Synthesis of Well-Defined Glycopolymers by π-Allylnickel-Catalyzed Living Coordination Polymerization

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Received August 1, 2000
Revised Manuscript Received April 12, 2001

Sugar-containing polymers have been paid much attention because of their specific characteristics which originate from the carbohydrate moieties. Besides their versatile potentials in the fields of medicine and biotechnology,[1] they are also expected to serve as useful functional materials, such as nonionic surfactants,[2] surface modifiers,[3] hydrogels,[4] and chiral templates for asymmetric synthesis and optical resolution of organic compounds.[5] These potential applications have prompted the synthesis of various types of glycopolymeric materials.

To date, most of the artificial sugar-containing materials have been prepared by means of the vinyl polymerization of the corresponding monomers, where the sugar is bound to the polymer chain by ester, amide, ether, or glycoside bonds.[6] Since they are mainly prepared by radical polymerization, it is difficult to provide well-defined glycopolymers, except for the report of the "living" radical polymerization by Fukuda et al.[7] It is known that architectural control of the sugar-carrying polymer is indispensable especially for medical and biochemical applications. Living polymerization is not only the most useful method to control the polymer structure, but also provides for the possibility of preparing block copolymers based on the envisioned purpose. Very recently, a few attempts to synthesize well-defined sugar-containing polymers via living polymerization have been reported, such as the ring-opening,[8] the ring-opening metathesis,[9,10] the cationic,[11] and the anionic polymerizations.[12] However, such studies are still quite limited, and new synthetic methodologies based on the living character of the polymerizations are expected to be developed.

In recent years, we reported the detailed studies on the living coordination polymerization of allene derivatives by allylnickel catalysts.[13] The distinguishing characteristic of this method is that there is almost no restriction on the substituents on the allene monomers and a variety of functionalized polymers can be obtained through the living mechanism. Therefore, this system might serve as an effective method for the synthesis of glycopolymers with controlled molecular weight and narrow molecular weight distribution.

As a first example to demonstrate this possibility, we describe the coordination polymerization of 1,2;5,6-di-*O*-isopropylidene-3-*O*-(allenyl)-α-D-glucofuranoside (**1**),[14] Scheme 1. The polymerization took place smoothly by adding **1** to a toluene solution of **2**/PPh_3 ([**2**]/[PPh_3] = 1:1) under nitrogen at room temperature.[15] The polymerization under various ratios of [**1**]/[**2**] provided polymers (**3**) in high yields, whose molecular weight distribution was constantly quite narrow (M_w/M_n < 1.07). As is clear from Figure 1, a linear relationship was obtained between the number-average molecular weight (M_n) of **3** and the ratio of [**1**]/[**2**].[16] These results support the living nature of the present polymerization system. The living character and the stability of the propagating end in this system was further demonstrated by the post-polymerization experiment. That is, quantitative reinitiation took place by the further addition of **1** to the polymer solution, which was kept at ambient temperature under nitrogen even for several days. As a result, a complete shift of the elution peak in GPC was observed toward a higher molecular weight region keeping the narrow molecular weight distribution.

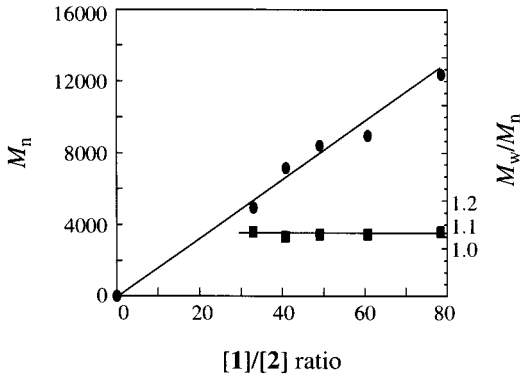
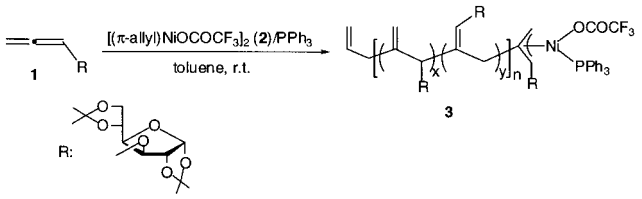


Figure 1. M_n and M_w/M_n vs feed ratio.

Scheme 1



The fully assigned ^1H NMR spectrum of **3** made it possible to estimate the ratio of the 1,2- to the 2,3-polymerization units to be 12:88 from the intensities of the peaks at 4.8−5.2 and 2.1−3.0 ppm (Figure 2). The ratio of the 1,2- to the 2,3-polymerizations was almost constant irrespective of the molecular weight of the polymer. Likewise, the polymerization of **1** by **2** (without PPh_3) yielded a polymer with higher content of the 2,3-polymerization unit (95% by ^1H NMR), although the molecular weight distribution became a little broader (e.g., **3** obtained from 32 equiv of **1**: M_n = 8,030, M_w/M_n = 1.22).[17]

Circular dichroism (CD) spectra of **1** and **3** indicated the higher order chiral conformation of the resulting polymer, which is mostly probably induced by the optically active pendent sugar moieties (Figure 3). That is, the spectrum of the monomer ($[\alpha]^{25}_D$ −8.8° (*c* 0.1, THF)) showed a positive Cotton effect at 273 nm, whereas much stronger negative effect was observed at

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10.1021/ma001344c CCC: $20.00
Published on Web 05/23/2001

