Manipulating the Thermoresponsive Behavior of Poly(*N*-isopropylacrylamide). 1. On the Conformational Behavior of a Series of *N*-Isopropylacrylamide−Styrene Statistical Copolymers

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ABSTRACT: Fluorescence techniques, including time-resolved (fluorescence) anisotropy (TRAMS), have been used to study the effects of hydrophobic modification upon the thermoresponsive behavior of NIPAM-based polymers. Incorporation of styrene, through statistical free radical copolymerization, changes the hydrophobic/hydrophilic balance of the macromolecule and lowers the lower critical solution temperature (LCST) of the system. Unfortunately, although simple copolymerization with styrene can be used to manipulate the system's LCST characteristics, the polymer loses its ability to release solubilized hydrophobic guests below the critical point. This results from the formation of intramolecular aggregates between the styryl residues of the polymer chain, which can accommodate guest solutes. This is a serious limitation to this form of chemical modification if the aim is to produce smart materials for controlled solubilization and release at specific temperatures.

Introduction

Smart behavior in polymer systems (e.g., the ability to expand and contract on demand) has been the focus of increasing activity by chemists during the past decade.[1−7] Changes in conformation can be induced by altering, for example, pH, salinity, pressure, or temperature (depending on the chemical structure/functionality of the macromolecule). An example of a polymer that can respond to the latter is poly(*N*-isopropylacrylamide), PNIPAM: the thermally induced phase separation of PNIPAM is a well-known phenomenon which occurs at 32 °C, the lower critical solution temperature (LCST).[2,4,7,8] Above the LCST, under semidilute conditions, a turbid solution forms which rapidly clears again upon cooling. In this respect, we have recently confirmed[7,9] (via time-resolved anisotropy measurements, TRAMS) that the LCST behavior in linear PNIPAM is governed by a two-stage mechanism.[2,10] The first step involves intramolecular coil collapse. This is followed by intermolecular aggregation between collapsed coils.

The ability of "smart" polymers to expand and contract "on demand" could lead to such systems being used as carriers with controlled release capabilities. For example, in the compact form, above its LCST, PNIPAM can solubilize low molar mass organic species.[9] The solute can subsequently be released into the aqueous phase by simply lowering the temperature of the dispersion below 32 °C. In view of this potential, it would be attractive if ways could be found to manipulate the LCST of the polymeric host, through chemical modification. We have recently modified PNIPAM[11,12] and synthesized microgels[13] based upon PNIPAM so that we can control the conformational switch of the polymer over a wide temperature range (e.g., from 4 to 100 °C), including the physiological temperature of 37 °C. The resultant modified polymers might then find application in a much more extended range of industrial and medical activities.

In this paper, as part of an ongoing program, we present the results of initial attempts to control the LCST behavior of PNIPAM through simple copolymerization with a hydrophobic comonomer, styrene. Styrene was chosen as the chemical modifier, since we have previously shown[5] that it can be used to alter the behavior of pH-sensitive "smart" polymers in aqueous media.

Experimental Section

Materials. *N*-Isopropylacrylamide, NIPAM (Aldrich, 97%), was purified by multiple recrystallization from a mixture (60/40%) of toluene and hexane (both spectroscopic grade, Aldrich).

Styrene was purified by washing with an aqueous solution of NaOH (5 wt %) to remove inhibitor, followed by distilled water until the washings were neutral to litmus and fractional distillation under high vacuum.

Acenaphthylene (ACE) was purified by multiple recrystallization from ethanol followed by vacuum sublimation.

Nitromethane (Aldrich, Gold Label) was used as received.

Acenaphthylene-labeled poly(*N*-isopropylacrylamide) [ACE-PNIPAM] was prepared by copolymerization of NIPAM with a trace amount (ca. 0.5 mol %) of ACE in dioxane solution (80 wt % of solvent) at 60 °C using AIBN as initiator. Fluorescently labeled styrene−NIPAM copolymers were prepared in a manner similar to that of the homopolymer. Two samples were synthesized: one contained 8.9 wt % styrene [ACE-(STY8.9)-NIPAM] while the second contained 16.9 wt % of hydrophobe [ACE-(STY16.9)-NIPAM].

All polymers were purified by multiple reprecipitation from dioxane into diethyl ether (May and Baker).

Contents of all copolymer samples were obtained by proton NMR and elemental analyses. Molecular weights were determined by aqueous GPC.[14] The data are listed in Table 1.

