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How Can Photoisomerization of Azobenzene Induce a Large Cloud Point Temperature Shift of PNIPAM?

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We present a comprehensive study of photo-induced phase transition of azobenzene-containing poly(*N*-isopropylacrylamide) (PNIPAM) in block copolymers (BCPs) upon the isomerization of azobenzene in the mixed solvent of water and dioxane. The BCP is composed of a poly[2-(dimethylamino)ethyl methacrylate] (PDMAEMA) block and a PNIPAM block decorated with ~2 mol% of azobenzene groups (P(NIPAM-*co*-MAzo)). In the mixed solvent of water and dioxane, the cloud point temperature (CPT) for the phase transition of the PNIPAM block displays a large shift >10 ^oC induced by the photoisomerization of azobenzene under UV or visible light. The CPT shift of PNIPAM is highly dependent on the solvent composition and the large shift only occurs at high dioxane concentration (>30%). The mechanism of photo-induced large CPT shift by the isomerization of azobenzene was investigated by means of ^1H NMR spin relaxation studies. With the addition of dioxane, the exchange of hydrogen bonding from PNIPAM-water to PNIPAM-dioxane was detected in the neighborhood of the CPT, thereby demonstrating the better solvation of the BCP chains and the azobenzene moieties by dioxane. We further demonstrate that the spin relaxation of azobenzene in the *trans*-*cis* isomerization only displayed a notable change at higher dioxane concentrations where the large shift of the CPT was observed. An improved understanding of the mechanism of photoinduced phase transition offers new insights into the rational design, synthesis and application of photoresponsive polymer materials.

1. Introduction

The interest in photoresponsive polymer micellar aggregates mainly arises from the temporal and spatial controllability of light as a stimulus for controlled drug delivery applications.[1-32] Photoresponsive polymer micelles are normally constructed from amphiphilic block copolymers (BCPs) with photoresponsive chromophores on the backbones or the side chains. The photochemical reactions of these chromophores can induce their polarity change that shifts/breaks the hydrophilic/hydrophobic balance of the polymers, thus disrupting their micellization.[20-22] By the incorporation of photoisomerizable chromophores in thermosensitive polymers that exhibit a thermally induced phase transition, it is known that the related cloud point temperature (CPT) of these polymers can be adjusted due to the change of dipole moments of chromophores undergoing the photoisomerization reactions, *e.g.* azobenzene and spiropyran.[18, 27, 33-37] Irie *et al.* were the first to study the photocontrollable CPT of azobenzene-functionalized PNIPAM (P(NIPAM-*co*-MAzo)).[18] With the *trans-cis* isomerization of azobenzene, they reported that the polarity change of azobenzene groups was able to influence the polymer-solvent and polymer-polymer interactions. As a result, the CPT of P(NIPAM-*co*-MAzo) displayed a ~6 ^oC increase with only ~2.7 mol% of azobenzene in the cis form. However, they have observed that the photoinduced shift of CPT is highly dependent on the azobenzene content. The CPT displayed only small shift by the photoisomerization at azobenzene contents other than the *critical azobenzene content* of ~2.7 mol%.

However, recent studies of some groups including ours suggested that the large photoinduced shift of CPT, which is essential for the application of phototriggered phase transitions, cannot easily be realized in the aqueous media and, in many cases, the shift is very small.[18, 27, 33-39] Moreover, the *critical azobenzene content*, that is the optimized azobenzene content in polymer for the largest shift of CPT, is difficult to determine, especially considering the diverse chemical structures of azobenzenes and polymers. Recently, Ueki *et al.* studied a photoinduced phase transition behavior of azobenzene-containing poly(benzyl methacrylate) (P(BNMA-*co*-MAzo)) in a hydrophobic ionic liquid, 1-ethyl-3-methylimidazolium bis(trifluoromethane sulfonyl)imide ([C_2mim][NTf_2]).[40] The CPT of P(BNMA-*co*-MAzo) can reversibly shift by as much as 22 ^oC between the *trans* and *cis* forms of azobenzene. Winnik and co-workers also reported the photoinduced phase transition of an azobenzene-functionalized telechelic PNIPAM, where a large shift of CPT was observed in mixed solvents of water and dioxane.[41] These studies motivated and inspired us to undertake the present work aiming to understand why and how solvents can bring large photoinduced CPT shifts.

In contrast to previous studies on the effects of solvents on photoinduced CPT shifts, we chose to investigate a new azobenzene-containing PNIPAM system, namely, double hydrophilic block copolymers (DHBCPs).[5, 30, 38, 42] In addition to gaining understanding on how solvents affect the CPT shift, investigation of DHBCPs is also of interest for designing photocontrollable micelles. Indeed, a DHBCP having a thermoresponsive block decorated by a few percent of photoresponsive chromophores (*e.g.* azobenzene) can self-assemble into micelles when its aqueous solution is heated above the CPT of the thermoresponsive block, as it becomes insoluble in water and dehydrated. With this type of micelles, if the photoisomerization of chromophores along with the polarity change can induce a significant shift of the CPT, they can be disintegrated as a result of photoinduced phase transition from the dehydrated state to the hydrated state for the thermoresponsive block.[38] Therefore, we synthesized a photoresponsive DHBCP that is composed of a poly(*N,N*-dimethylaminoethyl methacylate) (PDMAEMA) block and a block of PNIPAM randomly decorated with 2 mol% azobenzene moieties. By varying the composition of a cosolvent of water and dioxane, we show how a large shift of the CPT of PNIPAM upon the photoisomerization of azobenzene can be obtained. From the results of the NMR spin relaxation time studies, we discuss the effect of solvent on the CPT as well as the photoinduced CPT shift.

