Studies of the "Smart" Thermoresponsive Behavior of Copolymers of *N*-Isopropylacrylamide and *N*,*N*-Dimethylacrylamide in Dilute Aqueous Solution

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ABSTRACT: Various fluorescence techniques and cloud point measurements have been used to study the effects of altering the hydrophilic/hydrophobic balance in a series of *N*-isopropylacrylamide (NIPAM)/*N*,*N*-dimethylacrylamide (DMAC) statistical copolymers upon the smart thermal responses of these systems in dilute aqueous solution. As expected, incorporation of DMAC into the polymer structure raises its lower critical solution temperature to an extent dependent upon DMAC content. However, use of such a hydrophilic modifier reduces the magnitude of the collapse transition that characterizes the macromolecule's thermal response. In PNIPAM, the LCST is associated with a conformational transition between a coil and a globule. However, introduction of DMAC derivatives into the polymer expands its "globular" form into a much more open structure that progressively loses its capacity for solubilization of organic guests. Consequently, although copolymerization with more polar monomers can be used to raise the LCST of NIPAM-based thermoresponsive polymers, the value of this approach will be limited in applications requiring switchable carrier/release properties.

Introduction

Thermally induced phase separation is rarely encountered upon raising the temperature of fluid mixtures of low molar mass species. The archetypal example of a system exhibiting a lower critical solution temperature (LCST) is that of nicotine and water.[1] In contrast, observation of an LCST in aqueous solutions of certain water-soluble polymers is expected[2] to be a fairly common occurrence. The principles involved are well-established: specific interactions between solute and solvent are required which result in negative values for the changes in both the enthalpy, ΔH_m, and the entropy, ΔS_m, of mixing. Clearly, if phase separation is to be observed (upon heating) in aqueous solutions at atmospheric pressure, the relative magnitudes of ΔH_m and ΔS_m must be such as to effect a reversal in the sign of the free energy change, ΔG_m, at some temperature less than 100 °C. Given these prerequisites, Taylor and Cerankowski[2] have reasoned that the LCST of a water-soluble polymer will depend on its hydrophilic/hydrophobic balance. Consequently, they maintained that the LCST of a series of molecules containing a common monomer (which confers LCST characteristics in an aqueous medium) can be varied continuously through incorporation of a more hydrophilic component through copolymerization. This prediction has been validated in various reports of the LCST behaviors of a diverse range of copolymers (see, for example, refs 2−5 and references therein).

Poly(*N*-isopropylacrylamide), PNIPAM,[2] and copolymers containing NIPAM[2−6] have attracted much attention due to their ability to exhibit thermoresponsive "smart" behavior in aqueous solution. The rapidity with which the thermoreversible response of such species is established in aqueous media has been attributed[7] to the operation of a two-stage mechanism: individual chains collapse, in a coil-to-globule transition, prior to aggregation of the resultant globules. Support for this proposition has been furnished by light scattering,[8−11] fluorescence energy transfer,[12] and time-resolved fluorescence anisotropy measurements (TRAMS).[13] Evidence for the key role that the collapse of individual polymer chains adopts in effecting the rapid thermoreversibility of phase separation in NIPAM-based polymers in aqueous solution seems indisputable. However, debate continues concerning the major determinant of the coil-to-globule transition. Some authors[14,15] favor the breakdown of polymer−water hydrogen-bonding interactions in controlling the macromolecular contraction whereas others[4,5,8,9,16,17] attribute the chain collapse to changes in the "hydrophobic effect" which, it is argued, induces local structure in the solvent molecules surrounding the hydrophobic substituents of the polymer.

It is likely that both effects contribute to the observed thermoresponsive properties of NIPAM-based systems.[3,18] Recent work by Lin et al.[19] indicates that the LCST of PNIPAM is associated with changes in both hydrogen bonding and hydrophobic effects within the interacting polymer−solvent system. However, this does not resolve the issue as to which (if either) effect is primarily instrumental in induction of the conformational transition.

