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Facile Synthesis and Thermoresponsive Behaviors of a Well-Defined Pyrrolidone Based Hydrophilic Polymer

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ABSTRACT: A well-defined pyrrolidone based thermoresponsive polymer, poly[*N*-(2-methacryloyloxyethyl) pyrrolidone] (PNMP), was synthesized via reversible addition−fragmentation chain transfer radical polymerization or RAFT polymerization of *N*-(2-methacryloyloxyethyl) pyrrolidone monomer in methanol under a mild *visible light radiation* at 30 °C. The average molecular weights and polydispersity indices of PNMP polymers were characterized by gel permeation chromatography (GPC) and static light scattering analysis. The kinetic studies indicated that this RAFT polymerization exhibited a well-controlled behavior. The living character of this RAFT polymerization was confirmed by the facile synthesis of a series of well-defined PNMP-based block copolymers via RAFT polymerization under this mild visible light radiation at 30 °C using the above-synthesized PNMP polymer as a macromolecular chain transfer agent. Temperature-variation ^{1}H NMR unambiguously revealed that the PNMP polymer with weight-average molecular weight (M_w) of 105.4 kg mol^{-1} and polydispersity index (M_w/M_n) of 1.11 was molecularly dissolved in D_2O at ambient temperature, e.g. 22 °C. Upon elevating the solution temperature, the dehydration process of this fully hydrated PNMP polymer was triggered at 46.1 °C, leading to a dramatic decrease of integral ratios of proton resonance signals of PNMP to that of D_2O. Further elevating the solution temperature to 51.9 °C led to a sharp phase separation of PNMP polymer from aqueous solution. Laser light scattering analyses demonstrated that the cloud point of the PNMP polymer decreased with molecular weight in the M_w range of 20.6–105.4 kg mol^{-1}. Moreover, this PNMP polymer exhibited a remarkably reversible thermoresponsive dehydration/hydration and phase transition behaviors in aqueous solution. Unlike what was observed in PNIPAM aqueous solution, no hysteresis phenomenon was observed in PNMP aqueous solution during one heating-and-cooling cycle.

Introduction

Poly(*N*-vinyl pyrrolidone) (PVP) is a water-soluble polymer that has excellent biocompatibility,[1] strong coordination ability,[2–5] etc. It has been extensively utilized as a metal nanoparticle or nanorod stabilizer,[6,7] carbon nanotube dispersant,[8,9] hemocompatible surface-modifier,[10] drug delivery carriers,[11,12] and for bioconjugation and surface ligand immobilization.[13] Many properties of PVP polymer derive from its pyrrolidone functionalities. However, to the best of our aware, the pyrrolidone-based polymers are quite limited.[14,15] Clearly, developing a new type of pyrrolidone-based stimulus-responsive polymers is desirable from both academic and industrial point of views. This will enhance the properties of pyrrolidone-based polymer for more fantastic and sophisticated applications.

In recent years, much effort was devoted to the hydrophilic polymers that have a reversible temperature-dependent solubility behavior, i.e., thermoresponsive behavior.[16] For example, poly(*N*-isopropylacrylamide) (PNIPAM) can be molecularly dissolved in water at low temperature but can be rapidly phase-separated at 32 °C.[17] This critical temperature was named as a lower critical solution temperature (LCST). The phase separation was induced by either dissimilarity in the free volume of polymer and solvent[18,19] or hydrophobic bond formation in aqueous solution.[20] This phase transition may be adjusted by altering the hydrophobic moieties. For example, Poly(*N*-vinyl caprolactam) (PVCL) contains a seven-membered lactam, which has two methylene groups more than that of pyrrolidone of the water-soluble PVP, i.e., PVCL is more hydrophobic than PVP. Thus, PVCL molecularly dissolves into an aqueous solution at lower temperature, but phase separates over the LCST of 31 °C.[21–23]

Recently, Gan and co-workers[24,25] reported that poly(*N*-acryloyl-*N*′-propylpiperzine) exhibited a LCST of 37 °C in aqueous solution. However, if its *N*′-propyl was replaced by a less hydrophobic *N*′-methyl or *N*′-ethyl group, it was completely water-soluble and no thermoresponsive behavior could be detected on elevating the solution temperature.[24] Accordingly, it is reasonable to expect that inserting a hydrophobic spacer to the water-soluble PVP polymer might trigger a thermoresponsive behavior, without loss of the versatile performance of pyrrolidone functionalities.

Reversible addition−fragmentation chain transfer radical polymerization or RAFT polymerization is a powerful tool for the synthesis of well-defined polymers.[26–30] Recently, RAFT polymerization was extensively utilized for the synthesis of stimuli-responsive polymers.[31–39] Enlightened by the pioneer studies on UV-initiating RAFT polymerization separately by Pan and co-workers,[40] Quinn et al.,[41,42] more recently Barner and co-workers,[43] and our group[44] have developed a rapid and well-controlled ambient temperature RAFT polymerization under a mild long-wave UV–visible radiation. Our studies demonstrated that the living character of this ambient temperature RAFT polymerization strongly depended on the wave range of UV–visible radiation.[45] This approach was successful utilized for the highly efficient and well-controlled ambient temperature RAFT polymerization of styrenic-based monomers.[46] Most recently, we reported a rapid and well-controlled ambient temperature RAFT polymerization under a mild solar radiation in a visible wave range over 400 nm.[47] This approach provided a powerful tool for the facile synthesis of well-defined pyrrolidone-based polymers.

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This paper describes a novel design and facile synthesis of a well-defined pyrrolidone based thermoresponsive polymer, i.e., poly[*N*-(2-methacryloylxyethyl) pyrrolidone] (PNMP). This polymer was readily synthesized via ambient temperature RAFT polymerization of *N*-(2-methacryloyloxyethyl) pyrrolidone monomer in methanol under a mild *visible light radiation* at 30 °C. The controlled behavior of this RAFT polymerization was studied using ^{1}H NMR and gel permeation chromatography (GPC) analysis. To confirm the living character of this RAFT polymerization, a series of PNMP-based block copolymers were synthesized via chain-extending RAFT copolymerization using an above-synthesized PNMP as a macromolecular chain transfer agent under this mild visible light radiation at 30 °C. The temperature dependence of its molecular interaction and phase transition of PNMP polymers in aqueous solution were studied by temperature-variation ^{1}H NMR and laser light scattering analyses. The molecular weight dependence of its cloud point was also studied using laser light scattering analysis.

Experimental Section

Materials. 2-Cyanoprop-2-yl(4-fluoro)dithiobenzoate (CPFDB) was synthesized according to the literature procedure.[48] (2,4,6-Trimethylbenzoyl)diphenylphosphine oxide (TPO, 97%) was purchased from Runtec Chem. Co. and used as received. *N*-Hydroxyethyl pyrrolidone (95%) was purchased from Jianhua Co. Ltd. and was distilled under reduced pressure. *N,N′*-(Dimethylamino)ethyl methacrylate (DMA, Alfa Aesar, 98%) and poly(ethylene glycol) monomethacrylate (PEGMA, Aldrich, $M_n = 475$ g mol^{-1}, $M_w/M_n = 1.03$) were separately passed through a basic alumina column to remove inhibitor and stored at −20 °C. Glycidyl methacrylate (GMA, Yuanji Chem. Co. Ltd., 98%) was dried over 4 Å molecular sieves overnight, distilled under reduced pressure, and stored at −20 °C. 1,3-Propanesultone (J & K, 98%) was used as received. JB400 filters were purchased from Yaguang Sci. Edu. Equip. Co.

Radiation source. A mercury vapor lamp emitting separately at 254, 302, 313, 365, 405, 436, 545, and 577 nm, was employed as the radiation source. JB400 filters were utilized to cut off the shorter-wave UV radiation below 400 nm and adjust the light intensity. Thus, a mild visible light radiation emitting separately at 405, 436, 545, and 577 nm, with a mild intensity of 250 μW cm^{-2} at 420 nm, was achieved. The light intensity was measured on a UV-A radiometer equipped with a 420 nm sensor.

