

Polymer Communication

Hydrogen-bond-assisted isotactic-specific radical polymerization of *N*-isopropylacrylamide with pyridine *N*-oxide

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Abstract

Radical polymerization of *N*-isopropylacrylamide (NIPAAm) in CHCl_3 at low temperatures in the presence of pyridine *N*-oxide (PNO) was investigated. An isotactic poly(NIPAAm) with *meso* diad content of 61% was successfully prepared at -60°C in the presence of a two-fold amount of PNO. Thermodynamic analysis suggested that the isotactic-specificity was entropically induced, probably due to conformational fixation near the propagating chain-end through coordination by PNO.

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1. Introduction

Recently, preparations of isotactic poly(*N*-isopropylacrylamide)s [poly(NIPAAm)s] via anionic and radical polymerizations were reported. An anionic polymerization of trimethylsilyl-protected NIPAAm derivative with $t\text{-C}_4\text{H}_9\text{Li}/n\text{-(C}_4\text{H}_9)_3\text{Al}$ in toluene at -40°C followed by deprotection gave an isotactic poly(NIPAAm) with *meso* (*m*) diad content of 97% [1]. A radical polymerization of NIPAAm in methanol at -20°C in the presence of rare-earth metal trifluoromethanesulfonates (triflates) such as yttrium triflate gave directly an isotactic poly(NIPAAm) with *m* diad content of 92% [2,3]. In both cases, metal complex plays an important role for the stereocontrol. In general, however, isolation of the resulting polymer from metal compounds is difficult due to the strong interaction between the metal compounds and the obtained polymer. Thus, the development of metal-free stereospecific polymerization system has been strongly desired.

We have reported that a hydrogen-bonding interaction between NIPAAm and Lewis base is available for controlling stereospecificity of radical polymerization of NIPAAm in toluene at low temperatures [4–8]. The hydrogen-bond-induced stereospecificity depended on polymerization

conditions such as polymerization temperature and added Lewis bases. For instance, *O*-coordinating Lewis bases such as phosphoric acid derivatives were predominantly effective for syndiotactic-specific polymerization, whereas *N*-coordinating Lewis bases such as amines hardly affected the stereospecificity [4,5]. Among the examined Lewis bases, hexamethylphosphoramide (HMPA) exhibited the highest stereocontrolling power for preparation of syndiotactic poly(NIPAAm): syndiotacticity of the poly(NIPAAm) obtained with HMPA reached up to *racemo* (*r*) diad = 72% [6]. The highest syndiotacticity of poly(NIPAAm) so far reported is $r = 75\%$, the polymer with which was prepared by an anionic polymerization of *N*-isopropyl-*N*-methoxymethylacrylamide with alkyllithium/diethylzinc followed by deprotection [9]. Thus, we succeeded in syndiotactic-specific polymerization of NIPAAm by radical mechanism, being comparable with that by anionic one.

In 1994, enantioselective addition of allylic trichlorosilanes to aldehydes in the presence of chiral phosphoramides was reported [10]. Since then, it has been reported that Lewis bases such as not only phosphoramides but also pyridine *N*-oxide derivatives can be used as an efficient organocatalyst in asymmetric allylation reactions [11–17]. The fact prompted us to investigate in more detail the effect of Lewis bases other than phosphoric acid derivatives including HMPA on the stereospecificity of NIPAAm polymerization.

So, we started investigating the effect of simple pyridine *N*-oxide (PNO) on the stereospecificity of NIPAAm polymerization. An unexpected result that isotactic-rich poly(NIPAAm)s can be obtained by adding PNO instead of HMPA

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was obtained. This result seems to be the first step toward the methodology of direct preparation of isotactic poly(NIPAAm) under the metal free conditions. Therefore, we report here the preliminary results on the hydrogen-bond-assisted isotactic-specific NIPAAm polymerization.

2. Experimental section

N-Isopropylacrylamide (NIPAAm) (Tokyo Kasei Kogyo Co.) was recrystallized from hexane–benzene mixture. CHCl_3 was distilled before use. Tri-*n*-butylborane (*n*- Bu_3B) as a tetrahydrofuran (THF) solution (1.0 M) (Aldrich Chemical Co.) and PNO (Tokyo Kasei Kogyo Co.) were used without further purification for polymerization reaction.