Numerous reports have appeared concerning the effects of chemical modification (through copolymerization) upon the LCST of NIPAM-based systems. Developments in this field prior to 1992 have been summarized in an excellent review.[3] In general, modification

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Table 1. Characteristics of NIPAM/DMAC Copolymers

sample	DMAC content[a] of feed/mol %	DMAC content[a] of polymer/mol %	cloud point/°C
PNIPAM	0	0	32
NIPAM/DMAC 10	10.9	13	36
NIPAM/DMAC 20	20.1	27	39
NIPAM/DMAC 30	31.2	30	42
NIPAM/DMAC 40	40.1	50	50
NIPAM/DMAC 50	50.9	60	63
NIPAM/DMAC 60	60.0	66	72
NIPAM/DMAC 80	77.9	74	*b*

[a] Expressed in terms of total acrylamide content. [b] No cloud point observable below 100 °C at atmospheric pressure.

of the macromolecule's hydrophilic/hydrophobic balance changes its LCST in the manner predicted by Taylor and Cerankowski:[2] the more hydrophilic the copolymer, the higher is its LCST.[2−6,20−23]

In the current work, we have synthesized a series of NIPAM-based, thermoresponsive macromolecules within which the hydrophilic/hydrophobic balance has been altered by incorporation, through copolymerization, of varying amounts of *N*,*N*-dimethylacrylamide (DMAC). We have shown, in agreement with previous studies,[5] that increasing the DMAC content of a NIPAM/DMAC copolymer raises its LCST (relative to that of PNIPAM) to an extent which depends on the amount of the more hydrophilic comonomer (DMAC) present in the system. More importantly, we have applied time-resolved emission spectroscopic methods, upon fluorescently labeled polymers, to study the effect of increasing the DMAC content of NIPAM/DMAC copolymers upon the dynamic behavior of individual polymer chains in aqueous media. We have demonstrated that increasing the hydrophilic content of the NIPAM/DMAC copolymers results in production of increasingly expanded and flexible globules above the LCST of each particular system. In this respect, we have rationalized the observations of Shibayama et al.[5] (for NIPAM/DMAC) and Feil et al.[4] (for other NIPAM-based systems), who reported that increasing the hydrophilic content of the copolymer reduces the change in enthalpy which is observed upon passing through its LCST. Our data show that the major effect of incorporation of a more hydrophilic monomer is to alter the final state of the polymer above its LCST, thereby reducing the change in its condition across the transition that marks its LCST.

Experimental Section

Materials. *N*,*N*-Dimethylacrylamide, DMAC (Aldrich, 99%), was prepolymerized (UV irradiation) prior to fractional distillation under high vacuum ($<10^{-5}$ Torr) immediately prior to use. *N*-Isopropylacrylamide (Aldrich, 97%) was purified by multiple recrystallization from a mixture (60/40%) of toluene and hexane (both spectroscopic grade; Aldrich).

α,α′-Azobis(isobutyronitrile), AIBN (BDH, 97%), was recrystallized from ethanol (Aldrich, spectrophotometric grade).

1,4-Dioxane (Aldrich, 99.9%, HPLC grade) was used without further purification.

Acenaphthylene, ACE (Aldrich, 85%), was recrystallized (four times) from methanol (Aldrich, 99.9%, spectrophotometric grade) prior to sublimation (twice) under high vacuum.

NIPAM/DMAC copolymers were synthesized in dioxane solution (ca. 50 wt % dioxane) at 65 °C, under high vacuum, using AIBN as initiator. Polymerization was terminated at 20−30% conversion of monomer. The polymers were purified by multiple precipitations (six times) from dioxane into ether. Copolymer compositions were estimated by ^{1}H NMR (JEOL GSX400, 400 MHz spectrometer) and are listed in Table 1. Fluorescently labeled polymers contained ca. 0.6 mol % ACE in feed (producing a label concentration of about 1 mol % in the resultant polymer).

Instrumentation. Steady-state fluorescence spectra (uncorrected for wavelength dependence of excitation source intensity and instrument response) were measured on a Perkin-Elmer LS50 spectrometer.

Fluorescence lifetime data were acquired on an IBH System 5000 or an Edinburgh Instruments 199 time-correlated single-photon counter. Both spectrometers employed D_2 as discharge medium in the nanosecond flashlamps used as pulsed excitation sources.

