Photoregulated Association of *N*-(2-Hydroxypropyl)methacrylamide Copolymers with Azobenzene-Containing Side Chains

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ABSTRACT: The solution properties of *N*-(2-hydroxypropyl)methacrylamide copolymers containing photochromic azobenzene side chains were studied by light-scattering methods. While copolymers containing 4.4 and 8.3 mol % azobenzene were water soluble, copolymers with ≥9.3 mol % azobenzene were soluble in water only in the pseudomicellar form. Attempts have been made to influence the copolymer association behavior by UV photoirradiation exploiting the difference in solubilities of trans and cis configurations of azobenzene. It was found that metastable aggregates prepared by a stepwise increase in copolymer concentration in aqueous solutions readily dissociated in response to an external stimulus: UV irradiation. However, thermodynamically stable aggregates demonstrated only a limited response to UV irradiation.

Introduction

In recent years the association properties of copolymers in solution have been investigated with increasing attention.[1–11] Most of these studies evaluate solutions of block copolymers.[1–3] Block copolymers (diblock or triblock) associate and form micelles in selective solvents (i.e., in liquids which are good solvents for one block and precipitants for the other). Interest in hydrophobic/hydrophilic block copolymers forming water-soluble micelles with hydrophobic cores and hydrophilic shells has also rapidly increased.[4–11] The objectives of those studies were understanding the associational and conformational properties of the copolymers and the application of the micelles in the controlled release of hydrophobic substances into aqueous media.[9,10]

Additionally, a number of experimental studies of amphiphilic polymers in aqueous solutions have been published.[12–22] Early work on polysoaps covering both ionic and nonionic polymers was reviewed by Bekturov and Bakauova.[12] Functional amphiphilic molecules which exist in liquid crystalline phase in aqueous solutions can be attached as side chains to a polymer backbone. Depending on whether they are bound via the hydrophobic or hydrophilic part, two different types of polymers are produced. Both types of polymers should associate in solution, forming normal spherical, rodlike and disklike micelles.[14] A microscopic model for a formation of micelles in these systems has been developed recently.[23]

In our earlier paper[24] association phenomena were shown to occur in aqueous solutions of *N*-(2-hydroxypropyl)methacrylamide (HPMA) copolymers containing hydrophobic oligopeptide side chains terminated in *p*-nitroaniline. The hydrophobic end groups of the side chains play an important role in the association (aggregation) process. Recently, similar association behavior was observed in aqueous solutions of poly(L-glutamic acid)–adriamycin conjugates[25] and in cholesterol containing HPMA copolymers.[26] Random copolymers with amphiphilic properties in aqueous solution seem to possess an advantage over other micellar systems in that the association process can be relatively easily influenced by an external stimulus.

The aim of this study was the verification of this hypothesis. An attempt was made to control copolymer association reversibly by photoirradiation. The objectives were attained by incorporating a photochromic chromophore (azobenzene) into the side chains of *N*-(hydroxypropyl)methacrylamide copolymers. In recent years, considerable interest has been paid to synthetic photoresponsive polymers.[27–29] Photoinduced effects include light-induced conformational changes, solubility changes, photocontrol of membrane functions and photomechanical effects.[27] The study of photochromic properties of poly(L-glutamic acid) containing azobenzene units in the side chains has shown that the trans–cis photoisomerization may be accompanied by aggregation–disaggregation as well as precipitation–dissolution phenomena.[29]

The different solubilities of the existing photochromic configurations were exploited for a range of photoresponsive effects. In this contribution, the effect of irradiation on micellelike aggregate formation in aqueous solutions of HPMA copolymers containing azobenzene side chains is reported.

Experimental Section

Chemicals. *N*-(2-Hydroxypropyl)methacrylamide (HPMA) was prepared as previously described.[30] The initiator, 2,2′-azobis[isobutyronitrile] (AIBN) (recrystallized from methanol), was obtained from Fluka, and 4-aminoazobenzene and acryloyl chloride (freshly distilled before use) were received from Sigma. All other chemicals and solvents were of analytical or reagent grade.

