Synthesis of Well-Defined Chain-End- and In-Chain-Functionalized Polystyrenes with a Definite Number of Benzyl Chloride Moieties and D-Glucose Residues

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Summary: Novel well-defined chain-end- and in-chain-functionalized polystyrenes with six, eight, twelve, and sixteen benzyl chloride moieties and with four and eight D-glucose residues have been successfully synthesized by developing the methodology based on living anionic polymerization of using new functionalized agents derived from functionalized 1,1-diphenylethylene (DPE) derivatives. They are 1,10-dichloro-4,4-7,7-tetra(3-methoxymethylphenyl)decane, its iodide derivative, the dianion prepared from 1,1-bis(3-methoxymethylphenyl)ethylene and potassium naphthalenide, and 1,1-bis[3',5'-bis(1,2:5,6-di-*O*-isopropylidene-α-D-glucofuranose-3-oxymethyl)phenyl]ethylene. The developed methodology involves diverse modes of reactions of polystyryllithium with new functionalized agents and either the subsequent transformation reaction with BCl_3 into benzyl chloride moieties or acid-hydrolysis to regenerate D-glucose residues. The resulting chain-multi-functionalized polystyrenes were precisely controlled with respect to chain length and quantitatively functionalized within experimental errors.

Introduction

Although 1,1-diphenylethylene (DPE) and its derivatives belong to the styrene family, their anionic polymerization behavior is quite different from that of styrene. They are incapable of undergoing anionic polymerization and even oligomerization under normal conditions but quantitatively react with anionic initiators in a monoaddition manner. The reaction products are 1:1 monoaddition adduct anions, which are usually more stable than the original anionic initiators, but still highly reactive to undergo nucleophilic reaction with appropriate electrophiles and anionic polymerization of additional monomers.[1]

By utilizing such characteristic reactivity of DPE and its derivatives toward carbanionic species, a variety of well-defined chain-end- and in-chain-functionalized polymers have been synthesized with use of substituted DPE derivatives with functional groups.[2-12] For instance, chain-end-functionalized polymers are readily synthesized by the

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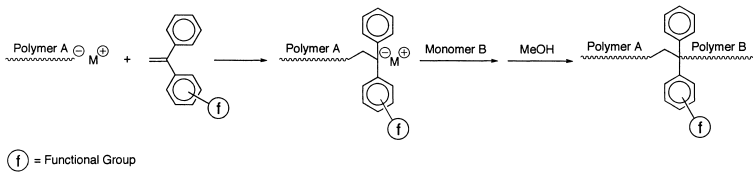
monoaddition reaction of living anionic polymers to functionalized DPE derivatives. With use of the reaction products of functionalized DPE derivatives and low molecular weight carbanionic species as anionic initiators in the polymerization, the functional groups can be introduced at the initiating chain ends of polymers. Furthermore, it is possible to synthesize in-chain-functionalized polymers by the reaction of living anionic polymers with functionalized DPE derivatives, followed by anionic polymerization of additional monomers to extend another polymer chains as illustrated in Scheme 1. This method named as "living functionalization reaction" by Quirk becomes very effective procedure for in-chain-functionalized homopolymers and block copolymers that are difficult to be synthesized by any other methods.[1]

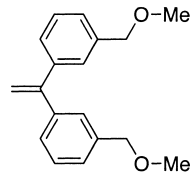
Scheme 1



Recently, we have been developing a versatile methodology for the synthesis of novel multi-functionalized polymers with well-defined structures.[13-21] The methodology involves diverse modes of reactions of living anionic polymers with functionalized DPE derivatives based on the DPE chemistry toward carbanionic species as mentioned above. Typical examples on the synthesis of multi-functionalized polystyrenes with benzyl chloride moieties are illustrated in Scheme 2[15]. Although benzyl chloride-functionalized DPE derivatives would be most effective for such polymer syntheses, their direct use may be difficult because the benzyl chloride functionality is not compatible with living anionic polymers and similar carbanionic species. Therefore, we first chose anion-stable methoxymethylphenyl (MMP) group as a precursor of benzyl chloride functionality. As an MMP-functionalized DPE derivative, 1,1-bis(3-methoxy-methylphenyl)ethylene (**1**) was newly synthesized and used in the functionalization reactions. After the reactions, the introduced MMP groups were quantitatively transformed into benzyl chloride functionalities by treatment with BCl_3.

At first, chain-end-functionalized polystyrene with two benzyl chloride moieties was synthesized by the addition reaction of polystyryllithium to **1**, followed by treatment with BCl_3. In order to synthesize chain-end- and in-chain-functionalized polystyrenes with two and four benzyl chloride moieties, polystyrenes having two MMP and one 3-

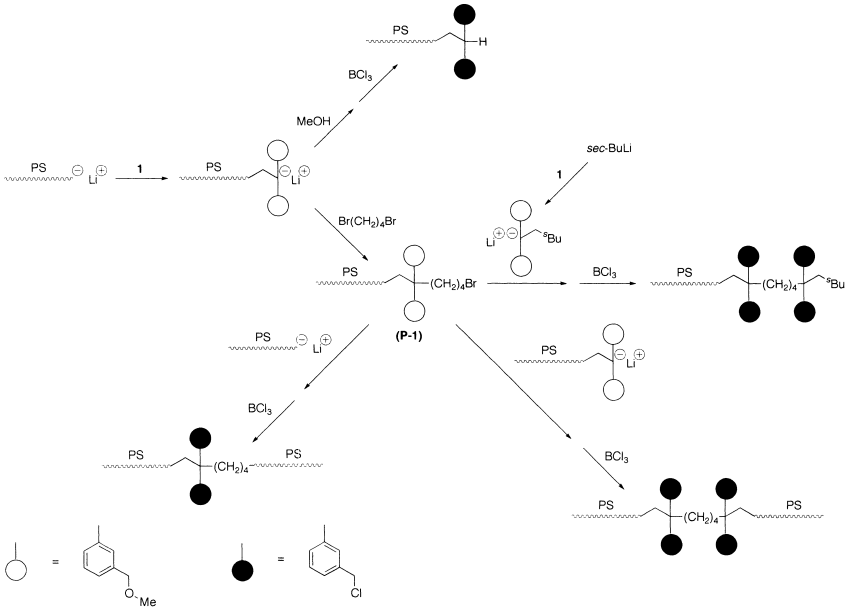
bromobutyl termini were prepared as prepolymers (**P-1**) by the reaction of polystyryllithium with **1**, followed by in-situ reacting with a 10-fold excess of 1,4-dibromobutane. Chain-end-functionalized polystyrene with four benzyl chloride moieties could be synthesized by the reaction of **P-1** with a functionalized anion prepared from **1** and *sec*-BuLi, followed by treatment with BCl_3. In-chain-functionalized polystyrene with two or four benzyl chloride moieties was synthesized by reactions of **P-1** with either polystyryllithium or polystyryllithium end-capped with **1**, respectively, followed by treatment with BCl_3. All of the resulting chain-functionalized polymers were precisely controlled with respect to chain length and quantitatively functionalized within analytical errors. We have also successfully synthesized various well-defined chain-end- and in-chain-functionalized polymers with one, two, or more D-glucose and D-galactose residues as well as 1,3-butadiene and α-methylstyrene moieties by developing the similar methodology using the corresponding functionalized DPE derivatives.