Time-resolved fluorescence anisotropy measurements (TRAMS) were made upon dilute (10^{-3} wt %) aqueous solutions of the ACE-labeled copolymers using time-correlated, single-photon counting. The orthogonally polarized decay data were analyzed at 340 nm, following excitation of the ACE label by vertically polarized synchrotron radiation, at 290 nm, from the SRS, Daresbury. The SRS and its use in the study of macromolecular dynamics, via TRAMS, have been described elsewhere.[24]

All emission spectroscopic studies were performed upon air-saturated solutions.

Results and Discussion

Cloud Point Measurements. Cloud points of the various polymers were estimated as the temperature at which turbidity first became apparent, visually, in solutions containing 10^{-2} wt % of polymer. The resultant data are listed in Table 1.

Increasing the content of the more hydrophilic monomer, DMAC, leads to an increase of the LCST of the system, to a degree dependent upon copolymer composition. The results are as might be expected from the predictions of Taylor and Cerankowski[2] and on the basis of other studies[2,4,5] in which the hydrophilic/hydrophobic balance of NIPAM-based systems was altered.

In those cases (NIPAM/DMAC10, NIPAM/DMAC20, and NIPAM/DMAC30) in which the compositions are comparable, the current estimates of LCST are lower, at any given DMAC content, than those quoted by Shibayama et al.[5] (DSC data) for analogous cross-linked NIPAM/DMAC gels. Clearly, cross-linking of the polymer, reducing its segmental mobility both below and above the LCST, increases the critical temperature, presumably by reducing $|\Delta S|$ for the transition. (Since ΔS_m is negative, reduction of its magnitude, $|\Delta S_m|$, will raise the temperature at which ΔG_m for the polymer−solvent mixing process becomes positive, given the assumption that for a particular DMAC composition cross-linking has a minimal effect upon ΔH_m.)

In the system of highest DMAC content, NIPAM/DMAC80, turbidity did not become apparent below the boiling point of the aqueous solution.

Fluorescence Studies of ACE-Labeled Systems. Various fluorescence spectroscopic techniques have been applied to assess the effects of the conformational transition of each NIPAM/DMAC copolymeric host upon the emission from its covalently bound ACE label. As discussed below, the photophysical characteristics of the ACE label (notably the anisotropy of its emission and the susceptibility of its excited state to deactivation by an aqueous-borne quencher) can provide unique insights into the effects of altering the hydrophilic/hydrophobic balance of the macromolecule upon the intramolecular conformational transition that accompanies its LCST.

(*i*) *Spectroscopy and Fluorescence Lifetime Measurements.* The fluorescence spectral profile of the ACE label bound to a water-soluble polymer is not particularly sensitive to changes in the polarity of its microenviron-

ment. Slight variations within the vibronic structure of the label's fluorescence were detected in the spectra obtained from dilute (10^{-2} wt % in polymer) solutions of PNIPAM and the lower content DMAC copolymers, as the temperature of the system was raised through its LCST. However, the changes that occur in the emission spectrum of the ACE label are not sufficiently significant to provide information upon the effect that incorporation of DMAC might have upon either the coiled or globular forms of each macromolecule which are adopted below or above, respectively, its LCST.

ACE-labeled poly(methacrylic acid) exhibits a marked change in the excited-state lifetime, τ_f, of its fluorescent tag, in the pH-controlled coil-to-globule transition between the polysalt and polyacid forms of the macromolecule.[25] Consequently, it might be expected that the ACE label, through τ_f, would provide a similar, simple means of detecting the LCST in NIPAM-based polymers. However, τ_f (estimated here from fluorescence decay profiles analyzed at 340 nm, following excitation at 290 nm) is *not* particularly sensitive to the onsets of the thermally induced conformational transitions in these NIPAM/DMAC copolymers. As for most fluorescent species in fluid media, the excited-state lifetimes of the labels decrease slightly as temperature increases. However, in the region of the LCST, there is only mildest of deviations from this trend as τ_f remains constant (at ca. 33 ns in the case of the ACE-labeled PNIPAM, for example) over a range of about 10 °C.