Typical polymerization procedure is as follows; NIPAAm (0.628 g, 5.5 mmol) was dissolved in CHCl_3 to prepare the 5 mL solution of 1.1 mol/L. Four milliliters of the solution was transferred to the glass ampoule and cooled at 0 °C. The polymerization was initiated by adding *n*- Bu_3B solution (0.44 mL) into the monomer solution. After 48 h, the reaction was terminated with a small amount of THF solution of 2,6-di-*t*-butyl-4-methylphenol at polymerization temperature. The polymerization mixture was poured into a large amount of diethyl ether, and the precipitated polymer was collected by filtration or centrifugation, and dried in vacuo. The polymer yield was determined gravimetrically.

The ^1H NMR spectra were measured on an EX-400 spectrometer (JEOL Ltd) operated at 400 MHz. The tacticities of the poly(NIPAAm)s were determined from ^1H NMR signals due to methylene group in main chain measured in deuterated dimethyl sulfoxide ($\text{DMSO}-d_6$) at 150 °C. The molecular weights and molecular weight distributions of the polymers were determined by size exclusion chromatography (SEC) (HLC 8220 instrument (Tosoh Co.)) equipped with TSK gels (SuperHM-M and SuperHM-H (Tosoh Co.)) using dimethylformamide (LiBr 10 mmol/L) as an eluent at 40 °C ([polymer] = 1.0 mg/mL, flow rate = 0.35 mL/min). The SEC

chromatogram was calibrated with standard polystyrene samples.

3. Results and discussion

Table 1 summarizes the results of radical polymerization of NIPAAm in CHCl_3 at low temperatures in the absence or presence of PNO. The polymer yield decreased with a decrease in polymerization temperature in the absence of PNO, probably because NIPAAm and/or poly(NIPAAm) were precipitated during the polymerization reaction at lower temperatures. Interestingly, the polymer yield increased by decreasing the temperature in the presence of PNO, although the addition of PNO remarkably reduced polymer yield at higher temperatures. The tendency was enhanced with an increase in the added amount of PNO. Fig. 1 shows the expanded ^1H NMR spectra of amide proton (*N*-H) and vinyl protons ($\text{H}_2\text{C}=\text{CH}-$) of NIPAAm alone ($[\text{NIPAAm}]_0 = 0.25$ mol/L) and NIPAAm mixed with an equimolar amount of PNO ($[\text{NIPAAm}]_0 = [\text{PNO}]_0 = 0.25$ mol/L) in chloroform-*d* at 0 °C. The signals due to not only the amide proton but also vinyl protons of NIPAAm monomer showed downfield shifts in the presence of PNO as compared with that in the spectrum of NIPAAm alone. These results indicate that PNO forms a complex with NIPAAm monomer through a hydrogen-bonding interaction as well as HMPA. Thus, the reason for the temperature dependence of polymer yield is not clear at this time, but it was suggested that, through a hydrogen-bonding interaction, PNO brought about some unique effect different from that by HMPA.

Fig. 2 demonstrates the relationship between the polymerization temperature and *m* diad of the poly(NIPAAm)s obtained in the absence or presence of PNO. The stereoregularities of the poly(NIPAAm)s obtained in the absence of PNO were almost atactic regardless of the polymerization temperature. Similar result was observed also in the polymerization in toluene [5,7]. Thus, it was confirmed that the kind of solvents hardly affects the stereospecificity of NIPAAm

Table 1
Radical polymerization of NIPAAm in CHCl_3 for 48 h at various temperatures in the absence or presence of PNO

Run	[PNO] ₀ (mol/L)	Temp. (°C)	Yield (%)	Tacticity/% ^a		$M_n^b \times 10^4$	M_w^b M_n
				<i>m</i>	<i>r</i>		
1	0.0	0	>99	45	55	0.98	1.4
2	0.0	−20	>99	46	54	1.33	1.5
3 ^c	0.0	−40	96	47	53	1.26	1.6
4 ^c	0.0	−60	26	46	54	1.69	1.6
5	1.0	0	27	48	52	0.81	1.3
6	1.0	−20	51	50	50	0.97	1.3
7	1.0	−40	60	52	48	1.12	1.4
8	1.0	−60	62	54	46	1.26	1.5
9	2.0	0	10	50	50	0.59	1.2
10	2.0	−20	26	52	48	0.76	1.2
11	2.0	−40	40	56	44	0.96	1.3
12	2.0	−60	58	61	39	1.11	1.5

[NIPAAm]₀, 1.0 mol/L; [*n*- Bu_3B]₀, 0.10 mol/L.