(**1**)

Herein, we present further development of the above-mentioned methodology for the syntheses of chain-end- and in-chain-functionalized polystyrenes with six or more benzyl chloride moieties and four or eight D-glucose residues. New functionalized α,ω-dihaloalkanes and dianionic species derived from **1** and a tetra-substituted DPE derivative are also presented as key agents for such polymer syntheses.

Scheme 2



Experimental Part

Materials. Monomers and solvents were purified according to the usual procedures. Styrene was finally distilled over dibutylmagnesium (*ca.* 3 mol %) on the vacuum line into ampoules with break seals that were prewashed with 1,1-diphenylhexyllithium in heptane. Isoprene was distilled over *n*-BuLi (*ca.* 2 mol %) at 0 °C on the vacuum line into ampoules with break seals that were prewashed with 1,1-diphenylhexyllithium in heptane. 1,1-Diphenylethylene was distilled over *n*-BuLi (*ca.* 2 mol %) on the vacuum line into ampoules with break seals that were prewashed with potassium naphthalenide in THF. 1,1-bis(3-methoxymethylphenyl)ethylene (**1**) was synthesized according to our papers previously reported.[15]

Synthesis of 1,10-dichloro-4,4-7,7-tetra(3-methoxymethylphenyl)decane (2) and its iodide derivative (2I). Under high vacuum conditions, the dimeric dianion was prepared by the reaction of **1** (1.35 g, 5.05 mmol) with potassium naphthalenide (5.03 mmol) in THF (50 mL) at –78 °C for 0.5 h. A THF solution of dimeric dianion was added dropwise to a THF (10 mL) solution of 1-bromo-3-chloropropane (0.932 g, 6.16

mmol) at –78 °C and the reaction mixture was allowed to stir for additional 0.5 h. After removal of the solvent under vacuum, the resulting mixture was then extracted with ether three times and the organic layer was washed with water, dried over magnesium sulfate and concentrated. Flash column chromatography (silica gel, hexanes at first and then hexanes/ EtOAc = 8/2, *v/v*) of the crude product gave white semi-solid material, **2**, (1.47 g, 2.14 mmol, 85%). It was freeze-dried three times from its absolute benzene solution and dried at 40 °C for overnight under high vacuum.

^{1}H NMR ($CDCl_3$, 300 MHz): δ = 1.08 (m, 4H, –CH_2–), 1.74 (s, 4H, –CH_2–), 2.17 (m, 4H, –CH_2–), 3.33 (s, 12H, –OCH_3), 3.35 (m, 4H, –CH_2Cl), 4.38 (s, 8H, PhCH_2–), 6.93-7.22 (m, 16H, Ar).

^{13}C NMR ($CDCl_3$, 75 MHz): δ = 148.2 (ArCAr), 137.7, 128.1, 127.3, 127.1, and 125.5 (Ar), 74.9 (CH_2OCH_3), 58.1 (CH_2OCH_3), 48.7 (CH_2Cl), 45.8 (CCH_2CH_2C), 34.9 (CH_2CH_2Cl), 31.3 (CCH_2CH_2).

Anal. Calcd for **2**, $C_{42}H_{52}Cl_2O_4$: C, 72.92; H, 7.58; Cl, 10.25, O, 9.25. Found: C, 73.19; H, 7.46; Cl, 10.01, O, 9.34.

2 (1.06 g, 1.54 mmol) and NaI (6.88 g, 46.0 mmol) were dissolved in dry acetone (100 mL) and the reaction mixture was refluxed for 3 days under an atmosphere of nitrogen. After usual workup, column chromatography (silica gel, hexanes: EtOAc = 7/3, *v/v*) of the crude product gave white semi-solid material, **2I**, (0.940 g, 1.08 mmol, 70%). It was freeze-dried three times from its absolute benzene solution and dried at 40 °C for overnight under high vacuum.

^{1}H NMR ($CDCl_3$, 300 MHz): δ = 1.13 (m, 4H, –CH_2–), 1.75 (s, 4H, –CH_2–), 2.15 (m, 4H, –CH_2–), 2.99 (m, 4H, –CH_2I), 3.33 (s, 12H, –OCH_3), 4.38 (s, 8H, PhCH_2–), 6.93-7.22 (m, 16H, Ar).

^{13}C NMR ($CDCl_3$, 75 MHz): δ = 148.2(ArCAr), 137.8, 128.4, 127.3, 127.1, and 125.5 (Ar), 74.9 (CH_2OCH_3), 58.1 (CH_2OCH_3), 48.8 (CH_2I), 45.8 (CCH_2CH_2C), 35.0 (CH_2CH_2I), 31.4 (CCH_2CH_2).

Anal. Calcd for **2I**, $C_{42}H_{52}I_2O_4$: C, 57.67; H, 5.99; I, 29.02, O, 7.32, Cl, 0.00. Found: C, 57.78; H, 6.12; I, 28.64, O, 7.46, Cl, 0.00.

1,1-Bis[3',5'-bis(methoxymethyl)phenyl]ethanol. Under an atmosphere of nitrogen,

dry ethyl acetate (0.800 mL, 8.19 mmol) was added dropwise to a solution of the Grignard reagent prepared from 3,5-bis(methoxymethyl)bromobenzene (4.01 g, 16.4 mmol) and Mg (0.870 g, 36.0 mmol) in 40 mL of dry THF at 0 °C. The reaction mixture was stirred at room temperature for 12 h. After removal of the solvent under vacuum, 2*N* HCl was added to the residue. The resulting mixture was then extracted with ether three times and the organic layer was washed with water and dried over magnesium sulfate. After evaporation by vacuum pump, a crude 1,1-bis[3',5'-bis(methoxymethyl)-phenyl]ethanol was obtained in 72% yield (2.17 g, 5.83 mmol) as a viscous oil. It was used without further purification.