Azo monomer, 4-(acryloylamino)azobenzene,[31] was synthesised by the reaction of acryloyl chloride with 4-aminoazobenzene in the presence of triethylamine in diethyl ether. The product was recrystallized twice from 90% ethanol. TLC (Merck Alufolien Kieselgel 60 F 254) in diethyl ether: one spot, R_f: 0.8. Mp 171 °C. The extinction coefficient (after 48 h in the dark) in ethanol (350 nm) was 2.95×10^4 L mol^{-1} cm^{-1}.

Spectral grade, dried ethanol was used as purchased (Quantum Chemical Corp.). Deionized water was used to prepare aqueous solvents.

Synthesis of Copolymers. Copolymers were prepared by radical precipitation polymerization of *N*-(2-hydroxypropyl)methacrylamide with 4-(acryloylamino)azobenzene in acetone. The polymerization mixture contained 15 wt % monomers (different molar ratios, cf. Table I) and 0.6 wt % AIBN. After polymerization, the precipitated copolymer was filtered off and reprecipitated twice from methanol into acetone. Purity was controlled with GPC chromatography using a Superose 6 column

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Table I
Composition and Molecular Characterization of Copolymers[a]

polym no.	amt of azo monomer (mol %) feed	amt of azo monomer (mol %) polymer	yield of polymer (wt %)	dn/dc (mL g^{-1})	$10^{-3}M_w$	τ (h^{-1})
1	5	4.4	73	0.181	60	6.7
2	10	8.3	71	0.189	90	9.7
3	11	9.3	69	0.190	100	
4	13	11.5	65	0.197	110	
5	15	12.5	61	0.199	130	12.2

[a] dn/dc = refractive index increment in ethanol; M_w = molar mass; τ = relaxation time for the thermal cis–trans isomerization in water.

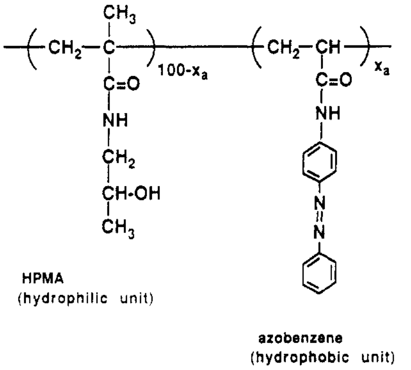

Figure 1. Chemical structure of the copolymers studied. x_A is the content of azobenzene groups.

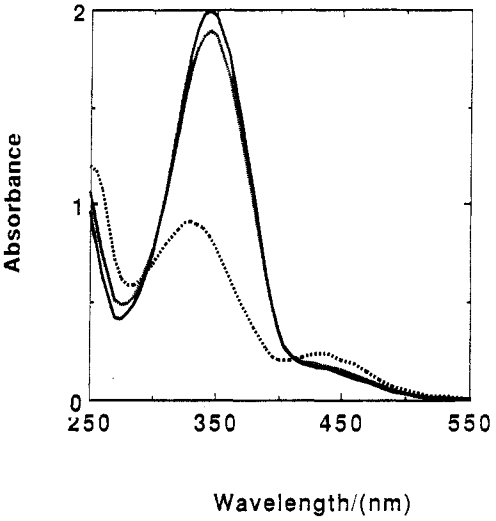

Figure 2. Absorption spectra in water of copolymer **2** (x_A = 8.3 mol %) at different trans/cis ratios: (—) dark; (- - -) photostationary state at 350 nm; (···) recovery after 2 h of irradiation with $\lambda \geq 420$ nm.

(FPLC Pharmacia system) with double detection (refractive index and UV 350 nm) in 0.02 M Tris (2-amino-2-(hydroxymethyl)-1,3-propanediol) pH 8.0 + 0.2 M NaCl buffer containing 30 vol % acetonitrile. The azo chromophore content was determined by UV spectrophotometry in ethanol. The properties of the copolymers prepared and investigated are summarized in Table I and their structures shown in Figure 1.

Solubilization of Copolymers in Aqueous Solutions. Copolymers insoluble in water (copolymers 3, 4, and 5) can be solubilized in the form of water-soluble aggregates by the two following methods: (a) a stepwise increase of the polymer concentration by dropwise addition of copolymer solutions in ethanol (0.01 g mL^{-1}) into water at continual stirring (the final concentration of copolymers in water solutions was $c = 1 \times 10^{-4}$ g mL^{-1}) and (b) dialysis of copolymer solutions ($c = 1 \times 10^{-4}$ g mL^{-1}) in a mixture of H_2O/ethanol (60 vol %) against water. Then the solutions were diluted to the concentration needed for the scattering measurements.