Synthesis of *N*-(2-Methacryloyloxyethyl) Pyrrolidone (NMP) Monomer. *N*-Hydroxyethyl pyrrolidone (32.25 g, 0.25 mol), triethylamine (30.30 g, 0.30 mol), and 60.0 mL anhydrous chloroform were charged in a 500 mL dried round-bottom flask. The flask was immersed in a thermostatic ice bath at 0 °C. Methacryloyl chloride (28.74 g, 0.275 mol) solution in 90.0 mL anhydrous chloroform was added dropwise to this flask in 2 h. The mixture was stirred at 10 °C for 12 h. The white ammonium salt was removed by filtration. The solution was concentrated by rotary evaporation and subsequently extracted using 5% Na_2CO_3 solution, saturated NaCl solution, and distilled water until neutralized. The solution was dried over anhydrous $MgSO_4$ and distilled under vacuum to give a transparent targeted monomer. Weight = 28.50 g, yield = 58%. ^{1}H NMR (δ, D_2O): 6.14 and 5.76 (2H, $CH_2{=}CHCH_3$), 4.40 (2H, $COOCH_2CH_2$), 3.65 (2H, $COOCH_2CH_2$), 3.60 (2H, $NCOCH_2CH_2CH_2$ in pyrrolidone ring), 2.45 (2H, $NCOCH_2CH_2CH_2$ in pyrrolidone ring), 2.08 (2H, $NCOCH_2CH_2CH_2$ in pyrrolidone ring), 1.95 (3H, $CH_2{=}CHCH_3$).

Ambient Temperature RAFT Polymerization of NMP Monomer under Visible Light Radiation. A protocol for ambient temperature RAFT polymerization of NMP monomer under visible light radiation is as follows: NMP (5.91 g, 30.0 mmol), CPFDB (71.7 mg, 0.3 mmol), TPO (26.1 mg, 0.075 mmol), and 2.60 g anhydrous methanol were charged in a 25 mL round-bottom flask capped with rubber septa. The solution was deoxygenated by purging with highly pure nitrogen gas for 40 min. The flask was immersed in a thermostatic water bath at 30 °C, under visible light radiation. Samples were collected using deoxygenated syringes at predetermined intervals and quenched by exposure to air and addition of trace amounts of hydroquinone inhibitor. One portion of sample was diluted in D_2O for ^{1}H NMR analysis on a 400 MHz Bruker AV-400 NMR spectrometer, and another portion was diluted in *N,N*-dimethylformamide (DMF) for GPC measurement. The NMP monomer conversions were assessed by ^{1}H NMR analysis according to eq 1, where $I_{6.14}$ is the integral of proton resonance signal at $\delta = 6.14$ ppm (one of $CH_2{=}CHCH_3$ of NMP monomer), $I_{4.20-4.40}$ is the integral of proton resonance signals at $\delta = 4.20$–4.40 ppm ($COOCH_2CH_2$ of PNMP polymer and NMP monomer).

$$\text{Conversion} = \frac{I_{4.20-4.40} - 2I_{6.14}}{I_{4.20-4.40}} \qquad (1)$$

Synthesis of PNMP-based Block Copolymers via Ambient Temperature RAFT Polymerization under Visible Light Radiation. PNMP-*b*-PDMA copolymer was synthesized as follows: an above-synthesized PNMP polymer ($M_{w,SLS} = 13.3$ kg mol^{-1}, $M_w/M_n = 1.12$) was utilized as a macromolecular chain transfer agent (macro-CTA). PNMP macro-CTA (0.59 g, 0.05 mmol), DMA monomer (2.355 g, 15 mmol), TPO (1.7 mg, 0.005 mmol) and 2.0 g methanol were charged to a 25 mL round-bottom flask capped with rubber septa. The solution was deoxygenated by purging with highly pure nitrogen gas for 40 min. The flask was immersed in a thermostatic water bath at 30 °C under visible light radiation for 5 h. The polymerization was ceased by exposure to air and addition of trace amounts of hydroquinone. The resultant copolymer was precipitated from large excess of hexane, dissolved in water, and freeze-dried overnight. ^{1}H NMR, 41% DMA monomer conversion; weight = 1.41 g; yield = 91%; and GPC, $M_n = 44.5$ kg mol^{-1}, $M_w/M_n = 1.10$.

The procedures for the synthesis of PNMP-*b*-PGMA and PNMP-*b*-PPEGMA copolymers were similar to that described above except that GMA or PEGMA monomer was.

Zwitterionization of Tertiary Amino Groups of PNMP-*b*-PDMA Copolymer was carried out according to the literature precedures.[49] First, 1.00 g PNMP$_{59}$-*b*-PDMA$_{61}$ (2.85 mmol DMA units) was dissolved in 20 mL of anhydrous dioxane in a 50 mL dried round-bottom flask equipped with a magnetic stir bar and capped with a rubber septum. 1,3-Propanesultone (0.36 g, 3.13 mmol) was added dropwise into the flask with stirring at 25 °C overnight. The residual 1,3-propanesultone was removed by Soxhlet extraction using tetrahydrofuran solvent. The polymer was dissolved in water and freeze-dried overnight. Disappearance of proton resonance signal at $\delta = 2.70$ ppm ($COOCH_2CH_2$ in PDMA units) suggested the essentially complete betainization.

Light Scattering Measurements. The weight-average molecular weights (M_w) of PNMP polymers were assessed by static light scattering (SLS) measurements on a Brookhaven instrument equipped with a 100 mW solid-state laser emitting at 532 nm, a BI-200SM goniometer, and a BI-9000 digital correlator scanning from 30° to 135° using a Zimm plots mode. BI-DNDC differential refractometer was used to determine the *dn*/*dc* of PNMP polymer solutions in methanol.

The temperature dependence of light scattering intensity of PNMP polymer aqueous solution was also studied on this Brookhaven instrument using a BI-TCD temperature controller to precisely adjust the solution temperature. The solution was heated or cooled in steps and stabilized at each predetermined temperature for 2 min. The light scattering intensities at an angle of 90° were recorded.

GPC measurements were performed on a PL-GPC120 setup equipped with a column set consisting of two PL gel 5 μm MIXED-D columns (7.5 × 300 mm, effective molecular weight range of 0.2–400.0 kg mol^{-1}) using *N,N*-dimethylformamide that contained 0.01 M LiBr as the eluent at 80 °C at a flow rate of 1.0 mL min^{-1}. Narrowly distributed polystyrene standards in the molecular weight range of 0.5–7500.0 kg mol^{-1} (PSS, Mainz, Germany) were utilized for calibration.

Results and Discussion

Recently, much effort has been devoted to the synthesis of well-controlled poly(*N*-vinyl pyrrolidone) (PVP) polymer,[50–52]

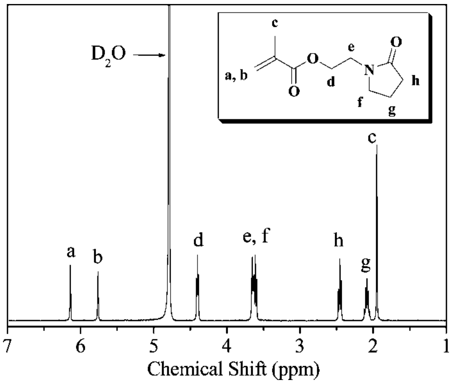

Figure 1. ^{1}H NMR spectrum of *N*-(2-methacryloyloxyethyl) pyrrolidone monomer in D$_2$O solution.

