeOH/CH_2Cl_2$ (5 mL, 2:1). The mixture was stirred at room temperature for 48 h. The solvent was evaporated, another portion of **7b** (25 mg) and $Et_3N$ (0.05 mL) in $CH_2Cl_2$ (3 mL) was added, and the mixture was stirred for a further 12 h. The polymeric product was washed with brine, the solvent was evaporated, and the residue was purified three times by dissolving it in $CHCl_3$ followed by precipitation into EtOAc/hexane (1:1) until excess **7b** was completely removed. This furnished **12a** (0.13 g, 74 %) as a colorless solid. $^1$H NMR ($CDCl_3$): $\delta$ = 1.35 (br; $CH_3$), 1.65 (br; $CH_2$), 2.35 (br; $ArCH_2$), 2.89 (br; $NHCH_2$), 4.85 (br; $CH_2$), 6.21 (br; NH), 6.94 (br; ArH), 7.11 (br; ArH), 7.28 ppm (br; ArH); $^{13}$C NMR ($CDCl_3$): $\delta$ = 28.23, 31.42, 32.95, 40.58, 66.69, 79.29, 125.27, 128.03, 128.25, 128.73, 132.08, 135.05, 137.15, 142.41, 157.06, 157.50, 168.86 ppm; GPC (DMF with 1 % LiBr, 80 °C, versus polystyrene standard): $M_n = 3.9\times10^6$, $M_w = 12.6\times10^6$, PDI = 3.2.

**Poly{3,5-bis-[3-(3-{3-[3,5-bis(3-{benzyloxyamino}propyl)benzoylamino]-propyl}-5-{3-[3-(3-{benzyloxyamino}propyl)-5-(3-{amino}propyl)benzoylamino]propyl}benzoylamino)propyl]benzylmethacrylamide·2 $CF_3COOH$} (12b)**: A solution of $CF_3COOH$ (0.11 mL, excess) in $CH_2Cl_2$ (2 mL) at 0 °C was slowly added to a solution of **12a** (50 mg, 0.019 mmol) in $CH_2Cl_2$ (3 mL). The mixture was stirred for 14 h and then the solvent was evaporated at room temperature. The polymer was purified by dissolving it in $CHCl_3$ followed by precipitation into EtOAc/hexane (1:2) to yield **12b** (45 mg, 90 %) as a slightly yellow solid. $^1$H NMR ($CDCl_3$/$CD_3OD$): $\delta$ = 1.65 (br; $CH_2$), 2.40 (br; $ArCH_2$), 2.94 (br; $NHCH_2$), 4.85 (br; $CH_2$), 6.94 (br; ArH), 7.11 (br; ArH), 7.28 ppm (br; ArH).

**Poly{3,5-bis-[3-(3-{3-[3,5-bis(3-{benzyloxyamino}propyl)benzoylamino]-propyl}-5-{3-[3-(3-{benzyloxyamino}propyl)-5-(3-{6-(4-azido-2-nitroanilino)hexanoylamino}propyl)benzoylamino]propyl}benzoylamino)propyl]-benzylmethacrylamide} (12c)**: A solution of *N*-succinimidyl-6-(4-azido-2-nitroanilino)hexanoate (7.5 mg, 3 equiv per repeating unit) in $CH_2Cl_2$ (2 mL) was added dropwise to a solution of **12b** (17 mg, 0.0065 mmol) and $Et_3N$ (0.01 mL) in $CH_2Cl_2$ (2 mL) at −20 °C in the dark. The mixture was stirred for 14 h and the solvent evaporated. The polymer was dissolved in $CHCl_3$ and precipitated into EtOAc/hexane (1:2) to yield **12c** (16 mg, 85 %) as a slightly red solid. $^1$H NMR ($CDCl_3$/$CD_3OD$): $\delta$ = 1.55 (br; $CH_2$), 1.75 (br; $CH_2$), 2.01 (br; $CH_2$), 2.40 (br; $ArCH_2$), 2.55 (br; CH2), 2.94 (br; $NHCH_2$), 3.05 (br; $NHCH_2$), 4.85 (br; $CH_2$), 6.7 (br; ArH), 6.95 (br; ArH), 7.11 (br; ArH), 7.55 ppm (br; ArH); IR: $\tilde{\nu}$ = 2118 $cm^{-1}$.