These spectroscopic studies provide no insight into the effects that DMAC-induced hydrophilic modification might have upon the polymer's conformational transformation. In contrast, TRAMS, fluorescence quenching, and pyrene solubilization experiments, as discussed below, indicate that the nature of the transition is significantly altered as the DMAC content of the copolymer is raised.

(*ii*) *Time-Resolved Anisotropy Measurements (TRAMS).* Consequent upon its mode of attachment to the polymer, motion of the ACE label reflects the mobility of the segment of the macromolecule in which it is incorporated (see, for example, refs 24, 27, and 28 and references therein). The label's dynamics are revealed in emission anisotropy experiments, and those involving TRAMS are particularly informative (relative to those performed under conditions of steady-state excitation) in this respect.

The TRAMS approach involves photoselection (from a random distribution of chromophores) by use of a pulse of polarized excitation, of those labels for which subsequent reorientation (through rotational motion) is to be studied. The time dependence of the intensities of fluorescence emitted in planes oriented parallel, $I_{||}(t)$, and perpendicular, $I_{\perp}(t)$, to that of the polarized excitation is analyzed. The data can be transformed into the resultant time-dependent anisotropy, $R(t)$, by means of eq 1.

$$R(t) = \frac{I_{||}(t) - I_{\perp}(t)}{I_{||} + 2I_{\perp}(t)} = \frac{D(t)}{S(t)} \qquad (1)$$

Here, $D(t)$ is the "difference function" which contains information regarding the rate of rotational diffusion of the chromophore (which is what we seek). $S(t)$, the "sum function", contains no such information: $S(t)$ merely reflects the rate of decay of the population of photoselected excited states.

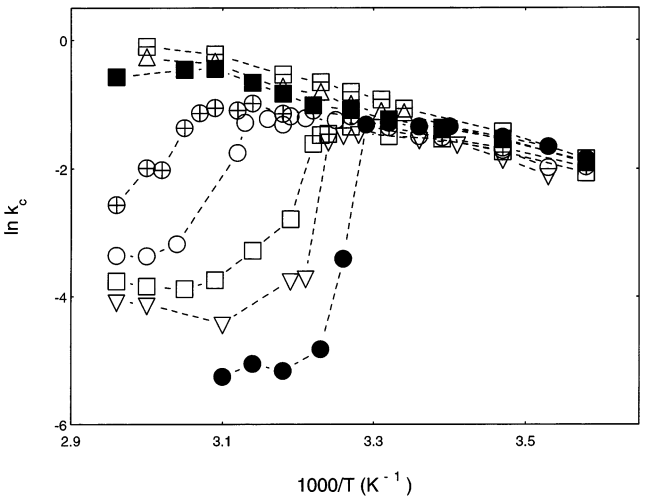

Figure 1. Temperature dependences of the segmental mobilities of PNIPAM (●), NIPAM/DMAC10 (▽), NIPAM/DMAC20 (□), NIPAM/DMAC30 (○), NIPAM/DMAC40 (⊕), NIPAM/DMAC50 (■), NIPAM/DMAC60 (△), and NIPAMDMAC80 (⊡). The rate parameter, k_c, quantifying the rate of segmental motion, is the reciprocal of τ_c.

Recovery of information concerning rotational relaxation of fluorescent species is complicated in instances in which the perturbing influence of the excitation pulse is significant within the time scales imposed by the lifetime of the excited state under study or its rate of rotational tumbling. We have discussed the problem elsewhere.[24] In the current study, we have employed the method of impulse reconvolution[29] in "deconvolution" of the observed difference function, $D(t)$.

The fluorescence anisotropy behavior of the ACE-labeled NIPAM/DMAC copolymers is complex, a general feature of water-soluble polymers.[26−28] This reflects the heterogeneous range of environments inhabited by the ACE label in aqueous dispersions of the NIPAM/DMAC copolymers. To obtain an effective means of quantifying the macromolecular segmental dynamics of the various copolymers, we have modeled the true anisotropy, $r(t)$, of the fluorescence from the label by use of a single-exponential function of the form

$$r(t) = r_0 \exp(-t/\tau_c) \qquad (2)$$

where τ_c is the correlation time characteristic of the label/segment reorientation and r_0 is the "intrinsic anisotropy" of the ACE label. The faster the relaxation rate of the label/polymer, the shorter is τ_c.