^{1}H NMR ($CDCl_3$, 300 MHz): δ = 7.30 and 7.22 (2s, 6H, Ar), 4.42 (s, 8H, CH_2OCH_3), 3.38 (s, 12H, CH_2OCH_3), 1.95 (s, 3H, CH_3).

1,1-Bis[3',5'-bis(methoxymethyl)phenyl]ethylene. A solution of 1,1-bis[3',5'-bis-(methoxymethyl)phenyl]ethanol (2.17 g, 5.83 mmol) and *p*-toluenesulfonic acid (0.30 g) in dry benzene (30 mL) was refluxed. After 3 h, aqueous sodium bicarbonate was added to neutralize the reaction mixture. It was extracted with ether, dried over magnesium sulfate and concentrated. Flash column chromatography on silica gel (hexanes/EtOAc = 8/2, *v/v*) afforded 1.92 g (5.42 mmol, 93%) of pure 1,1-bis[3',5'-bis(methoxymethyl)-phenyl]ethylene as a viscous oil.

^{1}H NMR ($CDCl_3$, 300 MHz): δ = 7.29 and 7.22 (2s, 6H, Ar), 5.47 (s, 2H, $C=CH_2$), 4.44 (s, 8H, CH_2OCH_3), 3.39 (s, 12H, CH_2OCH_3).

^{13}C NMR ($CDCl_3$, 75 MHz): δ = 149.6 ($C=CH_2$), 141.9, 138.4, 127.1, and 126.6 (Ar), 115.1 ($C=CH_2$), 74.60 (CH_2OCH_3), 58.31 (CH_2OCH_3).

1,1-Bis[3',5'-bis(chloromethyl)phenyl]ethylene. Under an atmosphere of nitrogen, BCl_3 (1.0 M in CH_2Cl_2, 44.0 mL, 44.0 mmol) was added dropwise to a dry carbon tetrachloride (40 mL) solution of 1,1-bis[3',5'-bis(methoxymethyl)phenyl]ethylene (1.92 g, 5.42 mmol) at 0 °C with stirring. The reaction mixture was stirred for additional 20 h at 0 °C and quenched with methanol. The reaction mixture was basified with NaOH aq, extracted with CCl_4, dried over magnesium sulfate and concentrated. Flash column chromatography on silica gel (hexanes/EtOAc = 9.5/0.5, *v/v*) afforded 1.93 g (5.19 mmol, 96%) of 1,1-bis[3',5'-bis(chloromethyl)phenyl]ethylene as a white solid: mp 93–94 °C.

^{1}H NMR ($CDCl_3$, 300 MHz): δ = 7.35 and 7.16 (2s, 6H, Ar), 5.55 (s, 2H, C=CH_2), 4.58 (s, 4H, CH_2Cl).

^{13}C NMR ($CDCl_3$, 75 MHz): δ = 148.1 (*C*=CH_2), 142.1, 138.3, 128.5, and 126.0 (Ar), 116.5 (C=*C*H_2), 45.70 (*C*H_2Cl).

1,1-Bis[3',5'-bis(1,2:5,6-di-O-isopropylidene-α-D-glucofuranose-3-oxymethyl)-phenyl]ethylene (4). Under an atmosphere of nitrogen, sodium hydride (0.600 g, 25.0 mmol) was added to a stirred solution of 1,2:5,6-di-*O*-isopropylidene-α-D-glucofuranose (5.42 g, 20.8 mmol) in dry DMF (30 mL) at 0 °C and the mixture was allowed to warm up to 25 °C and stir for 2 h. 1,1-Bis[3',5'-bis(chloromethyl)phenyl]ethylene (1.42 g, 3.82 mmol) in dry DMF (10 mL) was then added dropwise at room temperature and the mixture was stirred at 50 °C for 5 h. Water was added to decompose excess sodium hydride and the resulting mixture was extracted with ether three times. The organic layer was dried over magnesium sulfate. After evaporation, the crude product was purified by flash column chromatography on silica gel (hexanes / EtOAc = 6/4, *v/v*) to afford **4** in 83% yield (3.93 g, 3.17 mmol) as a white solid: mp 69–70 °C. The purity of **4** was confirmed to be more than 99% by TLC coupled with FID detector.

^{1}H NMR ($CDCl_3$, 300 MHz) : δ = 7.29 and 7.22 (2s, 6H, Ar), 5.88 (d, 4H, *J* = 3.60 Hz, α-furanose H-1), 5.48 (s, 2H, C=CH_2), 4.65 - 3.97 (m, 32H, H-2 – H-6 and ArCH_2–), 1.50 - 1.31 (m, 48H, CH_3).

^{13}C NMR ($CDCl_3$, 75 MHz) : δ = 149.3 (*C*=CH_2), 141.8, 138.1, 127.0, and 126.2 (Ar), 114.2 (C=*C*H_2), 111.9 and 109.1 (>*C* (O) (O)), 105.3 (C-1), 82.63, 82.04, 81.35, 72.57, and 67.43 (C-2 – C-6), 72.23 (Ar*C*H_2), 31.27 (CH_2*C*H_2CH_2), 26.92, 26.91, 26.33, and 25.49 (*C*H_3).

Synthesis of Prepolymers, Chain-End- and In-Chain-Functionalized Polystyrenes. The polymers used in the reactions were freeze-dried three times (8 h, 8 h, and 24 h) from their absolute benzene solutions and further dried at 40 °C for additional 24 h under high vacuum (10^{-6} torr). They were then dissolved in THF (usually 1 g of polymer in 10 ~ 20 mL of THF) and used in the reactions under appropriate conditions described in each section. The reaction of polystyryllithium with a 1.5-fold excess of **1** was carried out in THF at –78 °C for 0.5 h. Similarly, the reaction of *sec*-BuLi with a

1.5-fold excess of **1** was carried out under the same conditions.

The polymers were precipitated in large excess of methanol and reprecipitated two or three times from THF to methanol and freeze-dried from their absolute benzene solutions for 24 h and dried at 40 °C for additional 24 h under high vacuum conditions. If necessary, polymers were isolated by fractionation with SEC in THF.