^a Determined by ^1H NMR signals due to methylene group.

^b Determined by SEC (polystyrene standards).

^c Monomer, polymer or both were precipitated during a polymerization reaction.

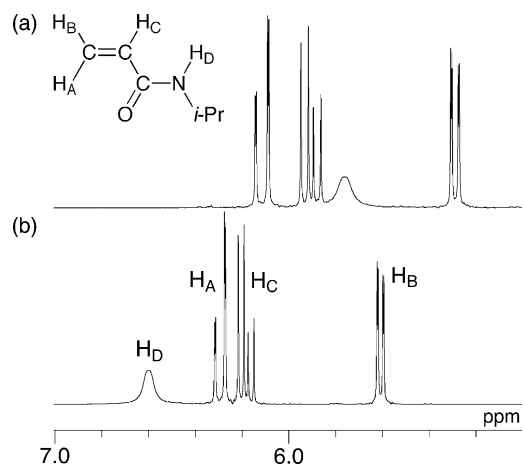


Fig. 1. Expanded ^1H NMR spectra of amide proton and vinyl protons of (a) NIPAAm and (b) an equimolar mixture of NIPAAm and PNO. Measured in chloroform- d at 0°C .

polymerization in the absence of Lewis bases. The addition of PNO, however, increased isotacticity of the obtained poly(NIPAAm)s. Both lowering the polymerization temperature and increasing the added amount of PNO enhanced the isotactic-specificity and poly(NIPAAm) with $m=61\%$ was obtained at -60°C in the presence of a two-fold amount of PNO. This means that PNO induced not syndiotactic-specificity but isotactic-specificity, although PNO would work as O -coordinating Lewis base as well as HMPA. Fig. 3 displays ^1H NMR spectra of poly(NIPAAm)s prepared at -60°C in the absence or presence of a two-fold amount of PNO. The isotacticity of the latter evidently increased in comparison with that of the former, although the isotacticity was not extremely high as compared with those obtained by an anionic polymerization of the protected-NIPAAm monomer [1] or a radical polymerization of NIPAAm in the presence of Lewis acids [2,3].

In order to evaluate the difference in activation enthalpy (ΔH^\ddagger) and the difference in activation entropy (ΔS^\ddagger) between isotactic and syndiotactic propagations, we conducted

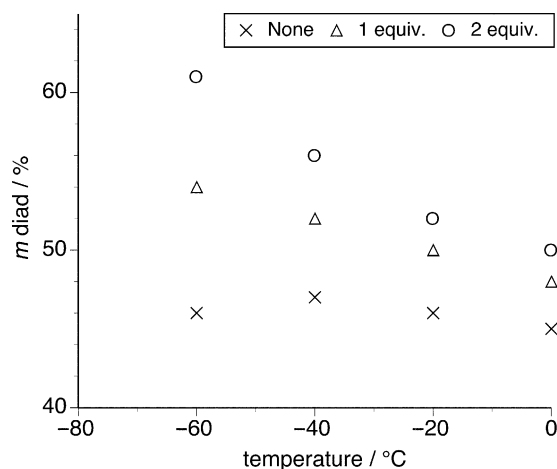


Fig. 2. Relationship between the polymerization temperature and m diad content of poly(NIPAAm) prepared in CHCl_3 at low temperatures in the absence or presence of PNO.