Figure 1 shows (in "Arrhenius form", with $k_c = \tau_c^{-1}$) the temperature dependence of τ_c for PNIPAM and the NIPAM/DMAC copolymers. Examination of these data reveals that, in general, the onset of the LCST (as detected in cloud point measurements) is accompanied by a reduction in the segmental mobility of the polymer. This is entirely consistent with the proposal[7−13] that the first stage in the mechanism governing the LCST behavior of NIPAM-based systems is an intramolecular coil-to-globule transition. The increasing segment density within the collapsing coil will place considerable restrictions upon chain mobility. However, the magnitude of the effect is dependent upon the composition of the NIPAM/DMAC copolymers: the greater the DMAC content of the system, the less dramatic is the change in polymer dynamics in the conformational transition.

The effects of copolymer composition upon chain dynamics mirror those that are evident from calorimet-

ric studies of NIPAM/DMAC gels:[5] as the DMAC content of the system is increased, the LCST is raised, the transition becomes more diffuse, and its "intensity" reduces. However, the TRAMS data reveal that this reduction in "intensity" occurs largely as a result of the influence of the DMAC upon the nature of the collapsed polymer coil. As shown in Figure 1, DMAC has little effect upon the segmental dynamics of the open coil forms of the polymers below their LCSTs. τ_c is reduced from ca. 5 ns for PNIPAM at 25 °C to only about 3 ns for NIPAM/DMAC80. Above the LCST, on the other hand, the presence of DMAC dramatically increases the segmental mobility of the macromolecule relative to that of the globular form of PNIPAM itself.[13] Clearly, the presence of the more hydrophilic monomer reduces the hydrophobic interactions between NIPAM units that induce contraction of the coil dimensions above the LCST. The TRAMS data indicate that as their hydrophilic content is increased, the NIPAM/DMAC copolymers adopt ever more open conformations above their respective LCSTs compared to that of the PNIPAM globule. This observation is supported by fluorescence quenching data (as described below) although it seems to contradict earlier microscopy work where it was reported[5] that the presence of DMAC did not affect the diameter of shrunken NIPAM/DMAC gels (albeit over a much more limited range of DMAC contents).

(*iii*) *Fluorescence Quenching Measurements.* An aqueous-borne quencher, such as nitromethane, can be used to probe the local environment of a fluorescent label, such as ACE, since the efficiency of quenching is a gauge of the accessibility of the label, by the quencher. For the case of a dynamic quencher, Q, the quenching of the fluorescent excited state, F*, represented as

$$F^* + Q \rightarrow F + Q^* \tag{3}$$

is expected to obey Stern−Volmer kinetics, wherein

$$\frac{\tau^0}{\tau} = 1 + k_q \tau^0 [Q] \tag{4}$$

where τ^0 and τ are the lifetimes of the excited state in the absence and presence of a given concentration of quencher, [Q], respectively. The bimolecular rate constant, k_q, is a measure of the ease with which F* can be accessed.

The decay behavior of the fluorescence from each of the ACE-labeled polymers is complex, whether the system is above, or below, its LCST. This is a fairly general observation for fluors dispersed in aqueous polymer solutions, whether as a molecular solute or as a covalently bound label.[25−28] The question then arises as how best to represent the lifetime of the probe's excited state. The approach that we have adopted here, as in earlier studies,[25−27,29] is to fit the time-resolved fluorescence from the label using a multiexponential function of sufficient complexity (dual or triple exponential) to provide a minimally acceptable description of the data and to calculate an average fluorescence lifetime, $\langle\tau\rangle$, from the resultant fitting parameters, A_i and τ_i, using eq 5.