2. Experimental Section

Materials

All chemicals were purchased from Aldrich and used as received unless otherwise stated. *N*-isopropylacylamide (NIPAM, 97%) was recrystallized from *n*-hexane. *N, N*-dimethyl aminoethyl methacylate (DMAEMA, 98%) was passed through a basic aluminium oxide column and distilled under vacuum prior to use. 2, 2'-Azobis(isobutyronitrile) (AIBN) was recrystallized from ethanol. 4-Methacryloyloxy-azobenzene (MAzo) was synthesized according to the reference.[43] The chain transfer agents (CTAs), *S*-1-dodecyl-*S′*-(*α, α′*-dimethyl-*α″*-acetic acid)trithiocarbonate (TTC) and 2-(2-cyanopropyl) dithiobenzoate (CPDB) were prepared with reported methods.[44, 45]

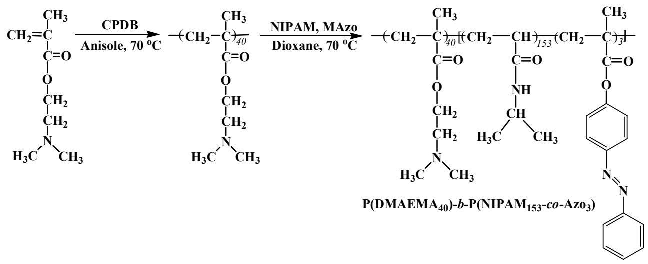

Figure 1. Synthetic route for P(DMAEMA$_{40}$)-*b*-P(NIPAM$_{153}$-*co*-MAzo$_3$).[46]

Synthesis of Polymers

The synthesis details of P(NIPAM$_{100}$-*co*-MAzo$_2$) and P(DMAEMA$_{40}$) homopolymers was reported elsewhere.[46] The synthetic route of P(DMAEMA$_{40}$)-*b*-P(NIPAM$_{153}$-*co*-MAzo$_3$) BCP was shown in Figure 1 The detailed synthetic procedure is as follows. NIAPM (570 mg, 5 mmol), MAzo (38 mg, 0.15 mmol), P(DMAEMA$_{40}$) (251 mg, 0.04 mmol) and AIBN (1.6 mg, 0.01 mmol) were dissolved in 2.5 mL anisole (99%, anhydride) in a 10 mL flask. After degassing under vacuum and refilling with nitrogen, the reaction mixture was placed in a pre-heated oil bath at 70 °C for 8 h. The solution was then cooled down to room temperature and the polymer was precipitated in ethyl ether three times and dried under vacuum for 24 h. From GPC measurement, the diblock copolymer had a M$_n$ of 16.3 kg/mol and a PDI of 1.4 (M$_w$/M$_n$). The composition of diblock copolymer was calculated from the ^{1}H NMR spectrum in CDCl$_3$. The number of DMAEMA, NIPAM and MAzo units in the sample were estimated to be 40, 153 and 3, respectively, and the mole ratio of MAzo units compared to PNIPAM in the diblock copolymer was 1.96%. As a control test, the random copolymer of P(NIPAM$_{100}$-*co*-MAzo$_2$) (azobenzene content 1.88 mol%) having a M$_n$ of 13.2 kg/mol and a polydispersity index PDI of 1.11 was also synthesized with TTC as a chain transfer agent (CTA).

Characterizations

GPC measurements were performed on a Waters system equipped with a refractive index detector (RI 410) and a photodiode array detector (PDA 996). THF was used as the eluent at an elution rate of 1 mL min^{-1}, and polystyrene standards were used for calibration. To characterize the thermo-responsive behavior, the transmittance of polymer solution was recorded at 550 nm with a Varian 50 Bio UV-vis spectrophotometer equipped with a single Peltier cell for controlled-temperature measurements. The temperature increased 1 °C/min unless otherwise stated. The photo-isomerization of azobenzene was obtained by using a UV-vis spot curing system (Novacure) with a 365 nm (90 mW cm^{-2}) or 400-500 nm (90 mW cm^{-2}) filter to generate the UV light or visible light for the respectively *trans-cis* or *cis-trans* isomerization.

NMR Measurements

^{1}H NMR spectra were obtained at room temperature on a Bruker AC 300 spectrometer (300 MHz for ^{1}H), while a Varian Unity Inova spectrometer (600 MHz for ^{1}H) was used to acquire NMR spectra and measure spin relaxation times under temperature control. The spin-spin relaxation times (T_2) were measured with the Hahn spin-echo method. Typical acquisition parameters were 5.6 μs π/2 r.f. pulses, 6 kHz spectral bandwidth, 3 s relaxation decay and ambient temperature control. Analysis and processing of free induction decays (FIDs) and spectra were carried out with Mestrelab Research's Mnora NMR software.