Solutions for fluorescence spectroscopic analyses contained 10^{-2} wt % polymer.

Instrumentation. Optical density measurements were made on a Hitachi U-2010 spectrophotometer.

Steady-state fluorescence spectra were measured on a Perkin-Elmer LS50 spectrometer.

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Table 1. Physical Characteristics of the NIPAM-Based Polymers

sample	$\bar{M}_n$/kg mol^{-1}	styrene content (mol %)	LCST^a (°C)
ACE-PNIPAM	21		32
ACE-STY(8.9)-NIPAM	19	8.9	20
ACE-STY(16.9)-NIPAM	21	16.9	9

[a] Estimated from optical density (OD) measurements ($\lambda = 500$ nm) as the T of onset of the increase in OD which accompanies the phase separation of the polymer (here, at 10^{-2} wt %).

Fluorescence lifetime data were acquired on an Edinburgh Instruments 199 time-correlated single photon counter.

Time-resolved anisotropy measurements (TRAMS) were made at the synchrotron radiation source, SRS, Daresbury, UK. A complete description of the experimental setup and a detailed discussion of analysis of anisotropy data can be found elsewhere.[15]

Results and Discussion

Time-Resolved Anisotropy Measurements (TRAMS). The principle of the TRAMS experiment and methods of data analysis has been discussed extensively elsewhere.[15,16] In brief, molecules are photoselected from the randomly oriented ensemble of chromophores using polarized excitation. The anisotropy of the fluorescence emitted at a particular time, t, following excitation, $r(t)$, is related to the intensities, $i_{\parallel}(t)$ and $i_{\perp}(t)$, measured in planes parallel and perpendicular, respectively, to the plane of polarization of the radiation incident upon the sample, by eq 1.

$$r(t) = \frac{i_{\parallel}(t) - i_{\perp}(t)}{i_{\parallel}(t) + 2i_{\perp}(t)} = \frac{d(t)}{s(t)} \tag{1}$$

The decays of the anisotropy of the fluorescence from each of the ACE-labeled, NIPAM-based polymers dispersed in aqueous media (10^{-3} wt %) were found to be complex under all conditions adopted. This appears to be a general feature in water-soluble polymers[9,17-20] and presumably reflects the heterogeneity of local environments afforded to the fluorescent label, within the interiors of both the water-swollen coils of the polymers below their LCSTs and the globular forms which exist at higher temperatures.

To characterize the "average" segmental mobility of the NIPAM-based polymers, a single-exponential model of the form

$$r(t) = r_0 \exp(-t/\tau_c) \tag{2}$$

was adopted in impulse reconvolution[21,22] analyses of the time-resolved fluorescence data. (The correlation time, τ_c, is the rate parameter which describes macromolecular mobility; the shorter the value of τ_c, the faster the rate of segmental motion.) The data resultant upon this form of analysis are shown in Arrhenius form in Figure 1, where $k_c = \tau_c^{-1}$ measures the *average* rate of macromolecular motion. Several features are worthy of note in consideration of Figure 1:

(a) Below the LCST of PNIPAM, the rate of macromolecular motion follows "normal" Arrhenius type behavior: the higher the temperature is, the greater the segmental mobility of the polymer backbone. Furthermore, the polymer exists as a flexible chain under these conditions. At 32 °C (the onset of phase separation in more concentrated samples), a dramatic reduction in k_c occurs which marks the conformational transition of PNIPAM from an open coil to a compact, slow moving globular structure.

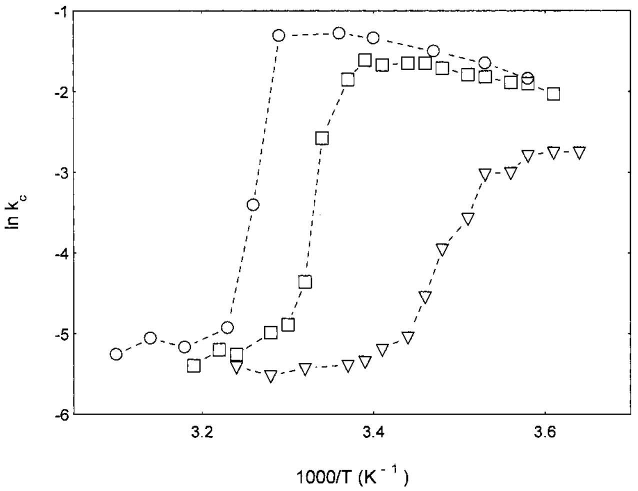

Figure 1. Arrhenius representation of the rate of macromolecular motion, k_c ($= \tau_c^{-1}$), in aqueous solution for ACE-NIPAM (○), ACE-STY(8.9)-NIPAM (□), and ACE-STY(16.9)-NIPAM (▽).