Static Light Scattering (SLS). Ethanol, a good solvent for all of the copolymers, was used for molecular characterization of the copolymers. SLS measurements were performed on a Brookhaven Instruments goniometer equipped with a He–Ne laser (vertically polarized, $\lambda = 632.8$ nm) at 22 °C. The data for weight-average molar mass, M_w, were evaluated by the standard Zimm method. Refractive index increments (dn/dc) for copolymers in water and ethanol were measured with a model RF-600 differential refractometer (C. N. Wood. Mfg. Co.). Molecular characteristics of the copolymers studied are presented in Table I.

Dynamic Light Scattering (DLS). DLS measurements were performed using a standard laser light multiangle Brookhaven Instruments spectrometer with a He–Ne and argon ion laser and 78 channel BI 2030 (Brookhaven Instruments), multibit, multitau autocorrelator. The samples were maintained in the refractive index matching liquid (toluene) at 22 °C.

The autocorrelation functions were analyzed using the method of cumulants (a quadratic fit) with measured baseline options by assuming homodyne detection.[32] From the first cumulant, Γ, the diffusion coefficient, D_C, was obtained from the equation $D_C = \Gamma(q)/q^2$, where q is the scattering vector ($q - 4\pi n \sin(\theta/2)/\lambda$, where n is the refractive index of a solvent, λ is the wavelength of the incident light, and θ is the scattering angle). The hydrodynamic radius R_H was calculated from the Stokes–Einstein equation: $R_H = kT/6\pi\eta D_O$, where k is Boltzmann's constant, T is the absolute temperature, η is the solvent viscosity, and D_O is the zero angle and concentration limit of D_C. The second cumulant, $\mu_2(q)$, measures the width of the diffusion coefficient distribution of the observed scatterers. The ratio μ_2/Γ^2, the polydispersity index (P_D), is used throughout the text as a qualitative estimation of polydispersity.

Photoirradiation. Photoirradiation was produced with a 200-W high-pressure mercury lamp. The collimated beam was filtered with Oriel band ($\lambda = 350 \pm 50$ nm) and cutoff ($\lambda \geq 420$ nm) filters. The light intensity at $\lambda \approx 350$ nm was 1.2 mW cm^{-2}. Spectral measurements were performed with a Lambda 7 Perkin-Elmer spectrophotometer at 22 °C. Isomerization was detected by monitoring changes in the absorbance at 348 nm (the absorption maximum of the trans isomer). The kinetics of the cis–trans thermal isomerization of the copolymers were evaluated using the kinetic relationship of first-order reactions: $\ln (A_e - A_O)/(A_e - A_t) = t/\tau$, where A_t is the absorbance at time t, A_e is the absorbance of the sample after 72 h in dark, A_O is the absorbance immediately after irradiation, and τ is the relaxation time for the thermal cis–trans isomerization. The shift of the absorption maximum of the cis and trans isomers was not considered in the calculations. The concentration of the chromophores in solutions used for spectroscopic measurements was adjusted to approximately 3.0×10^{-5} mol L^{-1}. The τ values are shown in Table I.

Results and Discussion

Photochromism. The UV absorption spectra of copolymer **2** (8.3 mol % azobenzene) solutions in water are shown in Figure 2. At room temperature, in the dark, azo chromophores are expected to essentially be in the more stable trans configuration.[33] In this condition, the absorption spectra of copolymers show a major absorption band at 348 nm and a weak one at 435 nm (Figure 2). Upon irradiation at 350 nm, the major absorption band progressively decreased and shifted to 332 nn, while the weak band at 435 nm became more intense. Irradiation for 1 h was sufficient to achieve the photostationary state. Irradiation in the region of the 435-nm band (2 h with

Table II
Parameters of the Copolymer Samples in Aqueous Solutions (Method a)[a]

sample	d*n*/d*c* (mL g^{-1})	M_w	R_H (nm)	N	ρ (g mL^{-1})	P_D
1	0.193	6.4×10^4	6.4	1.1	0.096	0.28
2	0.207	1.0×10^5	6.0	1.2	0.190	0.21
3		3.2×10^7	97.0	311	0.015	0.18
4		3.8×10^8	111	3350	0.110	0.18
5		3.9×10^8	118	2980	0.095	0.19

[a] N = association number; R_H = hydrodynamic radius; ρ = (M_w/N_AV, where V is the volume of sphere with radius R_H) is the average segmental density in a micelle; P_D = polydispersity index.

light of λ ≥ 420 nm) produced a partial back-conversion of the absorption spectra (ca. 90%). Irradiated samples left in the dark returned to their original absorption spectra.