3. Results and Discussion

Reversible Shift of CPT upon Photoisomerization of Azobenzene

The diblock copolymer of P(DMAEMA$_{40}$)-*b*-P(NIPAM$_{153}$-*co*-MAzo$_3$) was prepared by a two-step reversible addition fragmentation chain transfer (RAFT) polymerization with P(DMAEMA$_{40}$) as a macromolecular CTA. The mole fraction of MAzo estimated by ^{1}H NMR in CDCl$_3$ was ~1.9% compared to PNIPAM units. Azobenzene groups can undergo reversible isomerization with UV light (365 nm, *trans* to *cis*) or visible light (>420 nm, *cis* to *trans*). By the incorporation of azobenzene, it is expected that the CPT will be influenced by the photoisomerization. As shown in Figure 2 (a), the transmittance of 2 mg/mL of P(DMAEMA$_{40}$)-*b*-P(NIPAM$_{153}$-*co*-MAzo$_3$) in aqueous solution was recorded as a function of temperature before and after UV irradiation. The abrupt decrease of transmittance above 19 °C corresponds to the hydration to dehydration transition as the P(NIPAM$_{153}$-*co*-MAzo$_3$) block becomes insoluble. Due to the hydrophobicity of azobenzene, the CPT was lower compared to that of PNIPAM at ~32 °C. Subsequently, the polymer solution was exposed to UV light at 365 nm. After the full *trans-cis* isomerization, the transmittance of *cis*-rich polymer solution was recorded with the same procedure. However, only a slight increase of CPT (from *trans* to *cis* isomers) within 2 °C was achieved by light. The similar results were observed in the random copolymer of P(NIPAM-*co*-MAzo). The small shift of PNIPAM induced by photo-isomerization of azobenzene was not surprising according to other reports.[18, 27, 33-37] We note that under the experimental conditions (solution heating rate of 1 ^{o}C/min and highest temperature of 55 ^{o}C), at the end of transmittance measurements, cis azobenzene remained with only a slight thermal relaxation to the trans form (see Figure 6b).

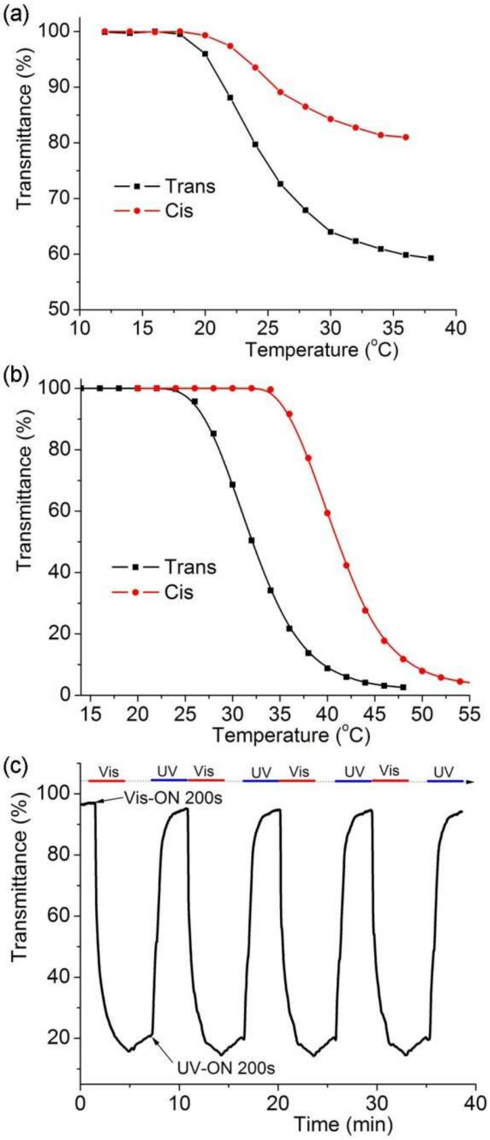

Figure 2. (a) Determination of the CPT of P(DMAEMA$_{40}$)-*b*-P(NIPAM$_{153}$-*co*-MAzo$_3$) in aqueous solution (2 mg/mL) before and after UV irradiation by plotting transmittance *vs*. temperature; (b) the CPT of P(DMAEMA$_{40}$)-*b*-P(NIPAM$_{153}$-*co*-MAzo$_3$) (6 mg/mL) in the mixed solvent of water and dioxane (50:50, vol) before and after UV irradiation; (c) the reversible change of transmittance of the diblock copolymer solution in (b) by alternating irradiation of UV (365 nm) and visible light (400~500 nm) after equilibrated at 30 ^{o}C.

To understand why the photoisomerization of azobenzene cannot induce a large CPT shift for PNIPAM, we conducted the same experiment in the mixed solvents. Based on previous reports, dioxane and water are known as one pair of "cononsolvents" for PNIPAM, which suggests that the mixed solvents (depending on the compositions) could behave as a nonsolvent at the temperature below its CPT in pure water.[47, 48] The CPT of 6 mg/mL of P(DMAEMA$_{40}$)-*b*-P(NIPAM$_{153}$-*co*-MAzo$_3$) in the mixed solvent of water and dioxane (50:50, vol) is shown in Figure 2(b). Surprisingly, the CPT was ~25 ^{o}C for *trans* isomers, while it increased to ~36 ^{o}C after exposure to UV, corresponding to a large increase of 11 ^{o}C. Likewise, with the random copolymer of P(NIPAM-*co*-MAzo) (~1.9 mol% azobenzene), the shift of CPT is as large as ~18 ^{o}C (see Figure S1).