Transformation Reaction to Benzyl Chloride Functionality with BCl_3. MMP-functionalized polymer (1 g) was dissolved in dry CH_2Cl_2 (10 ~ 20 mL) and a 5-fold excess of BCl_3 in CH_2Cl_2 toward each MMP group was added slowly to the solution at 0 °C. The reaction mixture was stirred at 0 °C for additional 0.5 h. After the reaction was terminated with degassed methanol, the polymer was precipitated in large excess of methanol, reprecipitated two or three times from THF to methanol. It was freeze-dried from its absolute benzene solution for 24 h and dried at 40 °C for additional 24 h under high vacuum conditions.

Degrees of benzyl chloride functionality were determined by ^{1}H NMR using two resonances at 4.4 ppm (chloromethylene protons) and at 0.6 ~ 0.8 ppm (methyl protons of the initiator fragment) or 6.2 ~ 7.2 ppm (aromatic protons).

Preparation of Anionic Living Polymers and Heteroarm Star-Branched Polymers. Polymerizations and reactions were carried out under high vacuum condition (10^{-6} torr) in sealed glass reactors with break seals. Styrene was polymerized with *sec*-BuLi in THF at -78 °C for 0.5 h. Isoprene was polymerized with *sec*-BuLi in heptane at 40 °C for 2 h. The concentrations of monomers and initiators were in the ranges of 0.5 ~ 0.9 *M* and 0.02 ~ 0.05 *M*, respectively.

Heteroarm A_2B_8 and A_2B_{12} star-branched polymers were synthesized by the reactions of polyisoprenyllithiums with in-chain-functionalized polystyrenes with eight and twelve benzyl chloride functionalities. The heptane solution of polyisoprenyllithium was cooled to –78 °C and then an equal amount of THF was added at –78 °C prior to the reaction. The reactions of polyisoprenyllithiums with benzyl chloride-functionalized polystyrenes were carried out in mixed solvents of THF and heptane (*ca.* 2/1, *v/v*) at –78 °C for 24 h. The polymers were precipitated in large excess of methanol and reprecipitated two or three times from THF to methanol and freeze-dried from their absolute benzene solutions for 24 h. The star-branched polymers were isolated by

fractionation with SEC in THF. The isolated polymers were again reprecipitated in methanol two times and freeze-dried from their absolute benzene solutions for 24 h and dried at 40 °C for additional 24 h under high vacuum conditions.

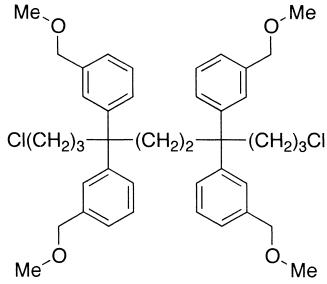
Measurements. ^{1}H (300 MHz) and ^{13}C (75 MHz) NMR spectra were measured in $CDCl_3$ using a BRUKER DPX spectrometer. Size-exclusion chromatography (SEC) was performed on a TOSOH HLC 8020 instrument with UV (254 nm) or refractive index detection. THF was used as a carrier solvent with a flow rate of 1.0 mL/min at 40 °C. Three polystyrene gel columns (TSK_{gel} $G4000H_{XL}$, $G3000H_{XL}$, $G2000H_{XL}$ or TSK_{gel} $G5000H_{XL}$, $G4000H_{XL}$, $G3000H_{XL}$) were used. Measurable molecular weight ranges are $10^3 \sim 5 \times 10^4$ and $10^4 \sim 5 \times 10^5$, respectively. Calibration curves were made to determine M_n and M_w/M_n values with standard polystyrene and polyisoprene samples, respectively. Fractionation with SEC was performed with a flow rate of 1.0 ml/min at 40 °C using a TOSOH HLC 8020 type fully automatic instrument equipped with TSK-$G4000H_6$ and TSK-$G5000H_6$ columns (measurable molecular weight range: $10^3 \sim 5 \times 10^4$ and $10^4 \sim 3 \times 10^5$). All runs for fractionation were made with THF as an eluent. The concentration of the polymer solution for fractionation was adjusted to 1.0 ~ 2.0 wt.-%, depending on the molecular weight of the sample. TLC coupled with flame ionization detector (FID) was performed by IATRON IATROSCAN NEW MK-5 equipped with IATROCORDER TC-21 from Iatron Co., Ltd. Specially designed quartz rods (150 mm × 2.0 mm) were used on which silica gel was sintered. Static light scattering (SLS) measurements were performed with an Ootsuka Electronics DSL-600R instrument in THF or benzene at 25 °C.

Results and Discussion

1. Synthesis of Chain-End- and In-Chain-Functionalized Polystyrenes with Six or More Benzyl Chloride Moieties

1.1. Polystyrenes Having Four or Six MMP and One 3-Chloropropyl Termini as Precursory Polymers. In order to synthesize chain-functionalized polystyrenes with six or more benzyl chloride moieties, we have synthesized 1,10-dichloro-4,4,7,7-tetra(3-methoxymethylphenyl)decane (**2**) from the MMP-functionalized DPE, **1**, as a new

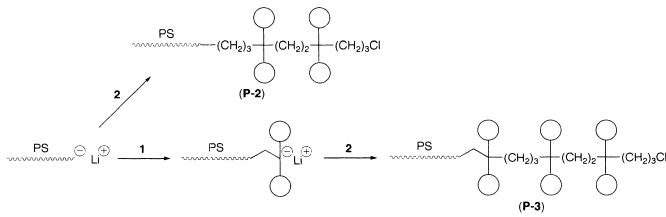
functionalized agent. It was obtained in 85% yield by the dimerization of **1** with potassium naphthalenide in THF at –78 °C for 0.5 h, followed by treatment with a 1.2-fold excess of 1-bromo-3-chloropropane at –78 °C for 0.5 h. The latter substitution reaction was observed to undergo completely selective monoalkylation with the bromide moiety.



(**2**)

ω-Chlorobutyl-functionalized polystyrenes with four and six MMP groups at their chain-ends (**P-2** and **P-3**) were synthesized as precursory polymers by reactions of **2** with polystyryllithium and polystyryllithium end-capped with **1**, as illustrated in Scheme 3. A 1.5-fold excess of **2** was used in each reaction. In the reaction of **2** with polystyryllithium, the characteristic orange color for polystyryllithium gradually faded and completely disappeared after several hours in THF at –78 °C. On the other hand, polystyryllithium end-capped with **1** was very sluggish to react with **2** in THF at –78 °C. The characteristic dark red color still remained even after 24 h. The reaction mixture was then allowed to warm up to –50 °C for additional 20 h to force the reaction to completion. Although the expected polymers were obtained in 75 ~ 93% yields, undesirable dimeric products were more or less formed in both reactions. Unfortunately, the dimer formation could not be completely suppressed by changing several experimental variables. Therefore, the prepolymers were finally isolated by fractionation with SEC to remove the dimers. The characterization results by SEC and ^{1}H NMR are summarized in Table 1.