Similar behavior was observed in low molecular weight azobenzene[34] where the reversible variation of the absorption spectra was associated with the cis–trans isomerization around the N=N double bond. On the basis of the azobenzene data,[34] the 348-nm band observed in the dark-adapted sample was assigned to the π–π^* transition in the trans isomer. In the cis isomer, this transition was seen at 332 nm. The weak band at 435 nm corresponded to a n_+–π^* transition for the trans configuration and to n_-–π^* for cis. The trans isomer was planar and practically apolar, whereas the cis configuration was not planar, bearing a high dipole moment, thus enhancing the polymer solubility.[35,36] The change in the planarity of the two isomers may further contribute to the differences in polymer solubility. Hydrophobic interactions and stacking of azobenzene side chains are favored when azobenzene moieties are in the planar trans configuration.[29] The importance of this factor increases with increasing content of azobenzene side chains.

The thermal isomerization process of an isolated chromophore was expected to follow a simple exponential law characterized by a single relaxation time τ.[37,38] Such behavior was observed in all copolymers measured, but with different τ values (Table I). τ values were long enough to enable the experiments with copolymers containing both configurations of azobenzene molecules.

Solution Properties. The solubility of HPMA copolymers in water was found to be a function of the molar content of azobenzene molecules, x_a, attached to the HPMA backbone. While copolymers 1 and 2 with x_a = 4.4 and 8.3 mol %, respectively, were water soluble, forming macromolecular solutions (with a very low content of dimers), copolymers with $x_a \geq 9.3$ mol % only dissolved in water in the pseudomicellar form using either a stepwise increase of the copolymer concentration (method a) or dialysis of H_2O/ethanol (60 mol %) solutions of the copolymers against water (method b).

More detailed data on copolymer behavior in aqueous solutions prepared with methods a are listed in Table II. The values for molar mass, M_w, hydrodynamic radius, R_H, and association number, N, increased significantly at $x_a \geq 9.3$ mol % indicative of aggregate formation in solution (Table II). The polydispersity index decreased from a value of 0.28 (copolymer 1) to 0.19 (copolymer 5), reflecting a narrowing of the size distribution due to macromolecular association. The average segmental density ρ (equivalent to M_w/N_AV, where V is the volume of a sphere with radius R_H and N_A is Avogadro's constant) reached its highest value for copolymer 2 with x_a = 8.3 mol %, indicative of a collapse of the macromolecular coils induced by a relatively high content of hydrophobic azobenzene groups. This copolymer had a content of azobenzene just below the limit for molecular solubility in water. It appears that unimer micelles were formed; there were, in this particular case, collapsed molecular formations with the azobenzene groups oriented inside and the hydrophilic polymer backbone outside. The aggregates observed for the copolymer with a content of azobenzene of x_a = 9.3 mol % (copolymer **3**) just above the solubility limit were very thin. Aggregates of copolymers **4** and **5** had a segmental density comparable to unimer coils. The small difference in ρ between samples **4** and **5** was not significant and was within experimental error for aggregate characterization and preparation. All aggregates were found to be stable without any substantial parameter changes for more than 4 weeks.