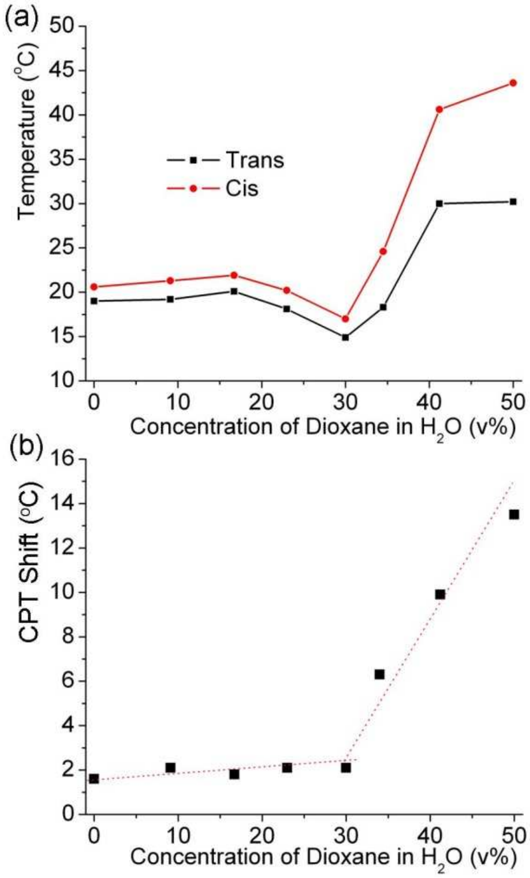

Figure 3. (a) Determination of the CPT of P(DMAEMA$_{40}$)-*b*-P(NIPAM$_{153}$-*co*-MAzo$_3$) (2 mg/mL) in the mixed solvent of H_2O and dioxane with the different compositions; (b) The CPT shift defined as CPT$_{cis}$-CPT$_{trans}$ induced by the isomerization of azobenzene at different concentrations of H_2O and dioxane.

The CPT shift induced by photoisomerization is reversible at different wavelengths of light and this large CPT shift can trigger the phase transition in the BCP solution. With 6 mg/mL of P(DMAEMA$_{40}$)-*b*-P(NIPAM$_{153}$-*co*-MAzo$_3$) in the mixed solvent of H_2O and dioxane (50:50, vol) as example, the changes in transmittance of solution were recorded at 30 ^{o}C upon alternating irradiation of UV and visible light (see Figure 2c). The increase of transmittance from 18% to 97% under UV light is observed, while the transmittance accordingly decreases with visible light irradiation. The transition between the opaque and transparent states took approximately two minutes, indicating the fast isomerization of azobenzene and the phase transition of polymer induced by light under these conditions. The reversible change of transmittance proves that the phase transition of P(NIPAM$_{153}$-*co*-MAzo$_3$) block can be-reversibly controlled over by light.

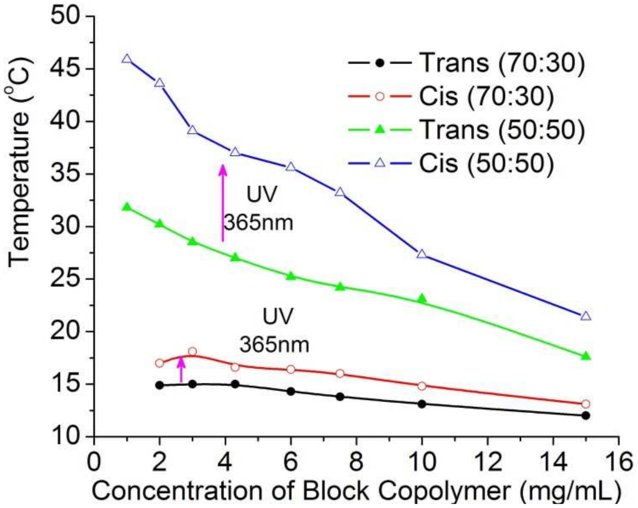

Figure 4. Different dependence of the phase separation temperature on the BCP concentration and isomerization of azobenzene for two representative compositions of the mixed solvent. Top two curves are for the CPTs of *trans*- (down, ▲) and *cis*- (up, Δ) azobenzene P(DMAEMA$_{40}$)-*b*-P(NIPAM$_{153}$-*co*-MAzo$_3$) in the mixed solvent of H_2O and dioxane (50:50, vol). Bottom two are for the CPTs of *trans*- (down, ●) and *cis*- (up, ○) azobenzene P(DMAEMA$_{40}$)-*b*-P(NIPAM$_{153}$-*co*-MAzo$_3$) in the mixed solvent of H_2O and dioxane (70:30, vol).

CPT Shift in the Mixed Solvent

Indeed, the CPT and CPT shift induced by the photoisomerization of the BCP are highly dependent on the composition of the mixed solvents, i.e. the volume ratio of H_2O and dioxane. The CPT of 2 mg/mL of P(DMAEMA$_{40}$)-*b*-P(NIPAM$_{153}$-*co*-MAzo$_3$) in various compositions of the mixed solvents were measured and the results are as given in Figure 3(a). For volume fractions of dioxane lower than 30%, the CPT decrease from ~19 °C to ~15 °C, clearly illustrating the “cononsolvent” pair of two good solvents (water and dioxane) of PNIPAM. While, with further increase in dioxane to 50 vol%, the CPT presents a gradual increase, as similarly reported by Schild *et al*.[47] After the UV irradiation, the *cis*-rich diblock copolymer showed a higher CPT compared with that of *trans*-rich species for all concentrations of dioxane, although the large shift of the CPT only appeared at volume fractions of dioxane higher than 30% as shown in Figure 3(b).