Scheme 3



The isolated polymers showed symmetrical monomodal SEC peaks with narrow molecular weight distributions, indicating that they were pure and free of their dimeric products. The degrees of MMP and 3-chloropropyl termini were observed to be quantitative within analytical limits. These results clearly indicate that both reactions proceed as desired to afford the expected precursory polymers, **P-2** and **P-3** in good yields. However, the undesirable dimeric products were always formed and therefore more optimization of the reactions should be needed.

Table 1. Synthesis of precursory polymers with four and six MMP and 3-chloropropyl groups

Polymer	$M_n \times 10^{-3}$		M_w/M_n [a]	Functionality [b]	
	Calcd	Obsd [a]		MMP	$-(CH_2)_3Cl$
P-2	6.2	5.4	1.05	3.98	1.09
P-2	10.0	10.0	1.05	4.00	1.01
P-3	6.6	5.9	1.08	5.98	1.00

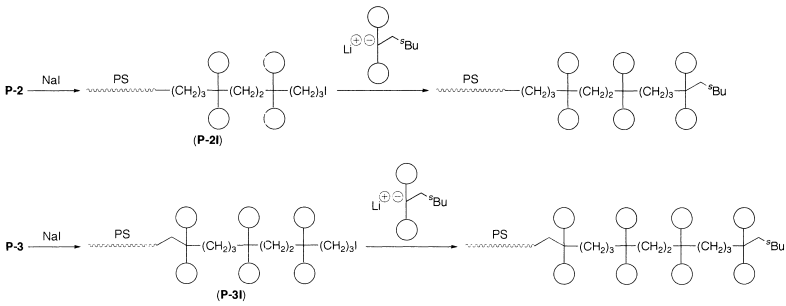
[a] Determined by SEC.
[b] Determined by ^{1}H NMR

1.2. Chain-End-Functionalized Polystyrenes with Six and Eight Benzyl Chloride Moieties. Basically, the title chain-end-functionalized polystyrenes were synthesized by reacting the precursor polymers, **P-2** and **P-3**, with a functionalized anion prepared from **1** and sec-BuLi as illustrated in Scheme 4. For the synthesis of chain-end-functionalized polystyrene with six benzyl chloride moieties, the reaction of **P-2** with the functionalized anion was carried out in THF at –78 °C. In this reaction, a 2.5-fold excess of the anion to 3-chloropropyl group was used. Since the low reactivity of 1,1-diphenylalkyl anion toward the chloride at –78 °C was observed in the reaction of **2** with polystyryllithium end-capped with **1** mentioned in the preceding section, the reaction was first carried out at –78 °C for 24 h and then at –50 °C for additional 24 h.

The resulting polymer showed a sharp monomodal SEC peak without any shoulders and tailings. The observed M_n value agreed well with that calculated and a narrow molecular weight distribution was attained (M_w/M_n = 1.06). However, the functionalization degree determined by ^{1}H NMR was 5.22 corresponding to 87% yield. The reaction seems incomplete and more reaction time may be required to complete the reaction.

The terminal chlorides of **P-2** and **P-3** were converted to more reactive iodides (**P-2I** and **P-3I**) by treating with a 10-fold excess of NaI in acetone at 60 °C for 72 h. The reactions were observed to proceed quantitatively, while the MMP groups stayed intact under the conditions. The ω-iodopropyl-functionalized prepolymer, **P-2I**, thus obtained was reacted with a 1.5-fold excess of the same functionalized anion in THF at –78 °C for 20 h. The resulting polymer exhibited a sharp monomodal SEC peak eluted at a reasonable molecular weight region. The degree of MMP group determined by ^{1}H NMR was nearly quantitative (98% yield). The use of the iodide was thus effective in the functionalization reaction. The ω-iodopropyl-functionalized prepolymer, **P-3I**, was also reacted with the functionalized anion under the identical conditions. Similarly, the reaction proceeded quantitatively to afford the expected chain-end-functionalized polystyrene with eight MMP groups.

Scheme 4



Both polymers were then treated with BCl_3. The ^{1}H NMR spectra of the resulting polymers showed that the resonances at 3.3 ppm and 4.3 ppm corresponding to methyl and methylene protons of the methoxymethyl groups completely disappeared, whereas new resonances for chloromethylene protons of the benzyl chloride emerged at 4.4 ppm. These results clearly indicate that MMP groups are quantitatively transformed into

benzyl chloride functionalities. The degrees of benzyl chloride functionality were 5.9_5 and 8.2_4, respectively, by using two resonances at 4.4 ppm and 0.6 ~ 0.8 ppm for methyl protons of the initiator fragment. After the transformation reaction, their SEC peaks were eluted almost at the same molecular weight regions and the molecular weight distributions remained narrow. Thus, the objective chain-end-functionalized polystyrenes with six and eight benzyl chloride moieties were successfully obtained in 100% yield. The results are summarized in Table 2.

Table 2. Synthesis of chain-end-functionalized polystyrenes with six and eight benzyl chloride moieties

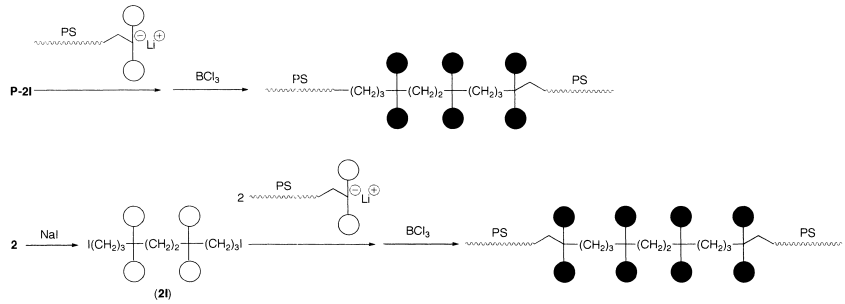
Prepolymer	$M_n \times 10^{-3}$		M_w/M_n[a]	Functionality[b]	
	Calcd	Obsd[a]		Calcd	Obsd (%)
P-2	5.7	5.6	1.06	6	5.22 (87)
P-2I	3.5	3.7	1.06	6	5.95 (99)
P-3I	5.2	5.8	1.04	8	8.24 (103)