(b) Copolymerization with styrene results in two main effects. Increasing the styryl content from 8.9 to 16.9% serves to shift the conformational transition to lower temperature. (This effect of increased hydrophobic/hydrophilic balance upon the conformational transition temperature has been predicted previously.[23]) Furthermore, the temperature marking the onset of decreased segmental mobility is the same (within experimental error) as that observed in optical transmittance measurements (cf. Table 1). In addition, the greater the hydrophobic content of the macromolecule is, the lower the change in magnitude of the transition. (This behavior appears to be a general feature in modification of PNIPAM:[11,12] copolymerization of NIPAM with dimethylacrylamide to make a more hydrophilic species also reduces the "intensity" of the transition. This effect has been and has been observed previously using other techniques such as calorimetry.[24,25]) This reduction in transition "intensity" upon making the polymer more hydrophobic would not be expected on the basis of one previous calorimetric study,[25] at least: Feil et al.[25] reported that increasing the hydrophobicity of NIPAM-based systems, through copolymerization with n-butyl methacrylate, increased ΔH for the transition as the LCST was lowered.

(c) The major effects of incorporation of styrene upon the dynamics of the modified smart polymer occur below the LCST. As the styryl composition of the macromolecule is raised, k_c decreases, which implies that motion of the chain becomes more hindered. The effect is greater than would be induced simply by local steric inhibitions upon segmental motion, as demonstrated by the behavior of the polymers in methanol (see below). This is presumably an early indication that, in aqueous media, intramolecular hydrophobic cavities exist under these conditions in the form of styrene aggregates, which serve to reduce the mobility of the polymer backbone.

In methanol (cf. Figure 2) each polymer exhibits normal Arrhenius behavior in its dynamics: the higher the temperature, the faster is the segmental motion of the backbone, and a linear relationship exists between ln k_c and inverse temperature. Such is to be expected,

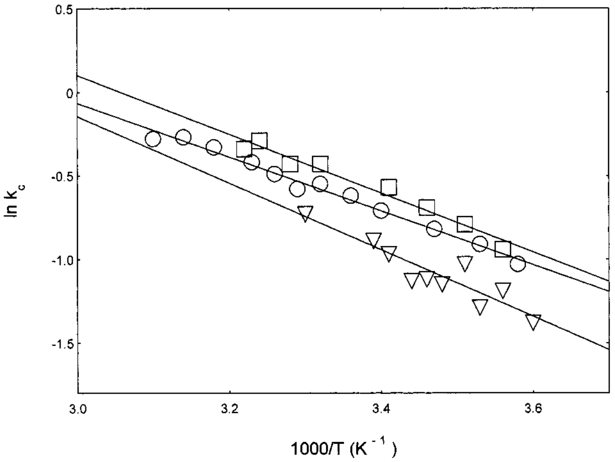

Figure 2. Arrhenius representation of the rate of macromolecular motion, k_c (= τ_c^{-1}), in methanol for ACE-NIPAM (○), ACE-STY(8.9)-NIPAM (□), and ACE-STY(16.9)-NIPAM (▽).

since none of these samples show LCST behavior in methanol. The fact that the presence of styrene affects the dynamics of a given polymer to a greater extent in water than in methanol suggests that relatively long-range intramolecular hydrophobic attractions might occur between the styryl residues in the aqueous medium. As we shall see below, the STY−NIPAM copolymers form intramolecular aggregates, even below the LCST of the system, which are capable of solubilizing organic guests.

The resultant activation energies, E_a, for the chain mobilities in methanol were estimated as 13.4 ± 0.5 kJ mol^{-1} for ACE-PNIPAM, 14.6 ± 0.5 kJ mol^{-1} for ACE-STY(8.9)-NIPAM, and 16.5 ± 0.5 kJ mol^{-1} for ACE-STY-(16.9)-NIPAM. A dependence of E_a upon styrene content is evident. However, given that the activation energy associated with solvent flow, E_η, is 11 kJ mol^{-1}, that for segmental motion, E_s, which according to Kramers'[26,27] theory is given by

$$E_s = E_a - E_\eta \tag{3}$$

appears to be unexpectedly low. As indicated previously,[9] we are currently involved in a research program that seeks clarification of the roles played by various solvents in determining E_a and E_s.