The shift of CPTs was also influenced by the BCP concentrations. As shown in Figure 4, for water/dioxane 70:30, the CPT of the polymer with both *trans* and *cis* isomers showed only a slight variation as a function of the polymer concentration. By increasing the BCP concentration from 2 to 15 mg/mL, the CPTs displayed a ~2 °C shift before and after the photoisomerization. This behavior was comparable with P(NIPAM-*co*-azo) in pure water.[48, 49] Conversely, for water/dioxane 50:50, the CPTs were highly dependent on the polymer concentration and showed a fast increase with decreasing polymer concentration. To better understand the mechanism of photoinduced phase separation in the presence of mixed solvent, the transition between the aggregated state and the molecular dissolved state has been further studied with NMR spectroscopy.

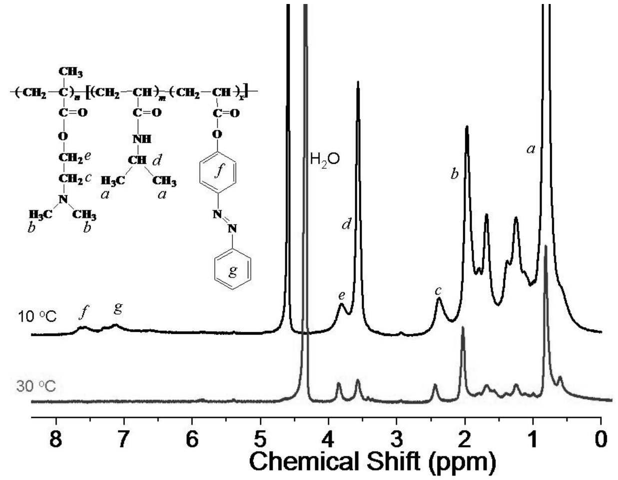

Figure 5. ^{1}H NMR spectra of P(DMAEMA$_{40}$)-*b*-P(NIPAM$_{153}$-*co*-MAzo$_3$) in D_2O (6 mg/mL) at T<CPT (10 °C) and T>CPT (30 °C).

Figure 5 shows the ^{1}H NMR spectra of P(DMAEMA$_{40}$)-*b*-P(NIPAM$_{153}$-*co*-MAzo$_3$) in D_2O below and above CPT. Generally, upon micellization of the polymer, its NMR line widths become broad and the peak intensities decrease due to reduced mobility of the micelle.[50-54] Upon increasing the temperature from 10 °C (T<CPT) to 30 °C (T>CPT), the intensity of peaks *a* (0.8 ppm) and *d* (3.6 ppm) of isopropyl side groups of PNIPAM amply decreased. This is the normal and expected behavior when a DHBCP forms micelles at T>CPT of the thermosensitive block. The hydration to dehydration transition of P(NIPAM-*co*-MAzo) blocks occurred, leading to the formation of micelles with a dehydrated P(NIPAM-*co*-MAzo) block in the micelle core.[55] Subsequently, the ^{1}H NMR spectra of P(DMAEMA$_{40}$)-*b*-P(NIPAM$_{153}$-*co*-MAzo$_3$) is recorded in D_2O and d_8-dioxane (50:50, vol) before and after UV irradiation to observe the CPT change induced by light (see Figure 6). By heating the polymer solution to T>CPT, it is surprising to find that the relative NMR intensities and peak widths of the P(NIPAM-*co*-MAzo) block displayed little changes before and after UV irradiation. The aromatic protons on azobenzene rings only presented variations of chemical shift from 7.4~8.1 to 6.9~7.4 ppm, corresponding to the *trans* to *cis* isomerization. This result suggests that most of the P(NIPAM-*co*-MAzo) chains were still soluble and mobile in the solution above the CPT, even though the solution turned to be highly opaque above the CPT. Such phase transition appears to be not the “conventional” dehydration with PNIPAM chains undergoing the coil to globule transition. Thus, further NMR studies have been carried out in order to interpret these observations.