[a] Determined by SEC.
[b] Determined by ^{1}H NMR

1.3. In-Chain-Functionalized Polystyrenes with Six, Eight, Twelve, and Sixteen Benzyl Chloride Moieties. For the synthesis of in-chain-functionalized polystyrene with six benzyl chloride moieties at the middle of the chain, **P-2** (M_n = 5 600) was reacted with a 1.3-fold excess of polystyryllithium end-functionalized with **1** (M_n = 5 600) in THF. The reaction proceeded very sluggishly and gave only in 5% yield at –78 °C for 144 h and at –40 °C for additional 24 h. Thus, the low reactivity of 1,1-diphenylalkyl anion toward the chloride was again demonstrated.

Alternatively, the more reactive **P-2I** (M_n = 5 800) was reacted with a 1.5-fold excess of the polystyryllithium end-functionalized with **1** (M_n = 3 800) (see Scheme 5). In this case, the reaction went to completion at –78 °C within 24 h. Since excess polystyryllithium was used in the reaction, the coupled polymer was isolated by fractionation with SEC. The isolated polymer was then treated with BCl_3. The results are summarized in Table 3.

Scheme 5



The resulting polymer was observed to possess a predictable molecular weight and a narrow molecular weight distribution. The degree of benzyl chloride functionality determined by ^{1}H NMR was 5.8$_8$ (98% yield). In this case, the introduced benzyl chloride moieties were placed at the two-fifths, but not at the middle of the chain. Thus, the placement of the functional group can be controlled by changing the molecular weights of both starting polymers.

Table 3. Synthesis of in-chain-functionalized polystyrenes with six, eight, twelve, and sixteen benzyl chloride moieties

$M_n \times 10^{-3}$		M_w/M_n [a]	Functionality [b]	
Calcd	Obsd [a]		Calcd	Obsd (%)
9.6	10.4	1.01	6	5.88 (98)
7.7	7.4	1.02	8	8.00 (100)
12.0	12.0	1.03	12	12.0 (100)
12.2	10.7	1.04	16	15.3 (95)

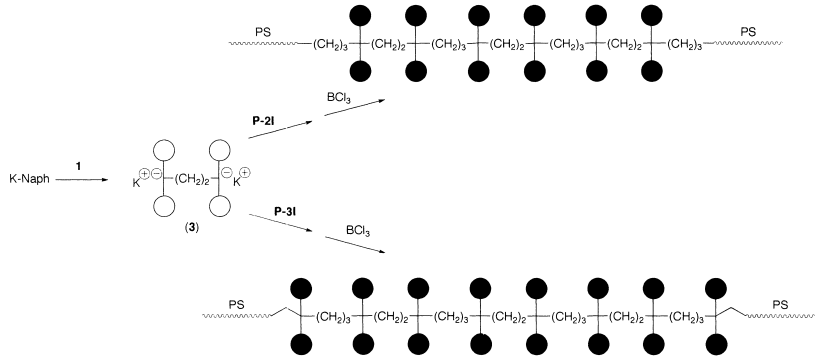
[a] Determined by SEC.
[b] Determined by ^{1}H NMR

For the synthesis of in-chain-functionalized polystyrene with eight benzyl chloride moieties, we first considered the coupling reaction between **2** and two equivalents of polystyryllithium end-capped with **1**. However, as the low reactivity of the chloride toward 1,1-diphenylalkyl anion was estimated, **2** was converted to the more reactive α,ω-diiodo derivative, **2I**, by treatment with NaI in acetone prior to the reaction. As illustrated in Scheme 5, the coupling reaction between **2I** and two equivalents of polystyryllithium end-capped with **1** (M_n = 3 500) was carried out in THF at –78 °C for 72 h. A 1.5-fold excess of the polymer anion was used. The expected coupled

polymer (M_n = 7 400) was quantitatively obtained under the conditions. After removal of unreacted polystyrene used in excess, the coupled polymer was treated with BCl_3. The resulting polymer showed a sharp monomodal SEC peak with a predictable molecular weight and a narrow molecular weight distribution. The degree of benzyl chloride functionality was quantitative (see also Table 3). The introduced eight benzyl chloride moieties were placed exactly at the middle of the chain in this case.

For the synthesis of in-chain-functionalized polystyrenes with twelve and sixteen benzyl chloride moieties, a dianionic species with four MMP groups, **3**, was used as a new key functionalized agent. The dianion, **3**, was readily and quantitatively prepared by the reaction of **1** with potassium naphthalenide (K-Naph) in THF at –78 °C for 0.5 h. The synthetic procedures for such in-chain-functionalized polymers are illustrated in Scheme 6.

Scheme 6



In-chain-functionalized polystyrene with twelve benzyl chloride moieties was synthesized by first reacting a 1.1-fold excess of **1** with **3**, followed by *in-situ* reaction with a 1.1-fold excess of **P-2I** (2.2 equivalents). The characteristic dark red color of **3** gradually faded with time, indicating that the reaction proceeded relatively slowly in THF at –78 °C. The reaction was terminated with degassed methanol after 49 h. Two peaks corresponding to the coupled product (M_n = 12 000) and the unreacted **P-2I** used in excess (M_n = 5 400) were observed in the SEC trace of the reaction mixture. The polymer eluted at the higher molecular weight side was isolated by fractionation with SEC. The isolated polymer was then treated with BCl_3.

The resulting polymer was observed to have a predictable M_n value and a narrow molecular weight distribution. In addition, a small high molecular weight polymer (< 5%), which seemed double the molecular weight (M_n = 24 000) of the expected polymer, was observed after the reaction with BCl_3. The most likely cause of the high molecular weight polymer formation was coupling between the polymer chains by undesirable Friedel-Crafts alkylation reaction catalyzed with BCl_3. It should be noted that the formation of high molecular weight polymer is not always, but sometimes observed in the transformation reaction with BCl_3.[22] After removal of the high molecular weight polymer from the desired polymers by fractionation with SEC, the degree of benzyl chloride functionality of the isolated polymer was determined by ^{1}H NMR to be 12.0 that exactly agreed with the expected value.