Fluorescence Quenching Measurements. Over a number of years, polymer chemists have used fluorescence quenching measurements to study the effects of conformational changes in macromolecular systems. The interested reader is directed to refs 5, 18, 19, and 25−28 (and references therein) for examples of the use of the technique. Briefly, dynamic collisional deactivation of a fluorescent species F* with a quencher Q (as in eq 4)

$$F^* + Q \rightarrow F + Q^* \tag{4}$$

can be described by the Stern−Volmer relationship

$$\tau^o/\tau = 1 + k_q\tau^o[Q] \tag{5}$$

where τ is the excited-state lifetime at some concentration Q, τ^o is that in the absence of Q, and k_q is the bimolecular quenching constant. (Consequently, k_q can be considered as a measure of the "ease of access" of Q to F*.) If a fluorescently labeled polymer is used, information regarding the "openness" or compactness of the chain and thence its conformational state can be accrued from such experiments.[5,29]

Table 2. Bimolecular Quenching Constants for NIPAM-Based Polymers in Aqueous Solution

sample	temp, °C	k_q ($\times 10^{-9}$), M^{-1} s^{-1}
ACE-PNIPAM	4	3.3
	22	7.0
	34	0.4
	45	0.2
ACE-STY(8.9)-NIPAM	4	2.9
	15	3.6
	35	0.4
ACE-STY(16.9)-NIPAM	4	1.3
	25	0.3

Stern−Volmer quenching experiments were carried out on each of the ACE-labeled polymer samples in both methanol and water, respectively, at various temperatures using CH_3NO_2 as a quencher. As has been observed previously with NIPAM-based systems,[9,11−13] the fluorescence decays were complex for the various polymers studied at each temperature and CH_3NO_2 concentration adopted, in both methanol and water. Using sums of exponentials for modeling, a triple-exponential function of the form of eq 6 was the minimum required to successfully fit the data on statistical grounds.

$$I(t) = A_1 \exp(-t/\tau_1) + A_2 \exp(-t/\tau_2) + A_3 \exp(-t/\tau_3) \tag{6}$$

To employ the data in Stern−Volmer analyses, an average lifetime, $\langle\tau\rangle$, of the ACE excited state was subsequently estimated from

$$\langle\tau\rangle = \frac{\sum A_i\tau_i^2}{\sum A_i\tau_i} \tag{7}$$

Linear Stern−Volmer plots were obtained for the various labeled polymer samples at each temperature and in each solvent. This gives confidence in the analytical procedures adopted. The resultant k_q values determined at various temperatures, in aqueous media, are listed in Table 2.

For ACE-PNIPAM, at temperatures below the LCST, a "normal" temperature response is obtained in that the value of k_q increases on going from 4 to 22 °C: as segmental motion is increased and as the rate at which the quencher diffuses through the solvent increases, so then will the extent of deactivation of the excited-state population also increase. Furthermore, k_q is close to that expected for a diffusion-controlled process in an aqueous medium, in this temperature range. This implies that, below the LCST, ACE-PNIPAM adopts an essentially open-chain conformation. In contrast, at 45 °C, a dramatic reduction is observed in the efficiency of quenching. This reflects the collapse of the polymer chain into a compact, globular structure which occurs at the LCST. Presumably, under these conditions, the ACE label is sequestered within the hydrophobic domains extant following phase separation. Similar behavior to that of the homopolymer is observed for ACE-STY(8.9)-NIPAM at all temperatures studied. Indeed, comparison of the two temperature extremes of 4 and 35 °C reveals that the quenching efficiency is remarkably similar for both ACE-PNIPAM and ACE-STY(8.9)-NIPAM. On the other hand, further examination of Table 2 shows that for ACE-STY(16.9)-NIPAM at 4 °C

Table 3. Bimolecular Quenching Constants for NIPAM-Based Polymers in Methanol

sample	temp, °C	k_q ($\times10^{-9}$), M^{-1} s^{-1}
ACE-PNIPAM	25	7.8
	42	9.3
ACE-STY(8.9)-NIPAM	15	6.3
	35	7.6
ACE-STY(16.9)-NIPAM	4	4.9
	25	6.5

a 2.5-fold reduction in k_q occurs when compared to that of the lower styrene content copolymer and the homopolymer, respectively. This provides convincing evidence to support that from TRAMS (see earlier), suggesting that intramolecular aggregates of styrene residues form to create hydrophobic cavities below the LCST of the STY(16.9) copolymer. At 25 °C (in excess of the LCST) a significant reduction is evident in the k_q value for ACE-STY(16.9)-NIPAM: this observation is consistent with collapse of the polymer coil to form a compact globular structure, which markedly reduces the rate of ingress of the quencher.