**Dansylated model compound 2c and polymers 12a(80) and 12a(100)**

*Ethyl-3,5-bis[3-(5-dimethylamino-1-naphthalenesulfonamide)propyl] benzoate (**2c**)*: Dansyl chloride (0.13 g, 0.48 mmol) in $CH_2Cl_2$ (4 mL) was added dropwise to a solution of **2b** (68 mg, 0.20 mmol) and $Et_3N$ (0.34 mL, 12 equiv) in $CH_2Cl_2$/MeOH (15 mL, 2:1) at −30 °C. The mixture was stirred at −30 °C for 20 min and monitored by TLC ($CH_2Cl_2$/MeOH/$Et_3N$ 100:10:1) until **2b** had disappeared. The reaction was then quenched with MeOH. The solution was washed with saturated brine and saturated $NaHCO_3$. The organic phase was dried over $MgSO_4$ and the solvent evaporated. Chromatographic separation (silica gel, EtOAc/hexane 1:2) was carried out to yield **2c** (0.14 g, 96 %) as a yellowish solid. $^1$H NMR ($CDCl_3$): $\delta$ = 1.38 (t, $J$ = 7.2 Hz, 3H; $CH_3$), 1.68 (m, 4H; $CH_2$), 2.48 (t, $J$ = 7.8 Hz, 4H; $ArCH_2$), 2.88 (s, 12H; $CH_3$), 2.92 (q, $J$ = 6.8 Hz, 4H; $NHCH_2$), 4.35 (q, $J$ = 7.2 Hz, 2H; $CH_2$), 5.26 (t, $J$ = 6.0 Hz, 2H; $NHCH_2$), 6.85 (s, 1H; ArH), 7.16 (s, 1H; ArH), 7.18 (s, 1H; ArH), 7.52 (m, 12H; ArH), 8.24 (d, $J$ = 6.3 Hz, 2H; ArH), 8.35 (d, $J$ = 8.7 Hz, 2H; ArH), 8.52 ppm (d, $J$ = 6.3 Hz, 2H; ArH); $^{13}$C NMR ($CDCl_3$): $\delta$ = 14.23, 31.05, 32.25, 42.61, 45.42, 60.95, 115.22, 118.79, 123.24, 127.01, 128.46, 129.61, 129.64, 129.86, 130.42, 130.65, 133.16, 134.80, 141.42, 152.00, 166.68 ppm; ESI-MS: $m/z$: 752.8 $[M+Na]^+$; elemental analysis calcd (%) for $C_{39}H_{46}N_4O_6S_2$ (730.81): C 64.09, H 6.34, N 7.66; found: C 64.05, H 6.49, N 7.51.

***12a(80)***: Dansyl chloride (1.50 mg, 5.00 μmol) in $CH_2Cl_2$ (2 mL) was added dropwise to a solution of **12a(80)** (15 mg, 6.71 μmol) and $Et_3N$ (21 μL, 12 equiv) in $CH_2Cl_2$ (4 mL) at −30 °C. The mixture was stirred at −10 °C for 2 h. The reaction was then quenched with MeOH. The solvent was evaporated and the polymer was purified by dissolving it in $CHCl_3$ followed by precipitation into EtOAc/hexane (1:2), and also by dissolving it in DMSO followed by precipitation into ethyl ether. This procedure was carried out several times until the bluish color on the TLC plate had disappeared. Compound **12a(80)** (11 mg) was produced as a greenish solid.

***12a(100)***: Dansyl chloride (2.20 mg, 7.68 μmol) in $CH_2Cl_2$ (2 mL) was added dropwise to a solution of **12a** (10 mg, 3.84 μmol) and $Et_3N$ (10 μL, excess) in $CH_2Cl_2$ (2 mL) at −30 °C. The mixture was stirred at −10 °C for 2 h. The reaction was then quenched with MeOH. The solvent was evaporated and the polymer was purified by dissolving it in $CHCl_3$ followed by precipitation into EtOAc/hexane (1:2), and also by dissolving it in DMSO followed by precipitation into ethyl ether. This procedure was carried out several times until the bluish color on the TLC plate had disappeared. Compound **12a(100)** (8 mg) was produced as a slightly gray solid.

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[1] a) A. D. Schlüter, J. P. Rabe, *Angew. Chem.* **2000**, *112*, 860–881; *Angew. Chem. Int. Ed.* **2000**, *39*, 864–883; b) A. Zhang, L. Shu, Z. Bo, A. D. Schlüter, *Macromol. Chem. Phys.* **2003**, *204*, 328–339; c) A. D. Schlüter, *Top. Curr. Chem.* **2005**, *245*, 151–191; d) H. Frauenrath, *Prog. Polym. Sci.* **2005**, *30*, 325–384.