The effects of irradiation by UV light (≈350 nm) on molecular and aggregate characteristics are shown in Table III. The coils of copolymer 1 (the lowest content of azobenzene, x_a = 4.4 mol %) were practically insensitive to the radiation. A small decrease of M_w and R_H was observed for copolymer 2 (x_a = 8.3 mol %) as a consequence of the dissociation of dimers due to enhanced solubility of macromolecules with the photoinduced cis configuration of the azobenzene. This effect was observed in solutions of aggregates, particularly for copolymer **3** which was close to the solubility limit. Large aggregates composed of 311 macromolecules dissociated upon irradiation to smaller ones with N = 2. The higher the content of azobenzene in the copolymer, the more stable the aggregates and the smaller the effect of the irradiation (Table III). The response of the aggregates to irradiation and/or their stability could also be roughly correlated to the average segmental density. Aggregates with a low density (the copolymer close to the solubility limit) were in a metastable phase; i.e., their free energy was higher than the free energy for N monomolecular micelles. Therefore, they could easily be transformed into the stable phase represented by more compact dimer and unimer micelles with an increase in azobenzene solubility upon irradiation. The relative long-term stability of these aggregates in aqueous solutions in the dark was probably due to a generally low solubility of the copolymers which rendered a spontaneous transition of the aggregates to the more stable unimer micelles. The more compact aggregates of copolymers **4** and **5** were more stable which was reflected in the smaller changes of aggregate parameters observed upon irradiation.

The thermal recovery process, the spontaneous conversion of the cis configuration to the more stable trans, resulted in a partial back-conversion only of the aggregate parameters. The most stable aggregates, those with the highest content of azobenzene (copolymer **5**), showed a significant increase of M_w and N in the course of the 4-day recovery time; N changed by 39% to reach 83% of the initial value (Table III), whereas practically negligible changes were found in the case of copolymer **3**. Only a small collapse of dimer micelles due to a decrease of the water solubility of the trans configuration was observed. It appeared that the more compact unimer and dimer micelles were preferred over swollen aggregates because of their lower free energy. This situation did not change, even in experiments when the rate of the cis–trans transformation was increased with an irradiation of λ ≥ 420 nm (results not shown).

To support the above conclusions concerning the importance of segmental density on the stability of aggregates, highly swollen aggregates ($\rho \approx 2 \times 10^{-4}$ g mL^{-1}) were prepared by method a using copolymer **3** in water/

Table III
Effect of Irradiation (λ = 360 nm) on Parameters of the Copolymer Samples in Aqueous Solutions (Method a)

	initial			irradiation (1 h)			recovery (96 h)		
sample	M_w	R_H (nm)	N	M_w	R_H (nm)	N	M_w	R_H (nm)	N
1	6.4×10^4	6.4	1.1	6.2×10^4	6.4	1			
2	1.0×10^5	6.0	1.2	8.7×10^4	5.4	1	9.0×10^4	5.4	1
3	3.2×10^7	97.0	311	2.1×10^5	12.2	2[a]	2.4×10^5	11.8	2.3
4	3.8×10^8	111	3350	4.0×10^7	92.5	385	5.8×10^7	94.0	564
5	3.9×10^8	118	2980	1.8×10^8	106	1780	2.6×10^8	107	2470

[a] Data after 3-h irradiation.

Table IV
Irradiation Effects in Solutions of Copolymer 3 (Method a) (Time Dependences)

	initial			irradiation (1 h)			irradiation (2 h)			irradiation (3 h)		
solvent	M_w	R_H (nm)	N	M_w	R_H (nm)	N	M_w	R_H (nm)	N	M_w	R_H (nm)	N
water (W)	3.2×10^7	97.0	311	3.8×10^5	19.6	3.7	2.5×10^5	14.1	2.4	2.1×10^5	12.2	2.0
Et/80 vol % W	1.4×10^7 [a]	340	136	1.3×10^5	13.0	1.3	1.2×10^5	12.8	1.1			

[a] $M_w^{app} = \Delta R(90°)/Kc$.

Table V
Parameters of the Copolymer Aggregates in Aqueous Solutions (Method b)

	initial				irradiation (1 h)		
sample	M_w	R_H (nm)	N	ρ (g mL^{-1})	M_w	R_H (nm)	N
3	1.7×10^7	93	160	0.008	1.2×10^7	87	117
4	5.7×10^8	153	5020	0.063	4.6×10^8	114	4090
5		250				230	

ethanol mixtures (80/20 by vol %). The copolymer was brought even closer to the solubility limit by the addition of 20 vol % ethanol, a thermodynamically good solvent for the copolymer. The irradiation effect on these rather large aggregates is shown in Table IV. The results obtained with the more dense aggregates prepared by the same method in water are shown for the sake of comparison. It followed from Table IV that aggregates in a mixed solvent system, as expected, were more easily destroyed by irradiation than the more compact aggregates in water. In the former case, the level of molecular solubility was practically achieved after 1 h of irradiation whereas, in the latter case, molecular solubility was not reached, even after 3 h of irradiation. In both cases, the major change in aggregate parameters arose during the first hour of irradiation. This was in agreement with the finding that 1 h of irradiation was sufficient to achieve the photostationary state.