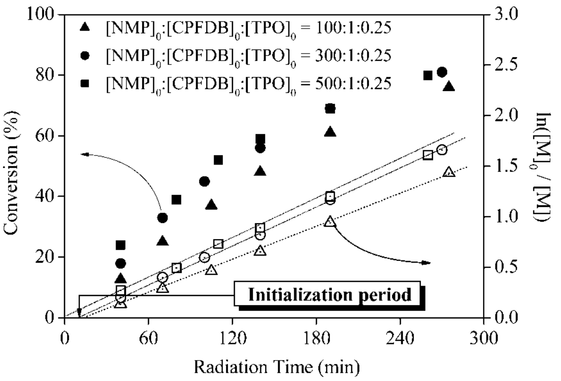

Figure 2. Kinetic curves of RAFT polymerization of *N*-(2-methacryloyloxyethyl) pyrrolidone (NMP) monomer using a 2-cyanoprop-2-yl(4-fluoro)dithiobenzoate (CPFDB) chain transfer agent and a (2,4,6-trimethylbenzoyl)diphenylphosphine oxide (TPO) photoinitiator at (▲) [NMP]$_0$:[CPFDB]$_0$:[TPO]$_0$ = 100:1:0.25, (●) [NMP]$_0$:[CPFDB]$_0$:[TPO]$_0$ = 300:1:0.25, (■) [NMP]$_0$:[CPFDB]$_0$:[TPO]$_0$ = 500:1:0.25, in 30 wt % methanol, under a visible light radiation with a mild intensity of 250 μW cm^{-2} at 420 nm at 30 °C.

due to its excellent properties that are derived from the pyrrolidone functionalities. However, to the best of our knowledge, only the present pyrrolidone-based polymer with narrow molecular weight distribution was well synthesized. Given the unique properties and extensive applications of pyrrolidone-based polymers, design and facile synthesis of a new type of pyrrolidone-based stimulus-responsive polymer is desirable.

A pyrrolidone-based monomer, *N*-(2-methacryloyloxyethyl) pyrrolidone (NMP) was synthesized via direct esterification of *N*-hydroxyethyl pyrrolidone by methacryloyl chloride. As shown in Figure 1, the integral ratio of proton resonance signals of $I_{6.14}:I_{5.76}:I_{4.40}:I_{3.60-3.70}:I_{2.45}:I_{2.08}:I_{1.95}$ equals to 1:1:2:4:2:2:3. This confirmed that the targeted monomer was synthesized. Moreover, except for the proton signal of D$_2$O, no proton resonance signal of other impurities could be detected, suggesting the high purity of this monomer.

Kinetic Studies on RAFT Polymerization of NMP Monomer under Visible Light Radiation at 30 °C. As shown in Figure 2, at feed molar ratios of [NMP]$_0$:[CPFDB]$_0$:[TPO]$_0$ ranging from 100:1:0.25 to 500:1:0.25, the semilogarithmic kinetic curves exhibited a linear tendency, suggesting a first-order kinetic character of this RAFT polymerization. This indicated that the radical concentration was constant and steady during RAFT process.

Similar to ambient temperature RAFT polymerization of glycidyl methacrylate (GMA) monomer under visible light radiation,[53] increasing the feed molar ratio of [NMP]$_0$:[CPFDB]$_0$:[TPO]$_0$ from 100:1:0.25 to 300:1:0.25 led to a slope increase of the semilogarithmic kinetic curves. This suggested an acceleration of the overall polymerization rate. Further, increasing [NMP]$_0$:[CPFDB]$_0$:[TPO]$_0$ to 500:1:0.25 led to a slight decrease of overall polymerization rate, particularly at relatively high monomer conversions, over 50%, presumably due to the significant solution viscosity increase caused by large molecular weights of PNMP polymers at high monomer conversions. However, on increasing [NMP]$_0$:[CPFDB]$_0$:[TPO]$_0$ from 100:1:0.25 to 300:1:0.25 and finally to 500:1:0.25, the initialization period[54,55] significantly shortened from 17 min to 11 min and finally to 0 min, respectively. This indicated that increasing the feed molar ratio of [NMP]$_0$:[CPFDB]$_0$:[TPO]$_0$ significantly suppressed the retardation effect of this ambient temperature RAFT polymerization.

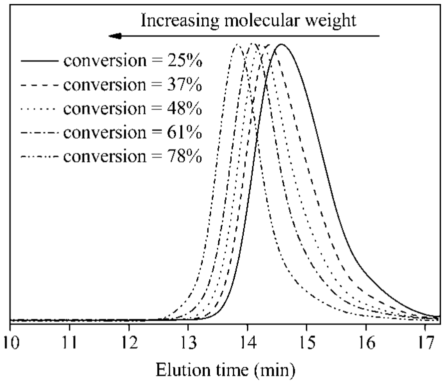

Figure 3. GPC trace evolution of poly[*N*-(2-methacryloyloxyethyl) pyrrolidone] (PNMP) polymers synthesized via RAFT polymerization of NMP monomer using a 2-cyanoprop-2-yl-(4-fluoro) dithiobenzoate (CPFDB) chain transfer agent and a (2,4,6-trimethylbenzoyl)diphenylphosphine oxide (TPO) photoinitiator at a [NMP]$_0$:[CPFDB]$_0$:[TPO]$_0$ = 100:1:0.25 in 30 wt % methanol under visible light radiation with a mild intensity of 250 μW cm^{-2} at 420 nm at 30 °C.

As shown in Figure 3, on increasing NMP monomer conversion, the GPC traces of PNMP polymers clearly shifted to the larger molecular weight side over the duration of the RAFT polymerization. Moreover, these GPC traces were significantly monomodal and reasonably symmetrical. This indicated a well-controlled behavior of this ambient temperature RAFT polymerization.

As shown in Figure 4, the number-average molecular weights (M_n) of PNMP polymers linearly increased with monomer conversions during this RAFT polymerization. Moreover, their polydispersity indices (M_w/M_n) were reasonably narrow at the early stage of RAFT polymerization, which fell to around 1.10 over 45% monomer conversions. This further confirmed a well-controlled behavior of this RAFT polymerization. Clearly, these M_n values were clearly overestimated by GPC analysis. These calibration errors were caused by using polystyrene standards, the polarity of which is much lower than that of the PNMP polymer. However, unreliable M_n values were assessed from ^{1}H NMR analysis due to the significant calculation errors caused by the large proton ratio of PNMP units to its CTA residues. Thus, the weight-average molecular weights (M_w) of PNMP polymers were assessed by the static light scattering (SLS) method prior to the investigation of their thermoresponsive behaviors in aqueous solution.

As shown in Figure 5, no signal at $\delta = 5.76$ ppm (one of $CH_2{=}CCH_3$ of NMP monomer) could be detected, indicating that NMP monomer was completely removed. The integral ratio of proton resonance signals of $I_{4.10}:I_{3.50-3.70}:I_{2.45}:I_{2.10}$ equals to 1:2:1:1, within analysis errors. These confirmed the intact structure of this targeted pyrrolidone-based polymer. Moreover, no proton resonance signals due to impurities could be detected, indicating the high purity of this PNMP polymer.

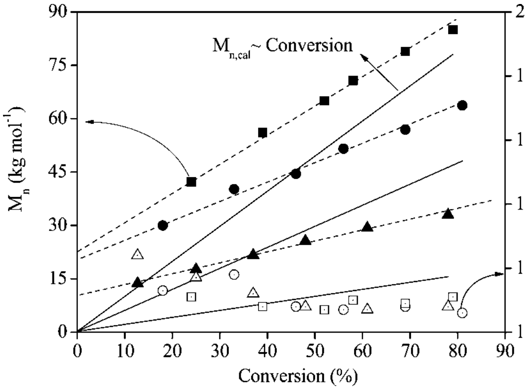

Figure 4. Number-average molecular weights (M_n) (solid) and polydispersity indices (M_w/M_n) (hollow) of poly[*N*-(2-methacryloyloxyethyl) pyrrolidone] (PNMP) polymers as a function of NMP monomer conversions. Conditions: RAFT polymerization of NMP monomer using a 2-cyanoprop-2-yl(4-fluoro) dithiobenzoate (CPFDB) chain transfer agent and a (2,4,6-trimethylbenzoyl)diphenylphosphine oxide (TPO) photoinitiator at (▲) $[NMP]_0$: $[CPFDB]_0$: $[TPO]_0 = 100:1:0.25$, (●) $[NMP]_0$: $[CPFDB]_0$: $[TPO]_0 = 300:1:0.25$, and (■) $[NMP]_0$:$[CPFDB]_0$: $[TPO]_0 = 500:1:0.25$ in 30 wt % methanol under visible light radiation with a mild intensity of 250 μW cm^{-2} at 420 nm at 30 °C. $M_{n,cal}$ were calculated according to the following equation: $M_{n,cal} = M_{NMP} \times \text{Conversion} \times [NMP]_0/[CPFDB]_0 + M_{CPFDB}$.