Similarly, the coupling reaction between **3** and two equivalents of **P-3I** was carried out in THF at –78 °C for the synthesis of in-chain-functionalized polymer with sixteen functional groups (see also Scheme 6). A 1.1-fold excess of **P-3I** (2.2 equivalents) was used in this reaction. The prepolymer was however very sluggish to react with **3**, requiring the following conditions to achieve even ~ 50% reaction. After the reaction proceeded at –78 °C for 50 h, the reaction mixture was allowed to gradually warm up to –50, –30, 0, and finally 25 °C for 12 h. The SEC showed two peaks corresponding to the coupled product and the unreacted **P-3I**, respectively. The coupled product was isolated by fractionation with SEC and the isolated polymer was treated with BCl_3. The results are also listed in Table 3.

The molecular weight observed by SEC agreed with the predictable value and its distribution was narrow, the M_w/M_n value being 1.04. The degree of benzyl chloride functionality determined by ^{1}H NMR was 15.3 $\pm$ 0.3 that corresponded to 95 $\pm$ 2% yield. We believe that this value is very close to 16 of the target one and accordingly the resulting polymer is the objective in-chain-functionalized polymer with sixteen benzyl chloride moieties. However, the problem of this polymer synthesis is a relatively low yield of the coupled polymer (~ 50%). Since the reaction seems similar to that used in the synthesis of in-chain-functionalized polymer with twelve functional groups, the yields of the coupled polymers might be quantitative under the same conditions. Although the cause for the low yield has not been understood at the present time, the

reaction should be reexamined.

1.4. Synthesis of Heteroarm Star-Branched Polymers. As we have recently demonstrated the successful synthesis of star-branched polymers by the reaction of benzyl chloride-functionalized polymers with living anionic polymers of styrene and isoprene,[14,17] the functionalized polystyrenes with benzyl chloride moieties synthesized herein may also be very suitable building blocks for synthesizing both regular and heteroarm star-branched polymers. Two representative heteroarm star-branched polymers are introduced in this section, although they were reported previously.[17]

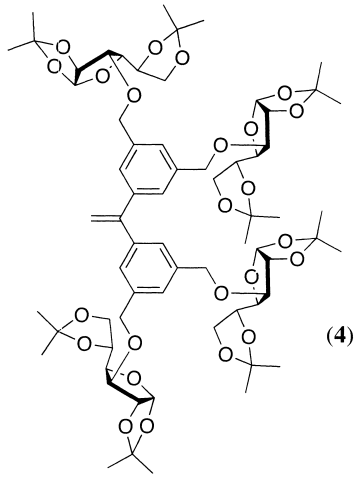
A 1.5-fold excess of polyisoprenyllithium was reacted with either in-chain-functionalized polystyrene with eight or twelve benzyl chloride moieties in THF-heptane mixtures (ca. 2/1, v/v) at –78 °C for 72 h. New symmetrical monomodal SEC peaks with narrow distributions possibly for the star-branched polymers appeared in the higher molecular weight sides after the reactions with polyisoprenyllithiums. After removal of the unreacted polyisoprenes used in excess by fractionation with SEC, the resulting polymers were characterized by SEC, SLS, and ^{1}H NMR, respectively.

Their observed molecular weights ($M_{n\ obsd}$ = 49 000 and 80 000) were closed to the designed values ($M_{n\ calcd}$ = 50 000, when M_n of the in-chain-functionalized polystyrene with eight benzyl chloride moieties was 7 400 and $M_{n\ calcd}$ of polyisoprenyllithium was 5 300, and $M_{n\ calcd}$ = 80 000, when M_n of the in-chain-functionalized polystyrene with twelve benzyl chloride moieties was 12 000 and $M_{n\ calcd}$ of polyisoprenyllithium was 5 700). The molecular weight distributions were narrow, M_w/M_n values being 1.04 and 1.04, respectively. The compositions of both polymers determined by ^{1}H NMR were very close to the calculated values. These results clearly indicate that the expected A_2B_8 and A_2B_{12} heteroarm star-branched polymers with well-defined structures are successfully synthesized. Further synthesis of heteroarm star-branched polymers by using the benzyl chloride-functionalized polystyrenes herein synthesized are now under investigation.

2. Synthesis of Chan-End- and In-Chain-Functionalized Polystyrenes with D-Glucose Residues

2.1. 1,1-Bis[3',5'-bis(1,2:5,6-di-O-isopropylidene-α-D-glucofuranose-3-oxymethyl)

phenyl]ethylene (4) as a New Functionalized Agent. In the functionalization reactions previously reported, substituted DPE derivatives with one or two functional groups were always used as functionalized agents. In this section, we have attempted to use a substituted DPE with four functional groups for the introduction of more functional groups into polymers. If such a DPE would satisfactorily react with living anionic polymer, four functional groups could simultaneously be introduced into a polymer chain by one reaction step. Furthermore, new functionalized agents with eight functional groups may be synthesized from the DPE. They are structurally similar to **2** and **3**, but may allow the introduction of eight or more functional groups into polymers. For this purpose, we have synthesized **4** as a new tetra-substituted DPE derivative and examined its possible utility in the functionalization reaction.



(4)

Since there are four sterically bulky substituents in **4**, it is essential to examine the reactivity of **4** toward carbanionic species. The addition reaction of polystyryllithium to a 1.2-fold excess of **4** was therefore attempted in THF at –78 °C for 0.5 h.[23] Upon addition of **4** to polystyryllithium, an immediate color change for reddish orange to dark magenta occurred. The color persisted during the reaction but disappeared instantaneously by quenching with degassed methanol as expected. A polymer was quantitatively obtained. The results are summarized in Table 4.