The properties of aggregates prepared by method b (dialysis against water) are shown in Table V. All of the aggregate parameters were comparable with the corresponding parameters of aggregates prepared by method a (Table II). However, there was a remarkable difference between the aggregates in response to irradiation. The aggregates in dialyzed solutions were more stable and produced only a small response to irradiation when compared with aggregates prepared by method a. It was evident that segmental density was not the only criterion for aggregate stability. The preparation procedure apparently plays a crucial role. The slower the process, the higher the stability of the aggregates. Metastable aggregates can evidently only be prepared by the relatively fast process a.

The above experimental observations gave rise to a question as to why aggregates, particularly the metastable ones, were created by the preparation method a and b. To answer this question, solution properties of copolymer 3 (x_a = 9.3 mol %) were evaluated in water/ethanol mixtures. The results are shown in Table VI and in Figure 3a,b. The copolymer was soluble in mixed solvent systems of up to 50 vol % water and solubilized by method a in mixtures with a higher content of water (≥60 vol %). The data in Table VI and Figure 3 show dramatic changes in aggregate parameters in the vicinity of the mixture composition of 70 vol % water. Aggregates arising in these solvent mixtures were too large to permit the analysis of scattering data by the regular Zimm method; $R_G q > 1$, where R_G is the radius of gyration of particles at all available scattering angles ($\theta \geq 20°$). Therefore, the quantity $\Delta R(90°)/Kc$, where K is the optical constant which includes the square of the refractive index increment and $\Delta R(90°)$ is the excess Rayleigh ratio, proportional to the intensity of the light

Table VI
Characteristics of Copolymer 3 in Water/Ethanol Mixtures

solvent	M_w	R_H (nm)	N	ρ (g mL^{-1})	P_D
ethanol (Et)	1.0×10^5	6.9	1	0.125	0.27
Et/20 vol % W	1.1×10^5	14.0	1.1	0.016	0.23
Et/40 vol % W	1.2×10^5	14.5	1.2	0.015	0.31
Et/50 vol % W	1.9×10^5	24.1	1.8	0.0054	0.40
Et/60 vol % W	4.7×10^5	55.0	4.6	0.0011	0.50
Et/70 vol % W		470			0.15
Et/80 vol % W	1.4×10^7	340			0.15
Et/90 vol % W	3.7×10^7	200	359	0.0018	0.20
water (W)	3.2×10^7	97.0	311	0.014	0.18

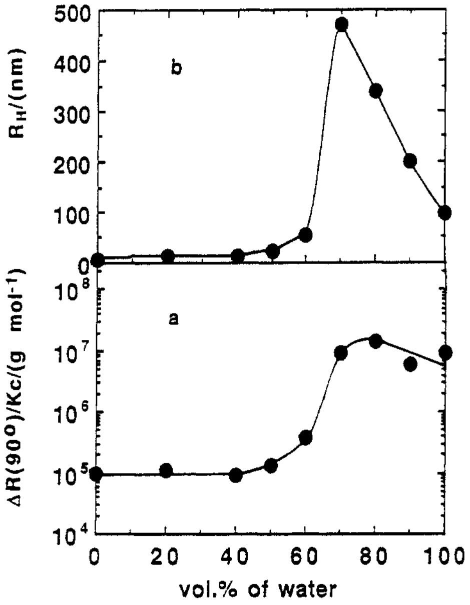

Figure 3. Plot of (a) the apparent molecular mass, $\Delta R(90°)/Kc$, and (b) the hydrodynamic radius, R_H, as a function of water/ethanol mixture composition.