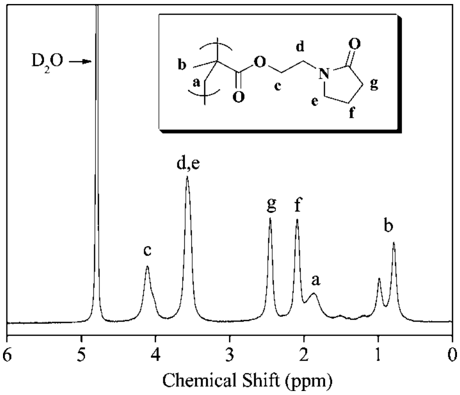

Figure 5. ^{1}H NMR spectrum of poly[*N*-(2-methacryloyloxyethyl) pyrrolidone] (PNMP) polymer synthesized via RAFT polymerization of NMP monomer using a 2-cyanoprop-2-yl(4-fluoro) dithiobenzoate (CPFDB) chain transfer agent and a (2,4,6-trimethylbenzoyl)diphenylphosphine oxide (TPO) photoinitiator at $[NMP]_0$:$[CPFDB]_0$:$[TPO]_0 = 500:1:0.25$ in 30 wt % methanol under visible light radiation with a mild intensity of 250 μW cm^{-2} at 420 nm at 30 °C. ^{1}H NMR: 79% NMP monomer conversion. GPC: $M_n = 85.0$ kg mol^{-1}, $M_w/M_n = 1.11$.

RAFT Polymerization of GMA Monomer using a PNMP Macro-CTA under Visible Light Radiation at 30 °C. In order to clarify the living character of the above-discussed RAFT polymerization, a chain-extending RAFT copolymerization under a visible light radiation at 30 °C was carried out using a PNMP polymer as a macromolecular chain transfer agent (PNMP macro-CTA). A highly reactive monomer, glycidyl methacrylate (GMA), was utilized as a functional monomer to enhance the properties of this pyrrolidone-based polymer.[56–58]

As shown in Figure 6a, the distinct chemical environment of two protons of $COOCH_2CH$ in PGMA units led to the different proton signals at $\delta = 4.30$ and 3.80 ppm, respectively. Moreover, the proton signals at $\delta = 3.20$ ppm ($COOCH_2CH$ of oxirane rings in PGMA units), $\delta = 2.80$ and 2.60 ppm ($COOCH_2CHOCH_2$ of oxirane rings in PGMA units) confirmed the intact oxirane rings of this PNMP-*b*-PGMA copolymer. Moreover, the integral ratio of I_f:I_a:I_g:I_h:I_e equals to 1.5:1:1.5: 1.5:1, within analysis errors, suggesting a 59:178 molar ratio of PNMP units to PGMA units, i.e., PNMP$_{59}$-*b*-PGMA$_{178}$. The M_w value of PNMP macro-CTA was assessed by SLS analysis to give a relatively reasonable degree of polymerization of 59.

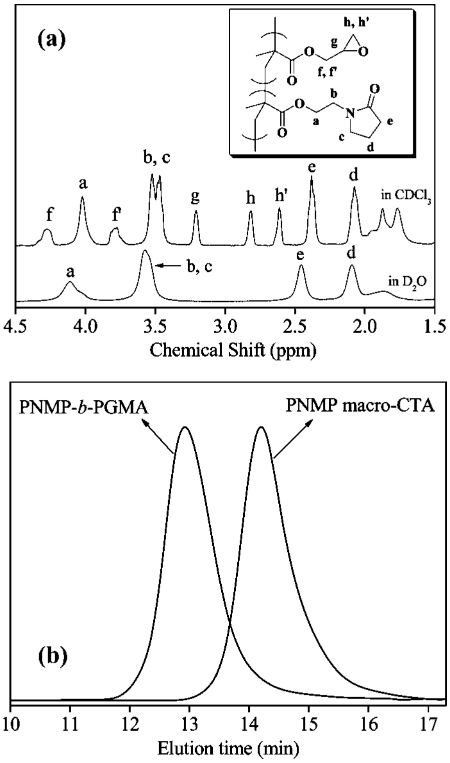

Figure 6. (a) ^{1}H NMR spectra of poly[*N*-(2-methacryloyloxyethyl) pyrrolidone] macromolecular chain transfer agent: (bottom) PNMP macro-CTA; GPC, $M_n = 21.6$ kg mol^{-1}, $M_w/M_n = 1.12$ and (top) its chain-extended block copolymer with poly(glycidyl methacrylate) (PNMP-*b*-PGMA). (b) GPC traces of PNMP macro-CTA and its chain-extended PNMP-*b*-PGMA copolymer. Copolymerization conditions: using a (2,4,6-trimethylbenzoyl)diphenylphosphine oxide (TPO) photoinitiator at a $[GMA]_0$:[PNMP macro-CTA]$_0$:$[TPO]_0 = 350:1:0.1$ in 40 wt % methanol under visible light radiation with a mild intensity of 200 μW cm^{-2} at 420 nm at 30 °C for 4 h. ^{1}H NMR: 51% GMA monomer conversion. GPC: $M_n = 50.9$ kg mol^{-1}, $M_w/M_n = 1.10$.

As shown in Figure 6b, the GPC trace of PNMP-*b*-PGMA copolymer clearly shifted to the larger molecular weight side. Moreover, the GPC trace of this block copolymer was significantly monomodal and symmetrical. This indicated a living character of this ambient temperature RAFT polymerization.

RAFT Polymerization of PEGMA Monomer using a PNMP Macro-CTA under Visible Light Radiation at 30 °C. As shown in Figure 7a, the protons of OCH_3 in PPEGMA units appear at $\delta = 3.30$–3.40 ppm. The protons of CH_2CH_2O and CH_2CH_2O in PPEGMA units appear at $\delta = 3.60$–3.70 ppm. The integral ratio of I_{a+f}:I_j:I_e equals to 1:0.4:0.8, suggesting a 59:20 molar ratio of PNMP units to PPEGMA units, i.e., PNMP$_{59}$-*b*-PEGMA$_{20}$. As shown in Figure 7b, the GPC trace of this PNMP$_{59}$-*b*-PEGMA$_{20}$ copolymer clearly shifted to the larger molecular weight side. Moreover, the GPC trace of this block copolymer was significantly monomodal and symmetrical. This indicated the living character of this RAFT polymerization.

This double hydrophilic PNMP$_{59}$-*b*-PEGMA$_{20}$ copolymer exhibited excellent water-solubility. Moreover, as well-known, PPEGMA possesses excellent biocompatibility[59] and nonadhesive nature to proteins.[60,61] Thus, it is reasonable to expect that this PNMP-*b*-PPEGMA copolymer is of interest in biomedical and pharmaceutical applications.