When dissolved in methanol, the k_q values obtained for the various NIPAM-based polymer samples are close to that expected for a diffusion-controlled process at each temperature in a solvent of viscosity corresponding to that of methanol, at that temperature (cf. Table 3). This infers that each polymer sample essentially adopts an open-chain conformation at each temperature accessed. Such would be expected for these samples which do not show LCST behavior in methanol.

Pyrene Solubilization Experiments. The ability of pyrene to act as a probe of the hydrophobicity of its immediate environment has been exploited over a number of years by polymer chemists interested in the conformational behavior of water-soluble systems.[5,9,13,18,30−32] Pyrene, used both as a label and simply dispersed as a probe, has provided valuable information regarding the polarity of its microenvironment through changes in both the vibrational fine structure[18,30−32] of its spectrum and its excited-state lifetime.[5,9,13,18]

Developed initially by spectroscopists interested in probing the interiors of micelles, the idea of using changes in two vibronic bands of the pyrene spectrum (3 and 1) has been borrowed and used to examine the conformational behavior of “smart” polymers.[5,9,13,18,30−32] For example, pyrene dispersed in the expanded form of poly(methacrylic acid), PMAA, at high pH has a 3/1 ratio of ca. 0.55.[18] (This is similar to that observed when pyrene is dissolved in water.) Upon contraction of the polymer at pH 3, the ratio increases to 1.0 due to encapsulation of the probe into the hydrophobic confines of the *hyper*coiled form of PMAA.[18] In this way, the 3/1 ratio of pyrene acts as a monitor of the conformational transition of the polyacid.

Pyrene (10^{-6} M) was dispersed in the various polymer samples, and its 3/1 ratio was measured for each, at various temperatures between 4 and 50 °C. The resultant data are plotted in Figure 3. The conformational transition of PNIPAM is very evident in the 3/1 data: the ratio increases from ca. 0.55 (which is similar to that obtained for pyrene in water) below the LCST to ca. 0.7 at temperatures in excess of 32 °C. Clearly, as the polymer contracts and phase separates, it is capable of sequestering the probe into a more hydrophobic environment than that of water. However, the value of the 3/1 ratio, which is attained above the LCST, is lower than that (ca. 1.0) realized in the *hyper*coiled form of PMAA:[18] presumably this indicates that the interiors of the globular form PNIPAM are less hydrophobic (or more water swollen) than those of PMAA.

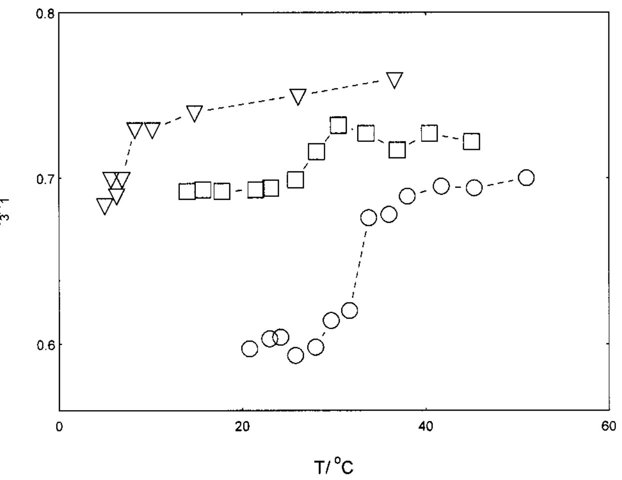

Figure 3. The 3/1 intensity ratios as a function of temperature, for pyrene (10^{-6} M) dispersed in ACE-PNIPAM[7] (○), ACE-STY(8.9)-NIPAM (□), and ACE-STY(16.9)-NIPAM, (▽). [All samples contained 10^{-2} wt % in polymer.]