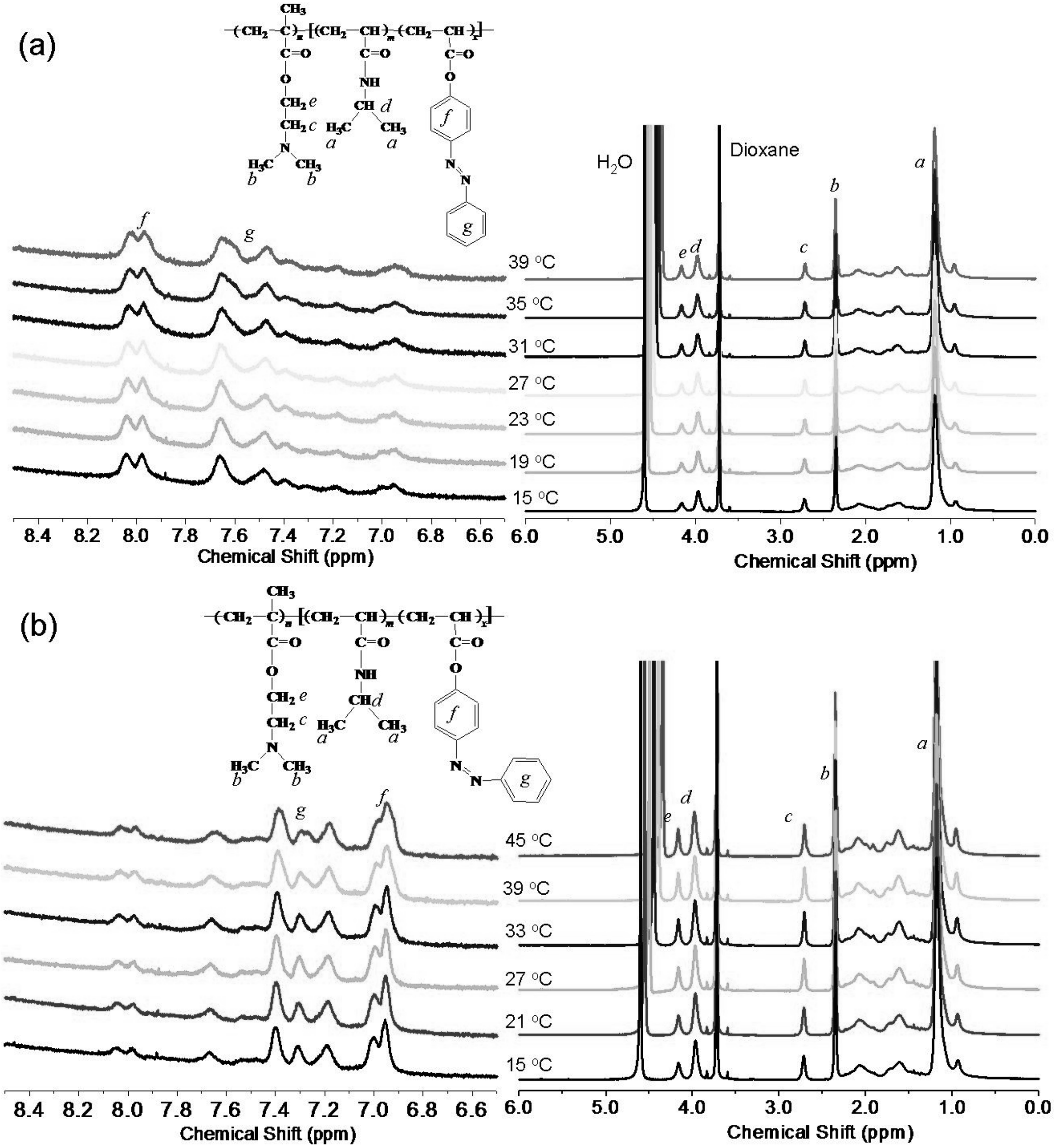

Figure 6. ^{1}H NMR spectra of P(DMAEMA$_{40}$)-*b*-P(NIPAM$_{153}$-*co*-MAzo$_3$) (6 mg/mL) in D$_2$O and d_8-dioxane (50:50, vol) before (a) and after (b) UV irradiation at various temperature.

By changing the composition of the mixed solvent, the NMR spectra of the BCP were recorded at different temperatures. Comparing the NMR spectra below and above the CPT, the fraction of phase-separated or dehydrated PNIPAM chains in the DHBCP, i.e., the fraction responsible for the reduced NMR intensity, could be quantitatively determined from the NMR peak intensity changes above the CPT. As the solubility of PDMAEMA block is insensitive to the change of solvent compositions, the methyl peak of PDMAEMA at ~2.3 ppm was used as an "internal standard" to measure the relative NMR intensities of the protons in the PNIPAM block. By subtracting the NMR spectra below the CPT from those above the CPT, the relative NMR intensity change (RNIC) of the methine peak at ~3.9 ppm of P(NIPAM-*co*-MAzo) was estimated from the following equation:

$$RNIC = \frac{I_{2.3}^{38^o C} / I_{3.9}^{38^o C}}{I_{2.3}^{8^o C} / I_{3.9}^{8^o C}}$$

where I_s^r is the absolute NMR integral of peak *s(ppm)* at temperature *r*. If the intensity of P(NIPAM-*co*-MAzo) decreases above the CPT, the value of RNIC is more than 1; while if the RNIC value is close to 1, it suggests that the appearance of the NMR spectra does not change with increasing the temperature from below to above the CPT.

Figure 7(a) plots the RNIC value as a function of the dioxane concentration in the mixed solvent. At low concentrations of dioxane (<20 vol%), the RNIC value is close to ~5, indicating the dramatic intensity change of P(NIPAM-*co*-MAzo) block by changing the temperature above and below the CPT. With increasing dioxane from 20 to 40 vol%, it is noted that the RNIC values are reduced from ~5 to ~1, which denotes the smaller decrease of peak intensities of P(NIPAM-*co*-MAzo) block with temperature change. Kourilova *et al.* recently reported that PNIPAM in the mixture solvent of water/acetone or water/ethanol displayed a decrease in the fraction of the phase-separated component by increasing the organic solvent as well.[56] When heating the polymer solution above the CPT of P(NIPAM-*co*-MAzo), the residual NMR signals arise from the well-dissolved component. Consequently, with the NMR analysis, the fraction of the phase-separated component (f_{ps}) of P(NIPAM-*co*-MAzo) could easily be determined from RNIC by the following equation:

$$f_{ps} = 1 - \frac{1}{RNIC}$$

By plotting f_{ps} as a function of the dioxane concentration in the mixed solvent, the fraction of phase separation component determined by NMR is shown in Figure 7(b). An apparent transition between two regimes around 35-40 vol% of dioxane becomes evident. With <35% of dioxane, the CPT of the BCP solution arises from the de-solvation (coil-globule transition) of the P(NIPAM-co-MAzo) chains just like the dehydration in water alone. In other words, in this regime, the temperature-induced changes in balancing the polymer-solvent, polymer-polymer and solvent-solvent intermolecular interactions are essentially the same as in water; the phase transition is mostly dictated by the changing hydrogen bonding between the polymer and water molecules. On the other hand, with >35% of dioxane, the de-solvated fraction of P(NIPAM-MAzo) chains at T>CPT drops to a very small amount, while most of those chains remain solvated. Therefore, in the second regime, the phase transition giving rise to the CPT, should be related to separation of two liquid phases in which a dominant amount of polymer chains are solubilized adopting the coil conformation. This changing phase transition behavior implies that as the concentration of dioxane increases, the interactions between the P(NIPAM-co-MAzo) chains and dioxane molecules start to take control over the phase transition. It is easy to picture that the two phases at T>CPT as a result of phase separation in a ternary solution, may differ in the BCP concentration and the composition of the two solvents. Considering the large difference in the refractive index between water and dioxane (1.333 for water and 1.422 for dioxane), it is no surprise to see the opalescence of the solution due to light scattering. Interestingly, these two regimes coincide with the different photoisomerization induced CPT shifts (Fig.3). Basically, a large photoinduced shift of CPT can be observed only in the second phase transition regime. More NMR experiments were performed in order to further confirm the results of the above analysis.

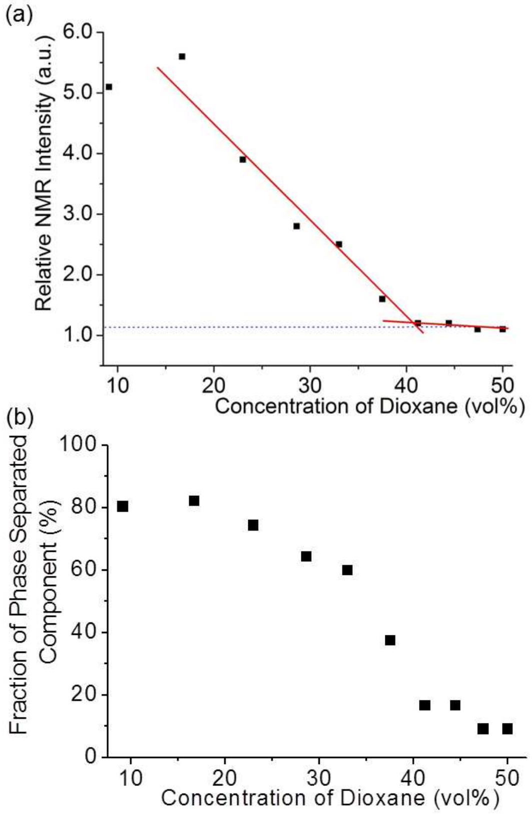

Figure 7. (a) The relative NMR intensity change (RNIC) *vs.* the concentration of dioxane in mixed solvent; and (b) the calculated fraction of phase-separated component of P(NIPAM-*co*-MAzo) chains.

Table 1. The T_2 relaxation times of P(DMAEMA$_{40}$)-*b*-P(NIPAM$_{153}$-*co*-MAzo$_3$) in the mixed solvent with various concentrations of d_8-Dioxane below and above the CPT.

Solvent	Temperature	T_2 of -CH$_3$ on P(NIPAM) block (ms)		T_2 of -CH$_2$- on P(DMAEMA) block (ms)*
		Fast	Slow	
0 vol% d_8-Dioxane	8 °C	28	91	29
	28 °C	32	112	61
30 vol% d_8-Dioxane	8 °C	23	64	68
	28 °C	28	74	117
50 vol% d_8-Dioxane	8 °C	22	50	109
	28 °C	39	107	144

[*] the side -CH$_2$O- groups.

NMR Relaxation Studies

As NMR relaxation times are sensitive to molecular motions and fluctuations, ^{1}H spin-spin relaxation times (T_2) were measured by using the Hahn spin-echo method to further reveal the changes of hydrogen bonding or other intermolecular interactions as a result of adding dioxane.[50-52] The bi-exponential relaxation decays with double T$_2$s represented two types of molecular motions in solution, one is the slow motions of polymer chain segments with restricted conformations (short T$_2$, or fast relaxation component), while the other is the rapid motional segments with high degrees of freedom (long T_2, or slow relaxation component). The T_2 measured from the methyl ($-CH_3$) side groups (at ~3.9 ppm) of the PNIPAM block at various concentrations of dioxane below and above CPT are given in Table 1. For T<CPT, the T_2 values for the slow relaxation component of PNIPAM block appeared to be sensitive to the solvent variation and displayed a continuous decrease from 91 ms to 64 and 50 ms with increasing dioxane from 0 to 30 and 50 vol%. The decrease of T_2 indicates that the solvation by dioxane restricts the freedom of motion for the polymer chain segments of the PNIPAM block, by the formation of hydrogen bonding between PNIPAM block and dioxane. Indeed, the solvation by dioxane of the P(NIPAM-co-MAzo) block could also be supported by the solubility change of azobenzene groups (highly hydrophobic), since the NMR signal intensity of aromatic protons on azobenzene kept increasing with the concentration of dioxane. For T>CPT, the T_2 of P(NIPAM-*co*-MAzo) block exhibited a strong dependence on the concentration of solvent composition.[57-59] At 0 and 30 vol% of dioxane, the T_2 of both slow and fast components displayed little increase with increasing temperature from 8 °C to 28 °C; whereas, the T_2 of the two components increased by a factor of ~2 at 50 vol% of dioxane. This result suggests that most of the PNIPAM chains access a locally more mobile environment at high dioxane composition.