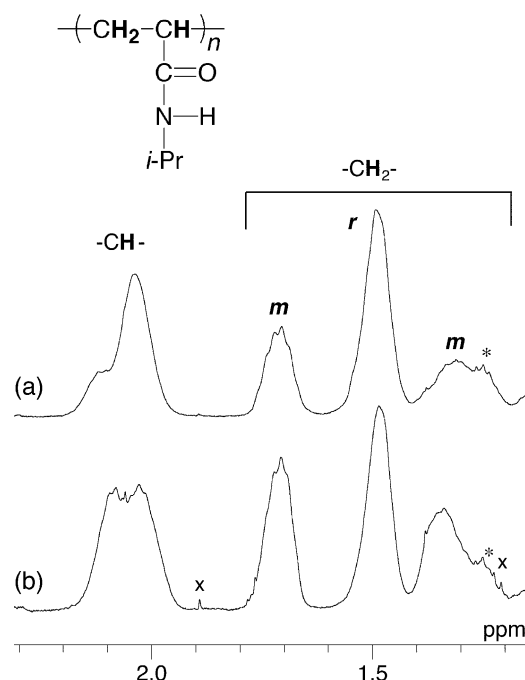


Fig. 3. Expanded ^1H NMR spectra of main-chain methine and methylene groups of poly(NIPAAm)s prepared in CHCl_3 at -60°C in the absence (a) or presence (b) of a two-fold amount of PNO, as measured in $\text{DMSO}-d_6$ at 150°C . * denotes ^{13}C satellite peak of $(\text{CH}_3)_2\text{CH}-$ and x denotes impurities.

Fordham's plots for NIPAAm polymerization in the absence or presence of PNO (Fig. 4). The values were determined by the linear dependences according to the following Eq. (1): [18]

$$\ln\left(\frac{P_i}{P_s}\right) = \frac{\Delta S_i^\ddagger - \Delta S_s^\ddagger}{R} - \frac{\Delta H_i^\ddagger - \Delta H_s^\ddagger}{RT} \quad (1)$$

where P_i and P_s denote the mole fractions of isotactic and syndiotactic diads, respectively. In Table 2, the obtained values are summarized together with those obtained for syndiotactic-specific polymerization of NIPAAm in the presence of HMPA [5]. Both values decreased with an increase in the added amount of PNO. The absolute values of the $\Delta S_i^\ddagger - \Delta S_s^\ddagger$ were quite larger than those with HMPA, whereas the absolute

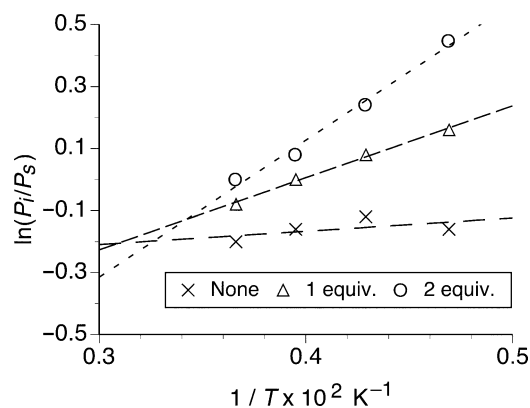


Fig. 4. Fordham's plots for radical polymerization of NIPAAm in the absence or presence of PNO.

Table 2
Activation parameters for NIPAAm polymerization in the absence or presence of PNO

PNO	$\Delta H_1^\ddagger - \Delta H_S^\ddagger$ (kJ/mol)	$\Delta S_1^\ddagger - \Delta S_S^\ddagger$ (J/mol K)
None	-0.36 ± 0.36	-2.8 ± 1.5
1 equiv	-1.93 ± 0.10	-7.7 ± 0.4
2 equiv (HMPA)	-3.67 ± 0.30	-13.6 ± 1.3
1 equiv ^a	1.85 ± 0.14	2.7 ± 0.5
2 equiv ^a	2.31 ± 0.09	3.7 ± 0.3

^a Data taken from Ref. [5].

values of the $\Delta H_1^\ddagger - \Delta H_S^\ddagger$ were comparable with those with HMPA. Thus, it was assumed that the isotactic-specificity was entropically induced, probably because conformation near the propagating chain-end was fixed through hydrogen-bond-assisted coordination by PNO.

4. Conclusion

Radical polymerization of NIPAAm was examined in the presence of PNO. We succeeded in a significant induction of isotactic-specificity of NIPAAm polymerization by adding PNO, although phosphoric acid derivatives such as HMPA predominantly induce syndiotactic-specificity. These results indicate that proper selection of the added Lewis base allows ones to control the stereospecificity of NIPAAm polymerization even under the metal free conditions. Further work is now under way to extend the present results to higher level of stereoregulation and to reveal the mechanism of the hydrogen-bond-assisted isotactic-specific propagation.

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