$$\langle\tau\rangle = \frac{\sum A_i \tau_i^2}{\sum A_i \tau_i} \tag{5}$$

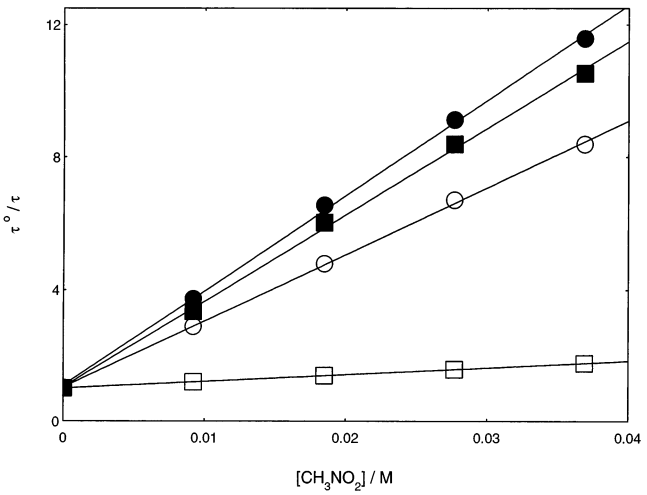

Figure 2. Stern−Volmer plots for the quenching of fluorescence from ACE-labeled NIPAM/DMAC10 at 45 °C (□) and 21 °C (■) and NIPAM/DMAC20 at 45 °C (○) and 21 °C (●).

Table 2. Quenching Data

polymer	*T*/°C	$10^9 k_q$/M^{-1} s^{-1}
PNIPAM	25	7.0
	42	0.2
NIPAM/DMAC10	21	7.8
	45	1.4
NIPAM/DMAC20	21	8.3
	45	6.7
NIPAM/DMAC30	21	7.5
	45	4.2

Using this approach, Stern−Volmer kinetics were found to hold in all cases for the quenching of ACE-labeled NIPAM/DMAC copolymers by nitromethane. Typical quenching plots are shown in Figure 2. Selected k_q values are listed in Table 2.

For each system, below the LCST, the value obtained for k_q (ca. 7.5×10^9 M^{-1} s^{-1}) is of the order expected for the diffusion-controlled quenching of a polymer-bound fluor by a mobile quencher at the given temperature and solvent viscosity. (For a discussion of the factors involved, see, for example, ref 25.) However, the conformational transformation occurring at the LCST in PNIPAM and NIPAM/DMAC10 clearly produces a dramatic reduction in quenching efficiency. As the polymer chains collapse, occlusion of the labels into the hydrophobic interiors of the globule markedly reduces the frequency of ACE−CH_3NO_2 encounters. Indeed, the degree of protection afforded to the ACE labels of PNIPAM or NIPAM/DMAC10 against quenching by CH_3NO_2 is comparable to that enjoyed by the same label within the hypercoiled form of poly(methacrylic acid) formed at low pH.[30]

At higher DMAC contents (≥20 mol %) the LCST has a significantly reduced effect upon k_q. Clearly, the rate of diffusion of the quencher within the coils of the copolymers is similar to that in water and/or the interiors of the copolymers below their LCSTs. This indicates that the higher DMAC content NIPAM/DMAC copolymers exist as relatively open, water-swollen structures both above and below their LCSTs. These quenching data support the findings of our TRAMS investigations, discussed above. It is evident that the presence of DMAC, at higher contents, destroys the ability of individual polymer chains (as studied at 10^{-3} wt % polymer) to form globular structures above the LCST of a given system. At higher concentrations of polymer

(e.g., 10^{-2} wt %) aggregation occurs to form conglomerates of these partially collapsed polymer coils which are sufficiently large to scatter visible light, producing the turbidity observed above the LCST of the system. On the basis of the quenching measurements, it is predictable that the higher DMAC content species will not have the capacity to solubilize hydrophobic guests. Tests of this assumption are discussed below.

Studies of Pyrene Solubilization. Pyrene was deposited upon the walls of a volumetric flask by evaporation of solvent from an aliquot of a master solution of the fluorescent probe in diethyl ether.

The pyrene was subsequently dispersed, from the thin film of solute, in the medium to be studied**.** For aqueous solutions of PNIPAM and the DMAC/NIPAM copolymers, attempts were made to solubilize pyrene at temperatures in excess of the LCST of the system. In each case, the concentration of pyrene was 10^{-6} M and that of polymer, when present, 10^{-2} wt %.