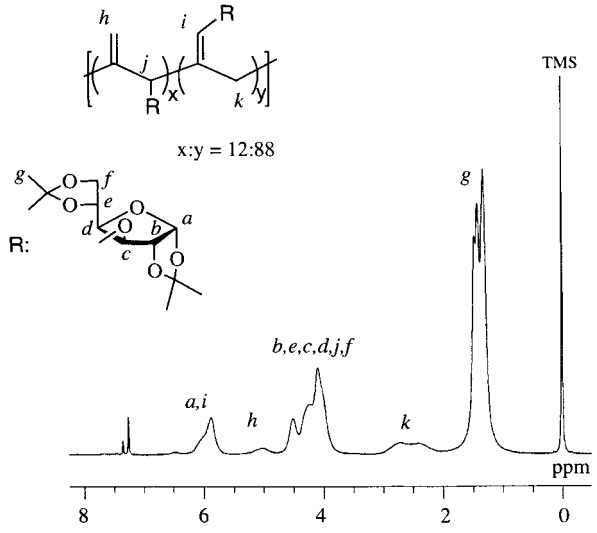

Figure 2. ^{1}H NMR spectrum of **3** (M_n = 12,400, M_w/M_n = 1.07) in $CDCl_3$.

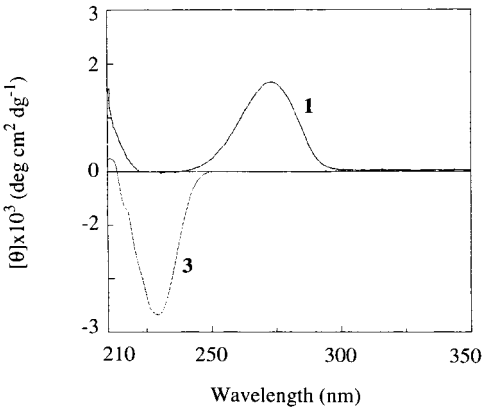

Figure 3. CD spectra of **1** and **3** (M_n = 12,400, M_w/M_n = 1.07) measured in THF (0.1 g/mL).

229 nm for the polymer ($[\alpha]^{25}_D$ −29.6° (*c* 0.1, THF)), suggesting the presence of the chiral main chain conformation of the polymer.[18]

As described above, the living coordination polymerization of an acetal-protected allenyl glycoside has been achieved successfully by [(π-allyl)NiOCOCF$_3$]$_2$/PPh$_3$ catalyst, giving rise a polymer with predictable molecular weight and narrow molecular weight distribution (M_w/M_n < 1.07) in high yield. The chiral polymer thus obtained is supposed to have a certain ordered chiral conformation in solution. Application of the polymer such as chiral recognition and design of well-defined glycopolymers with various sugar moieties are in progress.

Supporting Information Available: Figure representing the GPC profiles for the postpolymerization experiment. This material is available free of charge via the Internet at http://pubs. acs. org.

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(14) The monomer (**1**) was prepared by the propargylation of 1,2;5,6-di-*O*-isopropylidene-α-D-glucofuranoside followed by the base-catalyzed isomerization and was purified by silica gel column chromatography (eluent: benzene/EtOAc, 10:1). IR (neat): 3588, 3050, 2988, 2938, 2895, 1954, 1724, 1445, 1375, 1256, 1198, 1165, 1074, 1022, 889, 849 cm^{-1}. ^{1}H NMR (δ, $CDCl_3$): 6.70 (1H, t, J = 5.6 Hz, O−C*H*=), 5.87 (1H, d, J = 3.6 Hz, 1-H), 5.56, 5.53 (2H, 2d, J = 6.0 Hz, C=C*H*$_2$) 4.59 (1H, d, J = 3.6 Hz, 2-H), 4.34−4.04 (5H, m, 3,6-H), 1.50, 1.43, 1.35, 1.31 (12H, 4s, 2 × $O_2C(CH_3)_2$). ^{13}C NMR (δ, $CDCl_3$): 200.5, 128.3, 120.2, 111.9, 105.1, 92.1, 82.1, 80.3, 80.0, 77.3, 77.0, 76.7, 72.3, 67.0, 26.9, 26.8, 26.3, 25.3.

(15) A typical polymerization was conducted as follows: to a toluene solution of Ni(COD)$_2$ (0.10 M, 0.20 mL, 0.02 mmol), was added a toluene solution of allyl trifluoroacetate (1.0 M, 0.020 mL, 0.02 mmol) under nitrogen and the mixture was stirred at ambient temperature. After a toluene solution of PPh$_3$ (1.0 M, 0.020 mL, 0.02 mmol) was added to the resulted orange solution, **1** in toluene (0.49 M, 3.20 mL, 1.57 mmol) was added and allowed to react for 24 h. The polymer was obtained in 83% yield (0.386 g) by precipitation with *n*-hexane; IR (neat) 3588, 2988, 2938, 1670, 1458, 1375, 1254, 1217, 1146, 1074, 1022, 847, 733 cm^{-1}.

(16) As we described previously in ref 13d, the initiation efficiency of the present polymerization is also expected to be quantitative. The lower molecular weights observed in GPC might be caused by the calibration with polystyrene standards. Determination of the absolute molecular weight of **3** is currently being investigated.

(17) The increase of the 2,3-polymerization unit without PPh$_3$ is in accordance with the previous results on the polymerization of alkoxyallenes. See, ref 13, parts c and f.

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MA001344C