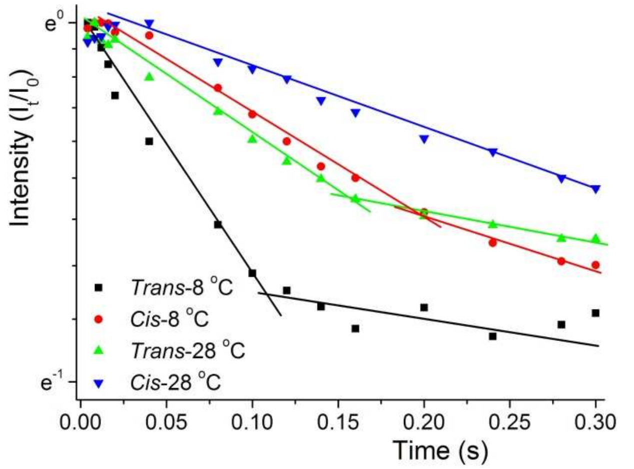

Figure 8. Decay curves (T_2 measurement) of aromatic protons on azobenzene (at 7.6~7.7 ppm for trans isomers and 6.9~7.0 ppm for cis isomers) of the diblock copolymer P(DMAEMA$_{40}$)-b-P(NIPAM$_{153}$-co-MAzo$_3$) in D_2O and d$_8$-dioxane (50:50, vol) below and above the CPT.

To gain more insight into the mechanism of large CPT shift by the photoisomerization of azobenzene, T_2 measurements were also made after the trans-cis photoisomerization,. However, the T_2 of PNIPAM block displayed few changes after photoisomerization at either T>CPT or T<CPT. This implies that the shift of CPT is not related to the change of polymer chain conformations or the solvation of polymer chains, but only the proportions of the non-micelle phase domains as the following NMR relaxation measurements demonstrate. The T_2 of aromatic protons of azobenzene were determined before and after UV irradiation. At low dioxane concentration, the NMR signals of aromatic protons in azobenzene are rather weak, due to its poor solubility. No reliable decay curves could be obtained. Figure 8 presents the decay curves of aromatic protons on azobenzene in 50 vol% of dioxane at 7.6~7.7 ppm for *trans* isomers and 6.9~7.0 ppm for *cis* isomers. At 8 °C, the *trans* isomers displayed a double exponential decay curve with a fast T_2 of 139 ms and a slow T_2 >3 s. Upon UV irradiation (365 nm), the T_2 of fast component increased to 324 ms, while the T_2 of slow component reduced to 676 ms while accompanied with a fraction change from 47% to 79% after UV, thereby indicating a better solvation of *cis* isomers and an increased proportion of the non-micelle two-phase state. This is further confirmed by the relaxation behavior of *trans* isomers at 28 °C that displays a similar decay curve as the *cis* isomers at 8 °C. Interestingly, with the isomerization at T>CPT, the *cis* isomer only has a single exponential decay curve with a T_2 of 598 ms at 28 °C. Thus, the conversion of the two relaxation components of azobenzene to a single component demonstrates the higher solubility of the *cis* isomer in the mixed solvent which produces the changes in the proportions of the phase domains (hence size and refractive index) of the PNIPAM block in the non-micelle two-phase state.

4. Conclusions

We have conducted a NMR study aiming to understand what produces a large photoinduced CPT shift in mixed solvents of water/dioxane for a DHBCP whose thermosensitive PNIPAM block contains a number of azobenzene moieties. We found that upon addition of dioxane in water, there is a transition between two regimes of LCST-type thermally induced phase separation in the block copolymer solution. When the dioxane content is below about 35%, PNIPAM chains become essentially de-solvated at T>CPT, undergoing the coil-globule transition just like PNIPAM chains in water alone (de-hydrated above CPT). However, when the dioxane content is above 35%, the phase separation at T>CPT results in two phases in which PNIPAM chains remain essentially solvated; that is, no coil-globule transition characteristic of PNIPAM in water occurs. As a matter of fact, a much larger photoinduced CPT shift as a result of the *trans-cis* isomerization of azobenzene was observed only in the second regime. In the light of the results, we propose what follows as the main conclusions of the present study. By adding dioxane into water, as long as the intermolecular interactions accounting for the solubilization of PNIPAM chains remain to be mainly H-bonding between water molecules and the polymer, i.e., the mixed solvent retains the aqueous character, the conversion of trans azobenzene to the *cis* isomer exerts little effect on the CPT because the photoinduced polarity change of the azobenzene moieties, being poorly solubilized by the solvent, does not impact the intermolecular interactions between PNIPAM and water. This is the case of the low-dioxane content regime (<35%). When the content of dioxane passes a certain level, the intermolecular interactions between PNIPAM and dioxane molecules begin to play a major role and the mixed solvent loses the aqueous character. In this high-dioxane content regime, with well-solubilized azobenzene moieties, their photoisomerization exerts greater effect on the intermolecular interactions between PNIPAM and the solvent molecules as a whole, resulting in more prominent shift of the CPT. It is also worth emphasizing the implication of the findings on the use of DHBCPs to prepare polymer micelles. In the present or a similar polymer/solvent system, micelles can be formed only in the first regime, where the de-solvation of the thermosensitive block occurs at T>CPT, while the micelles cannot be obtained in the second regime at T>CPT because of the absence of de-solvation of the thermosensitive chains.

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Notes and references

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Graphic for Table of Contents

Photoinduced LCST shift