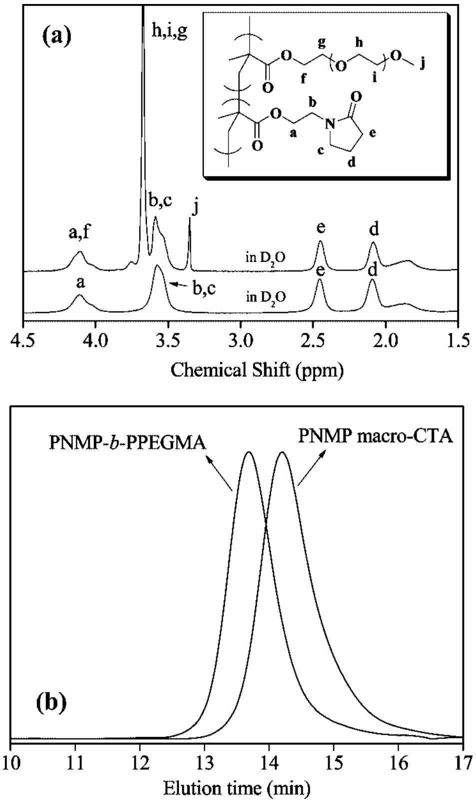

Figure 7. (a) ^{1}H NMR spectra of poly[*N*-(2-methacryloyloxyethyl) pyrrolidone] macromolecular chain transfer agent: (bottom) PNMP macro-CTA; GPC, M_n =21.6 kg mol^{-1}, M_w/M_n = 1.12 and (top) its chain-extended poly[*N*-(2-methacryloyloxyethyl) pyrrolidone]-*block*-poly[poly(ethylene glycol) monomethacrylate] (PNMP-*b*-PPEGMA). (b) GPC traces of PNMP macro-CTA and its chain-extended PNMP-*b*-PPEGMA. Copolymerization conditions: using a (2,4,6-trimethylbenzoyl) diphenylphosphine oxide (TPO) photoinitiator at [PEGMA]$_0$:[PNMP macro-CTA]$_0$:[TPO]$_0$ = 100:1:0.1 in 40 wt % methanol under visible light radiation with a mild intensity of 200 μW cm^{-2} at 420 nm at 30 °C for 1 h, where PEGMA monomer with M_n = 475 g mol^{-1} and M_w/M_n = 1.03 was used. ^{1}H NMR: 24% PEGMA monomer conversion. GPC: M_n = 34.7 kg mol^{-1}, M_w/M_n = 1.08.

RAFT Polymerization of *N,N'*-(Dimethylamino)ethyl Methacrylate using a PNMP Macro-CTA under Visible Light Radiation at 30 °C. As shown in Figure 8a, the protons of $CH_2N(CH_3)_2$ in PDMA units appear at δ = 2.70 ppm, the protons of $CH_2N(CH_3)_2$ in PDMA units appear at δ = 2.30 ppm, and the protons of $COOCH_2CH_2$ in PDMA units appear at δ = 4.10 ppm. Moreover, the integral ratio of I_{b+c}:I_g equals to 1:0.9, suggesting a 59:107 molar ratio of PNMP units to PDMA units, i.e., PNMP$_{59}$-*b*-PDMA$_{107}$.

As shown in Figure 8b, the GPC trace of this PNMP$_{59}$-*b*-PDMA$_{107}$ copolymer clearly shifted to the larger molecular weight side. Moreover, the GPC trace of this block copolymer was significantly monomodal and symmetrical. This indicated the living character of this RAFT polymerization.

Zwitterionization of Tertiary Amino Groups of PNMP-*b*-PDMA Copolymer. Poly[*N*-(2-methacryloyloxyethyl) pyrrolidone]-*block*-poly[3-dimethyl(methacryloyloxyethyl)ammonium propane sulfonate] (PNMP-*b*-PDMAPS) copolymer was synthesized from the above-synthesized PNMP-*b*-PDMA copolymer precursor according to the literature procedure.[49]

As shown in Figure 9, after betainization, the protons of $CH_2N(CH_3)_2$ and $COOCH_2CH_2$ in PDMA units at δ = 2.30 and 4.10 ppm shifted to δ = 3.25 and 4.50 ppm, respectively. Moreover, the protons of $CH_2N(CH_3)_2$ in PDMA units at δ = 2.70 ppm completely shifted to δ = 3.80 ppm. This indicated essentially the completion of this reaction. In addition, the proton signal integral ratio of this zwitterionic PNMP-*b*-PDMAPS copolymer suggested the intact pyrrolidone functionalities after betainization. The zwitterionic block is expected to render this pyrrolidone-based polymer with some unique properties of polybetaines, e.g., antipolyelectrolye effect.[62]

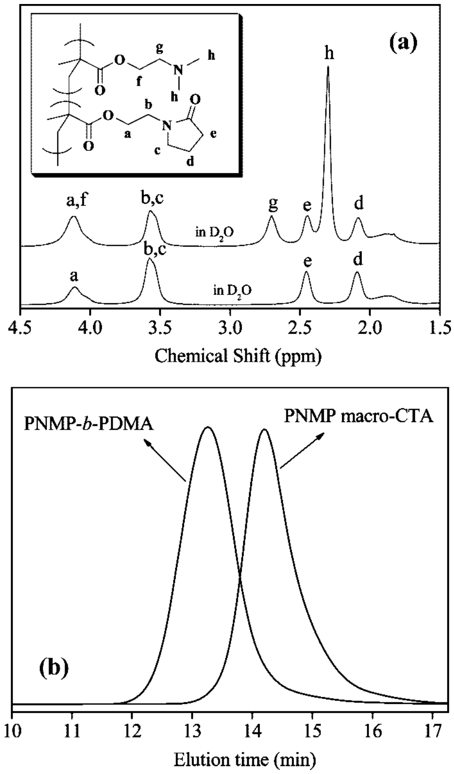

Figure 8. (a) ^{1}H NMR spectra of poly[*N*-(2-methacryloyloxyethyl) pyrrolidone] macromolecular chain transfer agent: (bottom) PNMP macro-CTA; GPC, M_n = 21.6 kg mol^{-1}, M_w/M_n = 1.12 and (top) its chain-extended block copolymer with poly[2-(dimethylamino)ethyl methacrylate] (PNMP-*b*-PDMA). (b) GPC traces of PNMP macro-CTA and its chain-extended PNMP-*b*-PDMA copolymer. Copolymerization conditions: using a (2,4,6-trimethylbenzoyl) diphenylphosphine oxide (TPO) photoinitiator at [DMA]$_0$:[PNMP macro-CTA]$_0$:[TPO]$_0$ = 300:1:0.1 in 40 wt % methanol under visible light radiation with a mild intensity of 200 μW cm^{-2} at 420 nm at 30 °C for 5 h. ^{1}H NMR: 41% DMA monomer conversion. GPC: M_n = 44.5 kg mol^{-1}, M_w/M_n = 1.10.

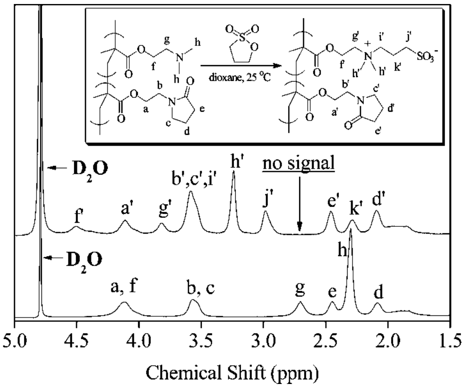

Figure 9. ^{1}H NMR spectra of poly[*N*-(2-methacryloyloxyethyl) pyrrolidone]-*block*-poly[2-(dimethyl-amino) ethyl methacrylate] (PNMP-*b*-PDMA) copolymer and its corresponding zwitterionic poly[*N*-(2-methacryloyloxyethyl) pyrrolidone]-*block*-poly[3-dimethyl(methacryloyloxyethyl)-ammonium propane sulfonate]) (PNMP-*b*-PDMAPS) copolymer.