Pyrene is frequently used as a spectroscopic sensor of the polarity of the microenvironment in which it is dispersed. In dilute pyrene solutions, for example, reduction in the polarity of the solvent causes changes in the profile of the probe's emission spectrum (generally quantified through increases in the ratio, I_3/I_1, the relative intensities of the first and third vibronic bands[31,32]) and shifts in its excitation spectra to longer wavelengths.[26] The lifetime of the excited state of pyrene is also sensitive to the polarity of the medium in which it is dispersed[33] and has been used as a sensor to detect the formation of hydrophobic microdomains within the coils of water-soluble polymers.[26−28,34] Indeed, the sensitivity of the excited-state lifetime of this dispersed probe to the nature of its local environment often makes it more reliable than the I_3/I_1 ratio[35] as a sensor of conformational change in a polymeric host. This proved to be the case in the current studies of these NIPAM/DMAC copolymer systems.

Time-resolved fluorescence data from dispersions of pyrene in the various NIPAM/DMAC polymers were collected at 400 nm following excitation at 340 nm. As in the case of the ACE label, the decay kinetics of the pyrene fluorescence are complex, reflecting the heterogeneous range of environments available to the probe.[26,28,34,35] Consequently, eq 5 was used, following multiexponential modeling of the decay curves, to provide an average fluorescence lifetime, $\langle\tau\rangle$, for the distribution of pyrene excited states.

The temperature dependence of $\langle\tau\rangle$ is shown for each of four of the systems studied in Figure 3. As the PNIPAM coil collapses into a globule, the pyrene molecules become preferentially solvated within the hydrophobic interiors of the macromolecular structure. This is reflected in a dramatic increase in $\langle\tau\rangle$ at the LCST. The value of the fluorescence lifetime (120−130 ns) obtained below the LCST is similar to that of pyrene in water.[26,35,36] Above the LCST, on the other hand, the excited-state lifetime of more than 170 ns indicates that a significant proportion of the pyrene molecules become sequestered within the protective confines of the globule's interior.

Incorporation of DMAC into the polymer's structure does not only alter the LCST of the resultant species, it also affects the solubilization capacity of the polymer for organic guests.

As can be seen in Figure 3, as little as 10 mol % DMAC reduces the change in $\langle\tau\rangle$, across the transition,

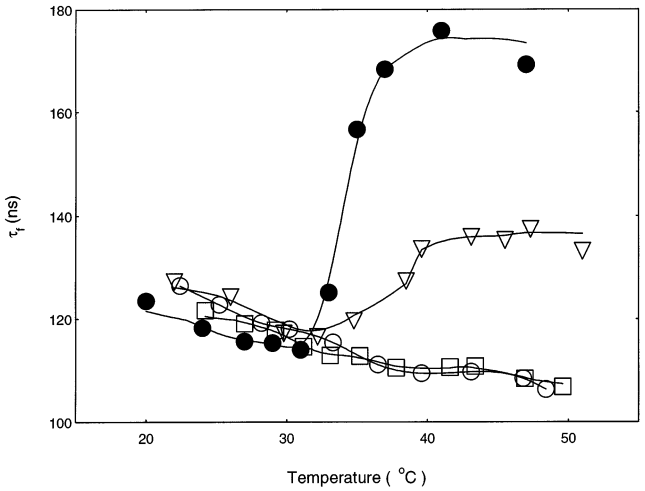

Figure 3. Variation of average excited-state lifetime of pyrene, dispersed in aqueous solutions of PNIPAM (●), NIPAM/DMAC10 (▽), NIPAM/DMAC20 (○), and NIPAM/DMAC30 (□).

to less than 20 ns (compared to one in excess of 50 ns in the case of PNIPAM). This indicates that, even at this low DMAC content, alteration of the hydrophilic/hydrophobic balance of the macromolecule through the introduction of the more polar comonomer, affects the nature of the collapsed form of the polymer, formed above its LCST. The pyrene experiences a more polar "average environment" in the copolymer than it occupies in PNIPAM above the respective LCSTs of the two hosts.