Table 4. Synthesis of chain-end and in-chain-functionalized polystyrenes with four and eight D-glucose residues

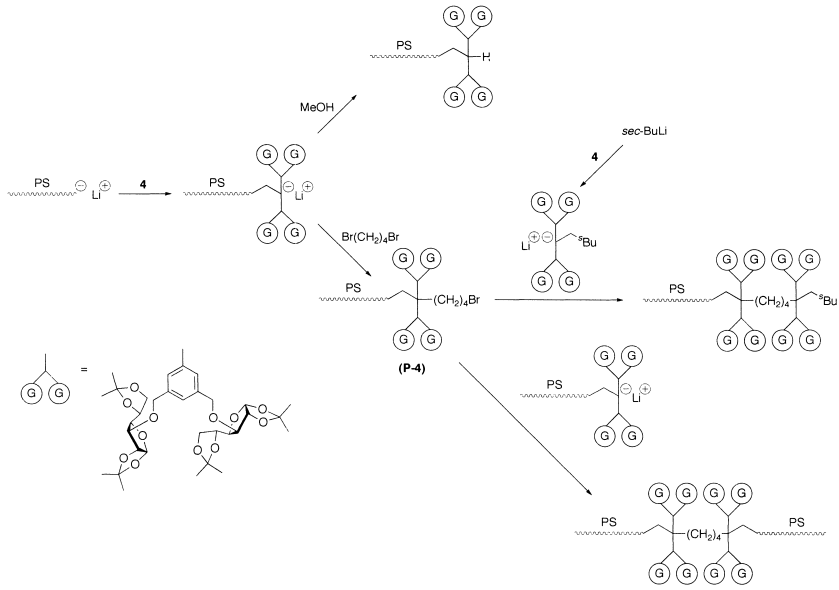
$M_n \times 10^{-3}$		M_w/M_n[a]	Functionality[b]		Placement
Calcd	Obsd[b]		Calcd	Obsd (%)	
13.0	14.4	1.05	4	4.07 (102)	Chain-End
14.3	14.3	1.07	8	7.84 (98)	Chain-End
21.8	20.3	1.04	8	8.08 (101)	In-Chain

[a] Determined by SEC.
[b] Determined by ^{1}H NMR

The polymer showed a single monomodal SEC peak with a narrow molecular weight distribution (M_w/M_n = 1.05). The observed M_n value was in agreement with that predicted. Characteristic resonances at 5.8 ppm and 4.0 ~ 4.5 ppm assigned to the α-glucofuranose H-1 and H2 ~ H6 protons and the benzyl ether protons were observed in the ^{1}H NMR spectrum. The end-functionalization degree of glucofuranose residue was determined to be 4.07 by using two resonances at 5.8 ppm and at 0.7 ppm for the methyl protons of the initiator fragment. Thus, the addition reaction of polystyryllithium to **4** satisfactorily proceeded without problem to simultaneously introduce four D-glucose residues, after acid hydrolysis, at the chain-end by one reaction step.

2.2. Chain-End- and In-Chain-Functionalized Polystyrenes with Eight D-Glucose Residues. For the synthesis of title functionalized polystyrenes, a polystyrene having four acetal-protected α-D-glucofuranose and 4-bromobutyl termini was prepared as a precursory polymer (**P-4**) as illustrated in Scheme 7. The polymer was obtained by the addition reaction of polystyryllithium to **4**, followed by treatment with a 10-fold excess of 1,4-dibromobutane in THF at –78 °C for 0.5 h. Two reactions proceeded as desired to afford the expected **P-4** with a predictable molecular weight and a narrow distribution ($M_{n\ calcd}$ = 12 000, $M_{n\ obsd}$ = 13 100, M_w/M_n = 1.07). The degrees of both chain-end-functionalities were quantitative within the analytical errors (f = 4.07 and 1.02).

Scheme 7



Chain-end-functionalized polystyrene with eight D-glucose residues was obtained by the reaction of **P-4** with a 1.2-fold excess of a functionalized anion prepared from **4** with *sec*-BuLi (see also Scheme 7). The reaction was carried out in THF at –78 °C for 24 h and terminated with degassed methanol. The resulting polymer was characterized by ^{1}H NMR, TLC-FID, and SEC, respectively. All of the analytical results confirm the expectation that the reactions proceed cleanly and quantitatively to afford the objective chain-end-functionalized polystyrene with eight acetal-protected D-glucofuranose residues (see also Table 4).

Acetal groups of the glucofuranose residues were deprotected by treatment with 6 *N* HCl in aqueous THF at room temperature for 24 h. Quantitative deprotection to regenerate D-glucose residues was confirmed by the observations that the resonances characteristic to the acetal groups were completely disappeared in the ^{1}H and ^{13}C NMR spectra.

In-chain-functionalized polystyrene with eight D-glucose residues was synthesized by the reaction of **P-4** with polystyryllithium end-capped with **4** in THF at –78 °C for 24 h (see also Scheme 7). The characteristic magenta color faded slowly and completely

disappeared after 24 h. Since a 1.2-fold excess of **P-4** was used, the objective coupled polymer was isolated by fractionation with SEC to remove unreacted excess **P-4**. The molecular weight of the isolated polymer was close to that calculated and the molecular weight distribution was narrow. The functionalization degree of D-glucose residue was determined by ^{1}H NMR to be 8.08. Thus, the new tetra-substituted DPE, **4**, was demonstrated to be a very effective agent to introduce four or eight *D*-glucose residues into polymer chains as expected. The synthesis of well-defined functionalized polymers with more numbers of D-glucose or other monosaccharide residues by using **4** and its derivatives is now under investigation.

Conclusions

We have presented the synthesis of chain-functionalized polystyrenes with six or more benzyl chloride moieties and with four or eight D-glucose residues by means of the methodology based on living anionic polymerization of using functionalized DPE derivatives. For these polymer syntheses, new MMP-functionalized α,ω-dihalodecanes, **2** and **2I**, and dianionic species, **3**, played important roles as key functionalized agents. The important feature of the methodology is that these new functionalized agents can readily be synthesized from **1**. Two precursory polymers prepared from **2**, **P-2** and **P-3**, were also used as new building blocks. As another functionalized agent, a tetra-substituted DPE, **4**, was newly synthesized and employed for the synthesis of chain-functionalized polystyrenes with four or more D-glucose residues.

By utilizing diverse modes of addition and coupling reactions of polystyryllithiums with **1** ~ **4**, novel chain-end-functionalized polystyrenes with six and eight benzyl chlorides, in-chain-functionalized polystyrenes with six, eight, twelve, and sixteen benzyl chlorides, chain-end-functionalized polystyrenes with four and eight D-glucose residues, and in-chain-functionalized polystyrene with eight D-glucose residues were successfully synthesized.

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[23] When the purified **4** mentioned in experimental section was used in the reaction with polystyryllithium, unfunctionalized polystyrene was detected in 3% yield by TLC-FID measurement. This may be the partial deactivation of polystyryllithium with impurities in **4**. By adding Bu_2Mg (5 mol%) prior to the reaction, polystyryllithium was quantitatively reacted with **4** to afford chain-end-functionalized polystyrene with four D-glucose residues after acid-hydrolysis. No unfunctionalized polystyrene was present in this case.