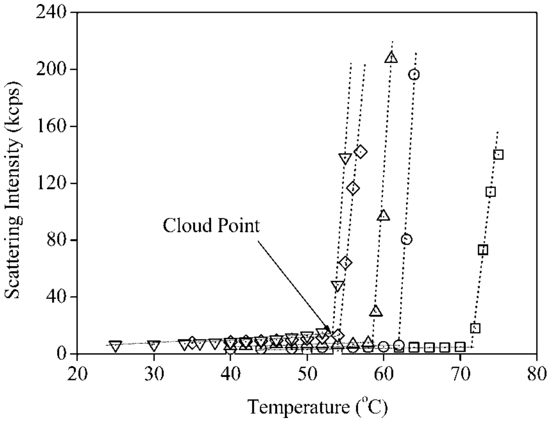

Figure 10. Light scattering intensities of 20.0 mg mL^{-1} PNMP polymer aqueous solutions as a function of solution temperature on heating, where PNMP polymers with various molecular weights were utilized: (⊡) $M_{w,\ SLS}$ = 20.6 kg mol^{-1}, M_w/M_n = 1.12; (○) $M_{w,\ SLS}$ = 42.0 kg mol^{-1}, M_w/M_n = 1.13; (Δ) $M_{w,\ SLS}$ = 64.5 kg mol^{-1}, M_w/M_n = 1.10; (◊) $M_{w,\ SLS}$ = 95.6 kg mol^{-1}, M_w/M_n = 1.13; (▽) $M_{w,\ SLS}$ = 105.4 kg mol^{-1}, M_w/M_n= 1.11.

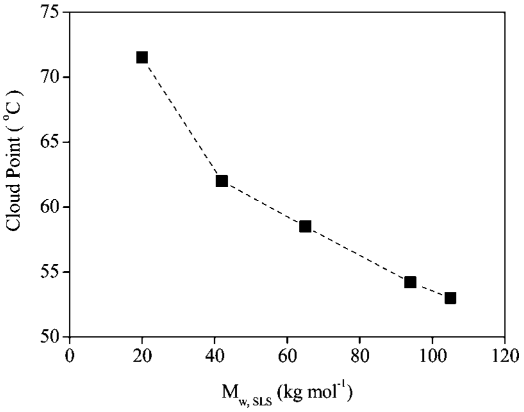

Figure 11. Cloud points of PNMP polymers as a function of their corresponding $M_{w,\ SLS}$.

Laser Light Scattering Analysis of Thermoresponsive Behavior of PNMP Polymer in Aqueous Solution. PNMP polymers with remarkably low polydispersity indices (M_w/M_n = 1.10–1.13) and a range of $M_{w,SLS}$, 20.6, 42.0, 64.5, 95.6, and 105.4 kg mol^{-1}, were utilized for this purpose. The weight-average molecular weights ($M_{w,\ SLS}$) of PNMP polymers were assessed reasonably well by SLS analysis.

As shown in Figure 10, PNMP polymers were rapidly dissolved in aqueous solution at low temperature, e.g., 22 °C, leading to significantly low light scattering intensities. However, on elevating the solution temperature, the light scattering intensity of each solution was dramatically improved at a particular temperature. This temperature was the so-called cloud point. The transparent aqueous solution rapidly transformed to an opaque solution above this cloud point. Further elevating the solution temperature led to the formation of aggregates, which finally precipitated from the aqueous solution.

As shown in Figure 11, the cloud point of PNMP polymer was strongly dependent on its molecular weight. PNMP polymer with $M_{w,SLS}$ of 20.6 kg mol^{-1} exhibited a cloud point at 71.5 °C. Increasing $M_{w,SLS}$ of PNMP to 42.0 kg mol^{-1}, this cloud point dramatically decreased to 62.0 °C. Similar to what was observed in the less-hydrophobic end-group-capped PNIPAM aqueous solution, this dramatic decrease was attributed to the reduced entropy of mixing with increasing molecular weight.[63,64]

Interestingly, the effect of nonpolar CTA end-groups on phase transition was negligible; otherwise, an opposite tendency should be observed.[64] This was presumably due to the hydrophobic nature of the spacer and backbone in the monomer units, which might predominantly contribute to the hydrophobic/hydrophilic balance of PNMP polymer in the investigated molecular weight range. Further, increasing the molecular weight from $M_{w,SLS}$ = 42.0 kg mol^{-1} led to a less pronounced decrease of cloud point, which decreased to 52.8 °C at $M_{w,SLS}$ of 105.4 kg mol^{-1}.

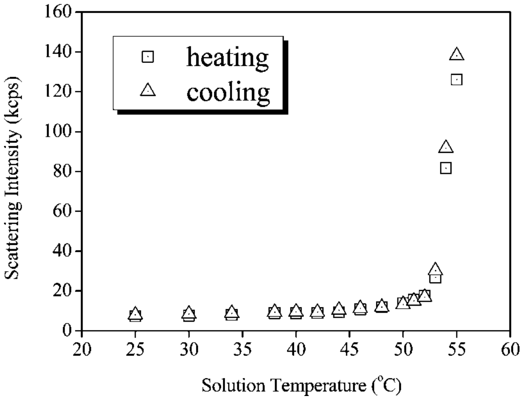

Figure 12. Temperature dependence of scattering intensity of 20.0 mg mL^{-1} PNMP polymer ($M_{w,\ SLS}$ = 105.4 kg mol^{-1}, M_w/M_n = 1.11) aqueous solution during one heating-and-cooling cycle. Conditions: (⊡) elevating the solution temperature in steps from 22 to 56 °C, the solution was stabilized at each predetermined temperature for 2 min; (Δ) decreasing the solution temperature in steps from 56 to 22 °C, the solution was stabilized at each predetermined temperature for 2 min.

The temperature dependence of light scattering intensity of 20.0 mg mL^{-1} PNMP ($M_{w,\ SLS}$ = 105.4 kg mol^{-1}, M_w/M_n = 1.11) aqueous solution during one heating-and-cooling cycle is shown in Figure 12. Clearly, the scattering intensity variation displayed a remarkably reversible evolution tendency. This indicated the remarkably reversible thermoresponsive phase transition behaviors of PNMP aqueous solution. Moreover, unlike what observed in the PNIPAM aqueous solution,[65] no hysteresis phenomenon was observed in the PNMP aqueous solution during one heating-and-cooling cycle. As well-documented,[65] the hysteresis phenomenon of the PNIPAM aqueous solution was caused by the association and dissociation of interchains via hydrogen bonding between >C=O and H−N<. However, the PNMP polymer has no possibility to form interchain hydrogen bonding.

Temperature-Variation ^{1}H NMR Studies on Temperature Dependence of Molecular Interaction of PNMP Polymer in Aqueous Solution. Generally, the proton resonance signals of a fully solvated polymer can be fully detected from ^{1}H NMR spectrum. Thus their integral ratios equal to the proton ratios of this polymer. However, upon desolvation in response to external stimulus, its proton resonance signals are unavoidably attenuated. Thus ^{1}H NMR can be employed to monitor the solvation/desolvation process of a polymer in solution.

As shown in Figure 13, a well-defined PNMP polymer ($M_{w,SLS}$ = 105.4 kg mol^{-1}, M_w/M_n = 1.11), was molecularly dissolved in aqueous solution at a low temperature, e.g., 22 °C. Thus, its proton resonance signals were completely detectable in D_2O solution from its ^{1}H NMR spectrum. On elevating the solution temperature, the proton resonance signals of this polymer gradually shifted to the low field and attenuated around 45 °C. This suggested the dehydration process of this PNMP polymer on elevating the solution temperature.

For further clarifying this attenuation tendency, the temperature dependence of this integral variation was quantitatively assessed using the proton signal of D_2O solvent as an external standard. Because the polymer concentration in D_2O solution is constant during the elevation of solution temperature from

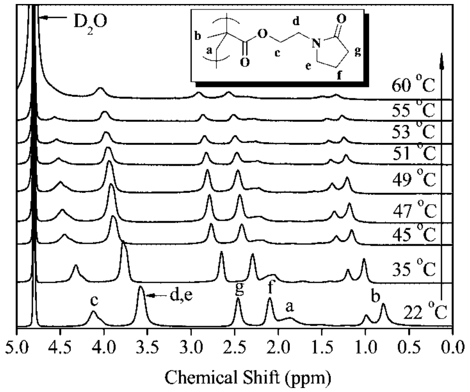

Figure 13. ^{1}H NMR spectrum evolution of PNMP polymer with a $M_{w,\ SLS}$ of 105.4 kg mol^{-1} and M_w/M_n of 1.11 in D_2O on elevating the solution temperature.