Several spectroscopic features of note become apparent when pyrene is dispersed within the ACE-STY(8.9)-NIPAM and ACE-STY(16.9)-NIPAM copolymer systems (cf. Figure 3):

(i) Incorporation of styrene serves to shift the conformational transition of the polymer (as sensed by the pyrene probe) to lower temperature (the greater the aromatic content, the lower the LCST).

(ii) The magnitude of the transition, as estimated from the change in 3/1 ratio, decreases upon modification of PNIPAM with styrene. Indeed, even below the LCSTs of the copolymers, the pyrene emission is characterized by a 3/1 ratio which is only obtained, using PNIPAM as host, *above* the critical temperature of the system.

(iii) The 3/1 ratio obtained above the LCST increases, relative to that observed for PNIPAM above its LCST, with increasing hydrophobe content.

Clearly, the modified polymers offer the probe solubilizing environments with greater degrees of hydrophobicity above their LCSTs than does PNIPAM itself. Furthermore, the fact that the 3/1 ratio for pyrene dispersed in both ACE-STY(16.9)-NIPAM and ACE-STY(8.9) below their respective LCSTs is ca. 0.7 (a value similar to that of PNIPAM *above* its LCST) provides supporting evidence (to that of TRAMS, see earlier) for the existence of solubilizing domains, formed through intramolecular aggregation of styryl residues, within these modified polymers.

The excited-state lifetime, τ_f, of pyrene is also sensitive to its environment[33] and has been used as a gauge of hydrophobicity in water-dispersible systems.[5,9,13,18] In this way, details regarding the conformational behavior of “smart” polymers have been revealed through use of pyrene dispersed in pH responsive[5,18] and thermoresponsive[9,13] macromolecular hosts. In our experience, the excited-state decay kinetics of the probe/polymer aqueous dispersions are complex, normally requiring multiexponential models to fit the data. (Presumably, this reflects the broad distribution of solubilization sites accessible to the pyrene.)

Decays of the fluorescence of pyrene dispersed (10^{-6} M) within the various NIPAM-based polymers were collected at various temperatures between 4 and 50 °C.

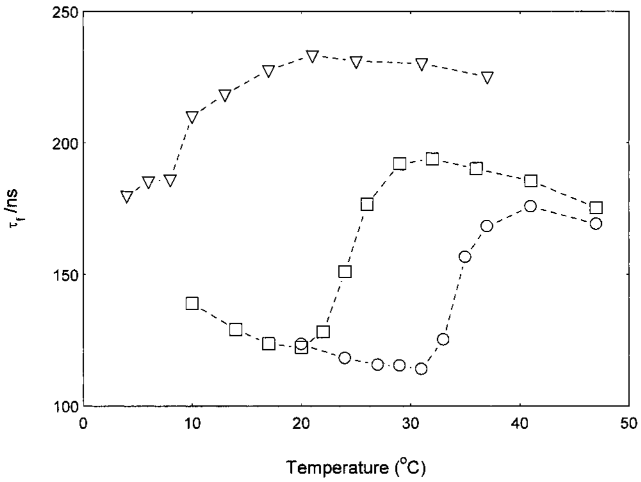

Figure 4. Mean lifetime data, $\langle\tau\rangle$, as a function of temperature, for pyrene (10^{-6} M) dispersed in ACE-PNIPAM[7] (○), ACE-STY(8.9)-NIPAM (□), and ACE-STY(16.9)-NIPAM (▽). [All samples contained 10^{-2} wt % in polymer.]

In the current work, modeling of the decay by a triple-exponential function of the form of eq 6 provided a statistically adequate description of the data. The average excited-state lifetime, $\langle\tau\rangle$, was calculated via eq 7.

Better resolution of the conformational transitions of the various polymers (than that from the 3/1 intensity ratios) is afforded by consideration of the $\langle\tau\rangle$ data (cf. Figure 4). The onset of the conformational transition of PNIPAM is clearly evident at ca. 32 °C: below this temperature a short $\langle\tau\rangle$ is apparent (ca. 130 ns), which is similar to that of pyrene in water.[13,18] Above the LCST, $\langle\tau\rangle$ increases to ca. 180 ns, which is characteristic of solutions of the probe in more hydrophobic media. Clearly, collapse of the PNIPAM chain into its compact globular structure creates an environment that is capable of encapsulating the pyrene. In this way, the plot amply demonstrates the reversible release and uptake of the probe that can be effected through variation of the temperature of the system. The thermal response of $\langle\tau\rangle$ mirrors that observed in changes in the vibrational fine structure of the probe's fluorescence and shows once more that copolymerization with styrene serves to shift the onset of the LCST to lower temperature. Again, the magnitude of the transition decreases with increasing hydrophobe content of the polymer.