It could be that the $\langle\tau\rangle$ data merely reflect the fact that the interior of the shrunken copolymer is more polar (due to the presence of DMAC) than that of the PNIPAM globule. (This, in turn, would increase the proportion of the pyrene probes partitioned into the aqueous phase, thereby reducing $\langle\tau\rangle$.) However, a more plausible explanation is that the intrinsically more polar DMAC/NIPAM copolymer is a less compact species being extensively permeated by the aqueous medium, again presenting the pyrene probes with a less hydrophobic host environment and producing a less dramatic partitioning between the "polymer-rich" and largely aqueous phases. Both the anisotropy and the fluorescence quenching experiments, described above, suggest also that the structures formed by the DMAC/NIPAM copolymers, above their LCSTS, are considerably more expanded and water-permeated than the PNIPAM globule.

Reference to Figure 3 reveals that, at higher DMAC contents, the NIPAM/DMAC systems lose their capacity to solubilize hydrophobic guests, such as pyrene, above their LCSTs. Below the LCST, none of the NIPAM-based systems (including the homopolymer[34]) has any significant propensity for accommodating pyrene as either an occluded or an adsorbed guest.

Conclusions

Fluorescence measurements upon dilute aqueous solutions of ACE-labeled NIPA/DMAC copolymers have shown that increasing the hydrophilic/hydrophobic balance of the macromolecule moderates the extent of its coil collapse at the LCST. As the DMAC content of the system is raised, increasingly open, water-permeated conformations are encountered above the LCST: the ease of access of a water-borne quencher (CH_3NO_2) to

the ACE label is enhanced, and the NIPAM/DMAC species enjoy enhanced degrees of segmental mobility. In addition, the coil collapse transition, marking the LCST, becomes more diffuse.

The current data confirm earlier findings involving calorimetry[4,5] and microscopy[5] experiments conducted upon aqueous NIPAM-based gels[5] and solutions of "linear" polymers[4] that, increasing the hydrophilic/hydrophobic balance of such thermoresponsive systems, serves both to raise the LCST and to extend the temperature range over which the transition is apparent. The TRAMS data reveal that the reduction in ΔH for the transition that accompanies the incorporation of a more hydrophilic monomer into a NIPAM-based species[4,5] is not simply a reflection of a reduction in the number of H-bonding or "hydrophobic" interactions between the polymer and solvent. A physical change is effected in the structures adopted by the copolymers both below and above their respective LCSTs upon incorporation of the more polar comonomer (DMAC in the current case). Below the LCST, the change in segmental mobility of the copolymer, induced by incorporation of DMAC, is slight. Above the LCST, the segmental mobility of the macromolecule is significantly enhanced as its DMAC content is increased. Studies of the quenching of fluorescence from the ACE label of the NIPAM/DMAC copolymers reinforce the TRAMS observations. Above the LCST of a given NIPAM/DMAC system, the polymer coil becomes increasingly permeated by water as its DMAC content is raised.

Given that both monomers in the current study are acrylamides, with an ability to H-bond to H_2O, it is tempting to suggest that the current data serve to support proposals that the origins of the LCST originate, primarily, from a disruption of hydrophobic effects,[4,5,8,9,16,17] as temperature increases, rather than H-bonding.[14,15] However, this issue is far from resolved by the current data.

Our studies of pyrene solubilization in the NIPAM/DMAC copolymers indicate that, as the DMAC content is increased, the polymer (rapidly) loses its capacity to partition hydrophobic guests between its interiors and the surrounding aqueous medium. This is a significant observation. It implies that, while we can manipulate the LCST of the potential polymeric host by alteration of its hydrophilic/hydrophobic balance through copolymerization (or *other* means of functionalization), such strategies can dramatically reduce its capability to perform the task that we hope its thermoresponsivity will accomplish. This conclusion is significant for applications based upon solute uptake/release, such as drug delivery, enhanced chemistry (including photochemistry and solar energy conversion) with facile product release, and production of solute-selective membranes. Clearly, for the achievement of such goals, alternative approaches to the control of a system's LCST might have to be considered.

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