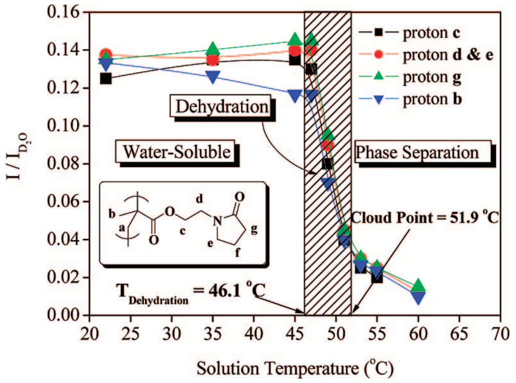

Figure 14. The evolution of integral ratios of each type of proton resonance signals in PNMP polymer with a $M_{w,\ SLS}$ of 105.4 kg mol^{-1} and M_w/M_n of 1.11 to that of D_2O (I/I_{D2O}) as a function of solution temperature.

22 to 60 °C, the integral ratio variation tendency of each proton signal in PNMP polymer to that of D_2O (I/I_{D2O}) illustrated the desolvation process of this polymer in D_2O solution.

As shown in Figure 14, on elevating the solution temperature from 22 to 46 °C, a negligible variation of the integral ratio of protons in either pyrrolidone rings or $COOCH_2CH_2$ was detected, within analysis errors. This indicated that this PNMP polymer was fully hydrated in D_2O solution. However, the integral ratio of methyl protons in the polymer backbone was slowly attenuated due to the nonpolar chemical environment of these protons.

On further elevating the solution temperature over 46.1 °C, the integral ratios of all protons in this PNMP polymer dramatically decreased. This suggested the beginning of dehydration process of this polymer in D_2O solution. This temperature was defined as dehydration temperature or $T_{dehydration}$. This dramatic tendency of decrease in intergral ratio continued up to 51.9 °C. This temperature is quite close to the cloud point of 52.8 °C of this PNMP polymer, as measured by the light scattering mentioned above. This cloud point difference was attributed to the polar difference between D_2O and H_2O. This confirmed the start of phase separation of this polymer from D_2O solution.

Further elevating solution temperature from 52 °C led to a slow decrease of these integral ratios, suggesting that the PNMP polymer has already collapsed and shrunken, thus leading to a significantly large scattering intensity, as observed from the light scattering measurements (see Figure 10).

Inversely, on cooling the solution from 60 to 22 °C, these integral ratios slowly increased at the beginning and dramatically increased from the cloud point up to approximately $T_{dehydration}$. Thereafter, these integral ratios leveled off. This demonstrated that PNMP polymer exhibited reversible thermoresponsive dehydration/hydration and phase transition behaviors in aqueous solution.

Further studies on the thermoresponsive behaviors of PNMP-based block copolymers are in progress. These results are going to be reported in the following paper. Because of the pyrrolidone functionality and the thermoresponsive behavior of this well-defined PNMP polymer, this polymer is envisaged to have significant potential applications, e.g., thermotriggered drug delivery, smart nanoparticle stabilizer, etc.

Conclusion

A well-defined pyrrolidone based thermoresponsive PNMP polymer was synthesized via RAFT polymerization of NMP monomer in methanol under mild visible light radiation at 30 °C. Kinetic studies indicated a well-controlled behavior of this ambient temperature RAFT polymerization. A relatively large molar feed ratio of $[NMP]_0$:$[CPFDB]_0$:$[TPO]_0$ led to the effects of both shortening the initialization period and accelerating the overall polymerization.

The living character of this polymer was confirmed by a facile synthesis of well-defined PNMP-*b*-PGMA, PNMP-*b*-PPEGMA, and PNMP-*b*-PDMA copolymers via ambient temperature RAFT polymerization under this mild visible light radiation. A PNMP-based block copolymer with a zwitterionic block was readily synthesized via betainization of the tertiary amino groups of PNMP-*b*-PDMA precursor at 25 °C.

Temperature-variation ^{1}H NMR analyses unambiguously revealed that this PNMP polymer ($M_w = 105.4$ kg mol^{-1}, $M_w/M_n = 1.11$) was molecularly dissolved in water at low temperature, e.g., 22 °C. Upon elevating the solution temperature, the dehydration process of this fully hydrated PNMP polymer was triggered at 46.1 °C, leading to a dramatic decrease of the integral ratios of proton resonance signals of PNMP to those of D_2O. Further, elevating the solution temperature up to 51.9 °C led to a sharp phase separation from the D_2O solution. Laser light scattering analyses demonstrated that the cloud point of PNMP polymer decreased with molecular weight in the M_w range of 20.6–105.4 kg mol^{-1}. Moreover, this PNMP polymer exhibited remarkable reversible thermoresponsive dehydration/hydration and phase transition behaviors in aqueous solution. Unlike what was observed in PNIPAM aqueous solution,[65] no hysteresis phenomenon was observed in PNMP aqueous solution during one heating-and-cooling cycle.

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References and Notes

(1) Robinson, B. V.; Sullivan, F. M.; Borzelleca, J. F.; Schwartz, S. L. *PVP: A Critical Review of the Kinetics and Toxicology of Polyvinylpyrrolidone (Povidone)*; Lewis Publishers: Chelsea, MI, 1990.
(2) Einaga, H.; Harada, M. *Langmuir* **2005**, *21*, 2578–2584.
(3) Tsunoyama, H.; Sakurai, H.; Negishi, Y.; Tsukuda, T. *J. Am. Chem. Soc.* **2005**, *127*, 9374–9375.
(4) Smith, J. N.; Meadows, J.; Williams, P. A. *Langmuir* **1996**, *12*, 3773–3778.
(5) Robinson, S.; Williams, P. A. *Langmuir* **2002**, *18*, 8743–8748.
(6) Xiong, Y.; Cai, H.; Wiley, B. J.; Wang, J.; Kim, M. J.; Xia, Y. *J. Am. Chem. Soc.* **2007**, *129*, 3665–3675.
(7) Ferrer, D.; Torres-Castro, A.; Gao, X.; Sepúlveda-Guzmán, S.; Ortiz-Méndez, U.; José-Yacamán, M. *Nano Lett.* **2007**, *7*, 1701–1705.
(8) Hasan, T.; Scardaci, V.; Tan, P.; Rozhin, A. G.; Milne, W. I.; Ferrari, A. C. *J. Phys. Chem. C* **2007**, *111*, 12594–12602.
(9) O'Connell, M. J.; Bachilo, S. M.; Huffman, C. B.; Moore, V. C.; Strano, M. S.; Haroz, E. H.; Rialon, K. L.; Boul, P. J.; Noon, W. H.;

Kittrell, C.; Ma, J.; Hauge, R. H.; Weisman, R. B.; Smalley, R. E. *Science* **2002**, *297*, 593–596.

(10) Wetzels, G. M. R.; Koole, L. H. *Biomaterials* **1999**, *20*, 1879–1887.

(11) D'Souza, A. J. M.; Schowen, R. L.; Topp, E. M. *J. Controlled Release* **2004**, *94*, 91–100.

(12) Le Garrec, D.; Gorb, S.; Luo, L.; Lessard, D.; Smith, D. C.; Yessine, M. A.; Ranger, M.; Leroux, J.-C. *J. Controlled Release* **2004**, *99*, 83–101.

(13) Zelikin, A. N.; Such, G. K.; Postma, A.; Caruso, F. *Biomacromolecules* **2007**, *8*, 2950–2953.

(14) Atobe, I.; Takataf, T.; Endo, T. *Macromolecules* **1994**, *27*, 193–196.

(15) He, W.; Gonsalves, K. E.; Pickett, J. H.; Halberstadt, C. *Biomacromolecules* **2003**, *4*, 75–79.

(16) Dimitrov, I.; Trzebicka, B.; Müller, A. H. E.; Dworak, A.; Tsvetanov, C. B. *Prog. Polym. Sci.* **2007**, *32*, 1275–1343.