The data supply conclusive evidence for the formation of hydrophobic cavities within the polymers which are capable of sequestering the pyrene above the LCST of each system. For the two hydrophobically modified copolymers, it is apparent that the spectroscopic probe is either occluded in a more protective environment than is provided by the PNIPAM globule or that a greater proportion of the pyrene molecules are partitioned within the hydrophobic domains. The effect is enhanced the greater the degree of hydrophobic domains. These observations agree with those made on the basis of 3/1 emission intensity ratios for the guest.

Below the LCST of the system, the $\langle\tau\rangle$ data show that the (STY 16.9)-NIPAM copolymer retains a significant capacity for solubilizations of the pyrene guest. This result agrees with that obtained using the 3/1 intensity ratio. However, on the basis of the guest's excited-state lifetime, it would be concluded that the copolymer of lower styrene content [(STY 8.9)-NIPAM] has no more capacity for pyrene solubilization that does PNIPAM itself.[37] In this respect, the inference to be drawn differs from that made upon consideration of 3/1 emission intensity data. Presumably, this reflects upon the fact that the 3/1 ratio is related to the "average hydrophobicity" of the environment sensed by the probe whereas $\langle\tau\rangle$ senses the degree of protection of the guest's excited state from the deactivating effects of its local environment.

These spectroscopic probe experiments provide valuable information regarding the use of chemical modification to vary the LCST of NIPAM-based smart systems. If the objective is to alter the temperature range over which controlled release of a hydrophobic guest can be effected, through reduction of the polymer's hydrophilic/hydrophobic balance, such a strategy can be confounded by creation of hydrophobic, solubilizing "pockets" within the polymer, which will retain the hydrophobic guest at low temperature. Recently, we have demonstrated[12] that *increasing* the hydrophilic/hydrophobic balance of NIPAM-based thermoresponsive systems reduces the capacity of the polymer to "carry" organic guests *above* the LCST of the modified polymer. Clearly, simple chemical modification is limited in terms of achieving controlled temperature release/uptake using polymers of this type.

Finding alternative ways of modifying PNIPAM is obviously crucial in order to create the desired thermoresponsive controlled release properties. This is the subject of continuing work in our laboratories.

Conclusions

1. Luminescence techniques have proven useful in probing the effects of chemical modification upon the "smart" behavior of PNIPAM.

2. Alteration of the hydrophobic/hydrophilic balance of NIPAM-based polymers, through random copolymerization with styrene, changes the LCST of the thermoresponsive polymer. Unfortunately, this stratagem serves to reduce the magnitude of the transition and also (at higher aromatic contents) leads to disruption of the controlled release capability of the system: intramolecular styrene aggregation creates solubilizing domains even below the LCST of a modified system when ca. 16 mol % styrene is copolymerized with NIPAM.

3. TRAMS experiments, upon dilute solutions of ACE-labeled polymers, have proved capable of revealing, at the molecular level, the effects of chemical modification upon the thermoresponsive behavior of these novel macromolecules.

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References and Notes

(1) *Polymers in Aqueous Media: Performance through Association*; Glass, J. E., Ed.; Advances in Chemistry Series 223; American Chemical Society: Washington, DC, 1989.
(2) Winnik, F. M. *Polymer* **1990**, *31*, 2125.
(3) Bednar, B.; Trnena, J.; Svoboda, P.; Vajda, S.; Fidler, V.; Prochazka, K. *Macromolecules* **1991**, *24*, 2054.
(4) Schild, H. G. *Prog. Polym. Sci.* **1992**, *17*, 163.
(5) Soutar, I.; Swanson, L. In *Luminescence Spectroscopic Studies of Water-Soluble Polymers*; Urban, M. R., Provder, T. E., Eds.; ACS Symposium Series 598; American Chemical Society: Washington, DC, 1995; p 388.