[2] J. Barner, F. Mallwitz, L. Shu, A. D. Schlüter, J. P. Rabe, *Angew. Chem.* **2003**, *115*, 1976–1979; *Angew. Chem. Int. Ed.* **2003**, *42*, 1932–1935.

[3] S. W. Hla, G. Meyer, K.-H. Rieder, *ChemPhysChem* **2001**, *2*, 361–366.

[4] We assume that in previously described experiments (refs. [2,9]) impurities also formed an ultrathin organic coating on HOPG. Given the complexity and the unspecific host capability of higher generation denpols, the presence of impurities stemming from solvents and reagents used during synthesis cannot be excluded even if several purification steps are applied. Carefully dried denpols give correct data in combustion analysis. This, however, is insufficient evidence to propose that there are no impurities still being entrapped in the branched layer around the backbone. The amount of material required to form a monolayer on a solid substrate is so small that it cannot possibly be detected by combustion analysis. The experiments described in references [2] and [9] were carried out with denpols prepared on the solid substrate directly from the reaction mixture. It is therefore necessary to assume that products from the final azidification step have interfered in one way or another with both the adsorption to and lateral diffusion of the denpols on the surface. A main advantage of the experiments described here is the fact that they can be carried out under ambient conditions. The price to be paid for this, and thus a further complication, is the unclear situation with adsorptions of compounds contained in the surrounding air prior to the application of the denpols.

[5] N. Severin, J. Barner, A. A. Kalachev, J. P. Rabe, *Nano Lett.* **2004**, *4*, 577–579.

[6] a) S. Fuchs, H. Otto, S. Jehle, P. Henklein, A. D. Schlüter, *Chem. Commun.* **2005**, 1830–1832; b) S. Fuchs, T. Kapp, H. Otto, T. Schöneberg, P. Franke, R. Gust, A. D. Schlüter, *Chem. Eur. J.* **2004**, *10*, 1167–1192, and references therein.

[7] For example, see: a) N. Ouali, S. Méry, A. Skoulios, *Macromolecules* **2000**, *33*, 6185–6193; b) A. Zhang, B. Zhang, E. Wächtersbach, M. Schmidt, A. D. Schlüter, *Chem. Eur. J.* **2003**, *9*, 6083–6092; c) M. Malkoch, A. Carlmark, A. Woldegiorgis, A. Hult, E. E. Malmström, *Macromolecules* **2004**, *37*, 322–329; d) A. Luebert, T. Q. Nguyen, F. Sun, S. S. Sheiko, H.-A. Klok, *Macromolecules* **2005**, *38*, 2064–2071; e) J. L. Mynar, T.-L. Choi, M. Yoshida, V. Kim, C. J. Hawker, J. M. J. Fréchet, *Chem. Commun.* **2005**, 5169–5171.

[8] R. Al-Hellani, A. D. Schlüter, unpublished results.

[9] L. Shu, A. D. Schlüter, C. Ecker, N. Severin, J. P. Rabe, *Angew. Chem.* **2001**, *113*, 4802–4805; *Angew. Chem. Int. Ed.* **2001**, *40*, 4666–4669.

[10] L. Shu, I. Gössl, J. P. Rabe, A. D. Schlüter, *Macromol. Chem. Phys.* **2002**, *203*, 2540–2550.

[11] The yield for this compound by mistake was given as 95%: S. Müller, A. D. Schlüter, *Chem. Eur. J.* **2005**, *11*, 5589–5610. The fully reproducible value is 65%, which was obtained in runs with up to 25 g of product.

[12] R. Klopsch, S. Koch, A. D. Schlüter, *Eur. J. Org. Chem.* **1998**, 1275–1283.

[13] For example, see: L. Shu, A. D. Schlüter, *Macromol. Chem. Phys.* **2000**, *201*, 239–245, and references therein.

[14] During the synthesis of model compound **2c** it was observed that if the reaction was performed at 0°C, the amines were doubly dansylated to a small extent (NMR spectroscopy). This is why, under the more forceful conditions, the temperature was not elevated above −10°C.

[15] C. Böttcher, B. Schade, C. Ecker, J. P. Rabe, L. Shu, A. D. Schlüter, *Chem. Eur. J.* **2005**, *11*, 2923–2928.

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