scattered in copolymer solutions at the scattering angle $\theta = 90°$, was used for Figure 3a, instead of the regular molecular mass values for a relative comparison of aggregates. The anomalous behavior of the copolymer solution at the solubility limit was similar to behavior observed for micellar systems of block copolymers just above the critical micelle concentration, c_{mc}, and named "anomalous micellization".[6,39,40] By analogy, critical micelle solution mixtures, y_{mc} = water/(ethanol + water) (≈ 0.5 for the actual case), can be introduced for mixed solutions. This effect was explained by the presence of a homopolymer,[40] identical to the core-forming blocks,[40] or by the presence of copolymer molecules with a high weight fraction of the core-forming blocks due to heterogeneity in chemical composition.[6] The latter explanation of the effect could be adopted for the system under study because the large heterogeneity in chemical composition in the statistically copolymerized samples used must be taken into account. In analogy to the block copolymers case the anomalous behavior could have been due to a fraction of copolymers with a high content of azobenzene groups which would form large aggregates even below the critical mixture composition (y_{mc}) of the major component of the system studied. Raising the water content in the water/ethanol mixture would create a phase separation of the minor insoluble components which could lead to the formation of a dilute emulsion. The droplets formed would be stabilized by the absorbed layer formed by the major component. As soon as the y_{mc} of the major component is reached, the insoluble minor component would either be incorporated into the cores of aggregates or form mixed aggregates, depending on the molecular characteristics.

Since the copolymer solution during dialysis against water (method b) passed through the regime of "anomalous micellization", the metastable aggregates in the final solvent mixture would be "frozen aggregates" originally created in the vicinity of y_{am}. The molecular mass of the aggregates (Table VI and Figure 3a) changed only a little with an increase in the water content of the solvent mixture above the regime of "anomalous micellization". As demonstrated in Figure 3b, the size of the aggregates should decrease during the dialysis. The larger the difference in the composition of the final solvent mixture from y_{mc}, the more compact and stable aggregates were created.

The process of aggregate creation with method a can be explained by an analogy with the previous case. In this procedure, the copolymer solution probably goes through the regime of "anomalous micellization" at the c_{mc} creating aggregates in a similar way.

It is difficult to imagine that the structure of aggregates, particularly in the case of large aggregates, would be similar to that of normal micelles with the hydrophobic azobenzene oriented into the core and the hydrophilic backbone chains forming the shell of the spherical micelles. Therefore, the existence of a more complex molecular architecture of the aggregates is probable, e.g., a layer structure similar to liposomes.[41] This idea would be supported by the "mesogene" nature of azobenzene which forms a liquid-crystalline phase (mesophase).[42] Such molecules would form well-defined layer structures with two-dimensional lattices of mesogenes. Small-angle X-ray scattering measurements of the aggregates are currently under way to verify this hypothesis.

Conclusions

In this contribution the effect of irradiation on aggregate formation in aqueous solutions of HPMA copolymers containing azobenzene side chains was studied by light-scattering methods. Micelles prepared by the dropwise addition of copolymer solution into water (method a) produced aggregates which were stable in the dark in aqueous solution but became metastable when irradiated by UV light ($\approx$350 nm). The higher the aggregate segmental density and azobenzene content, the more stable the aggregates. Irradiation increased the solubility of azobenzene, resulting in the partial dissolution of the aggregates. The more stable the aggregates, the smaller aggregate parameter changes observed after irradiation. The recovery process, accompanied by cis–trans thermal transition of azobenzene molecules, produced only a partial back-conversion of aggregate parameters. The more stable the aggregates, the more pronounced the back-conversion. Following UV irradiation in solution, more compact aggregate formation was favored over highly swollen aggregates. Dialysis of the copolymer solution against water (method b) produced the more stable aggregates. The slower the process of aggregate formation could be made, the more stable the structure of aggregates formed. Metastable aggregate behavior can be explained as aggregates created in the vicinity of y_{mc} and "frozen" during a fast preparation process. The larger the difference in the composition of the final solvent mixture from y_{mc}, the more compact and stable aggregates were formed. The experimental results obtained support the hypothesis that the solution behavior of HPMA copolymers containing azobenzene side chains in aqueous solutions can be easily influenced by an external stimulus. The influence of trans–cis isomerization of azobenzene on the association of macromolecules has demonstrated the important role of hydrophobic groups in side chains on the aggregation process of amphiphilic copolymers.

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