(6) *Water Soluble Polymers*: *Synthesis, Solution Properties and Applications*; Shalaby, S. W., McCormick, C. L., Butler, G. B., Eds.; ACS Symposium Series 467; American Chemical Society: Washington, DC, 1997.
(7) Chee, C. K.; Rimmer, S.; Soutar, I.; Swanson, L. *Polymer* **1997**, *38*, 483.
(8) Heskins, M.; Guillet, J. E. *Macromol. Sci. Chem.* **1968**, *A2*, 1441.
(9) Chee, C. K.; Rimmer, S.; Soutar, I.; Swanson, L. *Polymer* **2001**, *42*, 5079.
(10) Yamamoto, I.; Iwasaki, K.; Hirotsu, S. *J. Phys. Soc. Jpn.* **1989**, *58*, 210.
(11) Chee, C. K.; Rimmer, S.; Soutar, I.; Swanson, L. In *Stimuli-Responsive Water Soluble and Amphiphilic Polymers*; McCormick, C. L., Ed.; ACS Symposium Series 780; American Chemical Society: Washington, DC, 2001; Chapter 13, p 223.
(12) Barker, I. C.; Cowie, J. M. G.; Huckerby, T. N.; Shaw, D. A.; Soutar, I.; Swanson, L. Manuscript in preparation.
(13) Flint, N. J.; Gardebrecht, S.; Swanson, L. *J. Fluoresc.* **1998**, *8*, 343.
(14) Chee, C. K.; Rimmer, S.; Soutar, I.; Swanson, L., to be published.
(15) Soutar, I.; Swanson, L.; Imhof, R. E.; Rumbles, G. *Macromolecules* **1992**, *25*, 4399.
(16) Marsh, A. J.; Rumbles, G.; Soutar, I.; Swanson, L. *Chem. Phys. Lett.* **1992**, *195*, 31.
(17) Soutar, I.; Swanson, L. *Macromolecules* **1994**, *27*, 4304.
(18) Ebdon, J. R.; Hunt, B. J.; Lucas, D. M.; Soutar, I.; Swanson, L.; Lane, A. R. *Can. J. Chem.* **1995**, *73*, 1982.
(19) Soutar, I.; Swanson, L.; Thorpe, F. G.; Zhu, G. *Macromolecules* **1996**, *29*, 918.
(20) Soutar, I.; Swanson, L., to be published.
(21) Wahl, P. *Chem. Phys.* **1975**, *7*, 210.
(22) Barkley, M. D.; Kowalczyk, A. A.; Brand, L. *J. Chem. Phys.* **1981**, *75*, 3581.
(23) Taylor, L. D.; Cerankowski, L. D. *J. Polym. Sci., Polym. Chem.* **1975**, *13*, 2551.
(24) Shibayama, M.; Mitzutani, S.; Nomura, S. *Macromolecules* **1996**, *29*, 2019.
(25) Feil, H.; Bae, Y. H.; Feijen, J.; Kim, S. W. *Macromolecules* **1993**, *26*, 2496.
(26) Kramers, H. A. *Physica* **1940**, *7*, 284.
(27) Helfand, E.; Skolnick, J. *J. Chem. Phys.* **1982**, *77*, 5714.
(28) Delaire, J. A.; Rogers, M. A. J.; Webber, S. E. *J. Phys. Chem.* **1984**, *88*, 6219.
(29) Arora, K. S.; Turro, N. J. *J. Polym. Sci., Chem. Ed.* **1987**, *25*, 259.
(30) Chu, D. Y.; Thomas, J. K. *Macromolecules* **1989**, *17*, 2142.
(31) Soutar, I.; Swanson, L. *Eur. Polym. J.* **1993**, *29*, 371.
(32) Soutar, I.; Swanson, L. In *Current Trends in Polymer Photochemistry*; Allen, N. S., Ed.; Ellis Horwood Publishers: Chichester, UK, 1995.
(33) Chu, D. Y.; Thomas, J. K *Macromolecules* **1984**, *17*, 2142.
(34) Chu, D. Y.; Thomas, J. K. *J. Am. Chem. Soc.* **1986**, *108*, 6270.
(35) Olea, A. F.; Thomas, J. K. *Macromolecules* **1989**, *22*, 1165.
(36) Birks, J. B. *Photophysics of Aromatic Molecules*; Wiley-Interscience: London, 1970.
(37) We have demonstrated, recently, that TRAMS data reveal that, even below its LCST, a small fraction of pyrene molecules are associated with PNIPAM coils.[38]
(38) Chee, C. K.; Ghiggino, K. P.; Smith, T. A.; Rimmer, S.; Soutar, I.; Swanson, L. *Polymer* **2001**, *42*, 2235.

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