(17) Otake, K.; Inomata, H.; Konno, M.; Saito, S. *Macromolecules* **1990**, *23*, 283–289.

(18) Flory, P. J.; Orwoll, R. A.; Vrij, A. *J. Am. Chem. Soc.* **1964**, *86*, 3507–3514.

(19) Flory, P. J. *J. Am. Chem. Soc.* **1965**, *87*, 1833–1838.

(20) Tong, Z.; Zeng, F.; Zheng, X. *Macromolecules* **1999**, *32*, 4488–4490.

(21) Mikheeva, L. M.; Grinberg, N. V.; Mashkevich, A. Y.; Grinberg, V. Y. *Macromolecules* **1997**, *30*, 2693–2699.

(22) Maeda, Y.; Nakamura, T.; Ikeda, I. *Macromolecules* **2002**, *35*, 217–222.

(23) Boyko, V.; Richter, S.; Grillo, I.; Geissler, E. *Macromolecules* **2005**, *38*, 5266–5270.

(24) Gan, L. H.; Gan, Y. Y.; Deen, G. R. *Macromolecules* **2000**, *33*, 7893–7897.

(25) Gan, L. H.; Deen, G. R.; Loh, X. J.; Gan, Y. Y. *Polymer* **2001**, *42*, 65–69.

(26) Chiefari, J.; Chong, Y. K. B.; Ercole, F.; Krstina, J.; Jeffery, J.; Le, T. P. T.; Mayadunne, R. T. A.; Meijs, G. F.; Moad, C. L.; Moad, G.; Rizzardo, E.; Thang, S. H. *Macromolecules* **1998**, *31*, 5559–5562.

(27) Moad, G.; Rizzardo, E.; Thang, S. H. *Aust. J. Chem.* **2005**, *58*, 379–410.

(28) Moad, G.; Rizzardo, E.; Thang, S. H. *Aust. J. Chem.* **2006**, *59*, 669–692.

(29) Favier, A.; Charreyre, M. *Macromol. Rapid Commun.* **2006**, *27*, 653–692.

(30) Perrier, S.; Takolpuckdee, P. *J. Polym. Sci., Part A: Polym. Chem.* **2005**, *43*, 5347–5393.

(31) Lokitz, B. S.; York, A. W.; Stempka, J. E.; Treat, N. D.; Li, Y.; Jarrett, W. L.; McCormick, C. L. *Macromolecules* **2007**, *40*, 6473–6480.

(32) McCormick, C. L.; Lowe, A. B. *Acc. Chem. Res.* **2004**, *37*, 312–325.

(33) Li, Y.; Smith, A. E.; Lokitz, B. S.; McCormick, C. L. *Macromolecules* **2007**, *40*, 8524–8526.

(34) Mertoglu, M.; Laschewsky, A.; Skrabania, K.; Wieland, C. *Macromolecules* **2005**, *38*, 3601–3614.

(35) Laschewsky, A.; Mertoglu, M.; Kubowicz, S.; Thünemann, A. F. *Macromolecules* **2006**, *39*, 9337–9345.

(36) McCullough, L. A.; Dufour, B.; Tang, C.; Zhang, R.; Kowalewski, T.; Matyjaszewski, K. *Macromolecules* **2007**, *40*, 7745–7747.

(37) Schilli, C. M.; Zhang, M.; Rizzardo, E.; Thang, S. H.; Chong, Y. K.; Edwards, K.; Karlsson, G.; Müller, A. H. E. *Macromolecules* **2004**, *37*, 7861–7866.

(38) Li, Y.; Lokitz, B. S.; Armes, S. P.; McCormick, C. L. *Macromolecules* **2006**, *39*, 2726–2728.

(39) Zhang, J.; Jiang, X.; Zhang, Y.; Li, Y.; Liu, S. *Macromolecules* **2007**, *40*, 9125–9132.

(40) You, Y.; Hong, C.; Bai, R.; Pan, C.; Wang, J. *Mocromol. Chem. Phys.* **2002**, *203*, 477–483.

(41) Quinn, J. F.; Barner, L.; Barner-Kowollik, C.; Rizzardo, E.; Davis, T. P. *Macromolecules* **2002**, *35*, 7620–7627.

(42) Quinn, J. F.; Davis, T. P.; Barner, L.; Barner-Kowollik, C. *Polymer* **2007**, *48*, 6467–6480.

(43) Muthukrishnan, S.; Pan, E. H.; Stenzel, M. H.; Barner-Kowollik, C.; Davis, T. P.; Lewis, D.; Barner, L. *Macromolecules* **2007**, *40*, 2978–2980.

(44) Lu, L.; Yang, N.; Cai, Y. *Chem. Commun.* **2005**, 5287–5288.

(45) Lu, L.; Zhang, H.; Yang, N.; Cai, Y. *Macromolecules* **2006**, *39*, 3770–3776.

(46) Zhang, H.; Deng, J.; Lu, L.; Cai, Y. *Macromolecules* **2007**, *40*, 9252–9261.

(47) Jiang, W.; Lu, L.; Cai, Y. *Macromol. Rapid Commun.* **2007**, *28*, 725–728.

(48) Benaglia, M.; Rizzardo, E.; Alberti, A.; Guerra, M. *Macromolecules* **2005**, *38*, 3129–3140.

(49) Lowe, A. B.; Billingham, N. C.; Armes, S. P. *Chem. Commun.* **1996**, 1555–1556.

(50) Wan, D.; Satoh, K.; Kamigaito, M.; Okamoto, Y. *Macromolecules* **2005**, *38*, 10397–10405.

(51) Kaneyoshi, H.; Matyjaszewski, K. *Macromolecules* **2006**, *39*, 2757–2763.

(52) Yusa, S.; Yamago, S.; Sugahara, M.; Morikawa, S.; Yamamoto, T.; Morishima, Y. *Macromolecules* **2007**, *40*, 5907–5915.

(53) Yin, H.; Zheng, H.; Lu, L.; Liu, P.; Cai, Y. *J. Polym. Sci., Part A: Polym. Chem.* **2007**, *22*, 5091–5102.

(54) McLeary, J. B.; McKenzie, J. M.; Tonge, M. P.; Sanderson, R. D.; Klumperman, B. *Chem. Commun.* **2004**, 1950–1951.

(55) McLeary, J. B.; Calitz, F. M.; McKenzie, J. M.; Tonge, M. P.; Sanderson, R. D.; Klumperman, B. *Macromolecules* **2004**, *37*, 2383–2394.

(56) Xu, F.; Cai, Q.; Li, Y.; Kang, E.; Neoh, K. G. *Biomacromolecules* **2005**, *6*, 1012–1020.

(57) Yamamoto, S.; Moriya, O.; Endo, T. *Macromolecules* **2003**, *36*, 1514–1521.

(58) Kang, E.; Zhang, Y. *Adv. Mater.* **2000**, *12*, 1481–1494.

(59) Xu, F. J.; Li, Y. L.; Kang, E. T.; Neoh, K. G. *Biomacromolecules* **2005**, *6*, 1759–1768.

(60) Tao, L.; Mantovani, G.; Lecolley, F.; Haddleton, D. M. *J. Am. Chem. Soc.* **2004**, *126*, 13220–13221.

(61) Zhang, F.; Kang, E. T.; Neoh, K. G.; Wang, P.; Tan, K. L. *Biomaterials* **2001**, *22*, 1541–1548.

(62) Lowe, A. B.; McCormick, C. L. *Chem. Rev.* **2002**, *102*, 4177–4190.

(63) Xia, Y.; Yin, X.; Burke, N. A. D.; Stöver, H. D. H. *Macromolecules* **2005**, *38*, 5937–5943.

(64) Furyk, S.; Zhang, Y.; Ortiz-Acosta, D.; Cremer, P. S.; Bergbreiter, D. E. *J. Polym. Sci., Part A: Polym. Chem.* **2006**, *44*, 1492–1501.

(65) Cheng, H.; Shen, L.; Wu, C. *Macromolecules* **2006**, *39*, 2325–2329.

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