Notes

Photoregulated Association of Water-Soluble Copolymers with Spirobenzopyran-Containing Side Chains

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Photochromic molecules are known to be transformed under photoirradiation into other isomers that can be reversibly transformed to the initial state, either thermally or photochemically. Isomerizations are always accompanied by some changes in physical and chemical properties of the chromophores, such as in the dipole moment (azobenzene), the generation of charges (triphenylmethane leucohydroxide (TMLH)), and zwitterionic structure (spirobenzopyran (SBP)).[1] The isomerization consequently results in solubility changes of photochromic molecules, e.g., the cis configuration of azobenzene with a higher dipole moment and ionized TMLH and SBP dyes are more soluble in water than the more stable dark configurations.[1] Thus, solution properties of copolymers containing photochromic moieties can be modified by irradiation through the solubility changes of photochromic molecules. Photochromic properties of azobenzene bound to a water-soluble polymeric *N*-(2-hydroxypropyl)methacrylamide (HPMA) backbone *via* side chains were exploited in photoregulation of adsorption[2] and random association processes.[2,3] A more complex solution behavior can be expected in the case of polymers containing SBP moieties that are capable of forming a zwitterionic structure upon UV irradiation. In contrast to polyelectrolytes, zwitterionic polyampholytes (polyzwitterions) have shown an enhancement in viscosity in the presence of added electrolytes. This so-called "antipolyelectrolyte" behavior was explained by changes in intra- and interchain random association of macromolecules resulting from attractive electrostatic dipole−dipole interactions of zwitterionic moieties.[4,5] The random association of polyzwitterions was directly observed by static and dynamic light scattering methods in aqueous solutions of zwitterionic homopolymers based on sulfobetaine monomers[6] and HPMA copolymers containing *N*-(2-hydroxyethyl)piperazine-*N*′-ethanesulfonic acid in side chains.[7] In turn, NaCl breaks up the intermolecular association and promotes polymer solubility if intermolecular electrostatic attractions are shielded.[6]

In this paper we present the results of photoinduced random association of HPMA copolymers containing photochromic sprirobenzopyran moieties at side chain termini as studied by static and dynamic light scattering and spectroscopic methods.

HPMA copolymers with various amounts of spirobenzopyran containing side chains (see Chart 1), attached via $(NHCH_2CO)_2$ spacers (HPMA−SBP copolymers), were prepared by free radical copolymerization of HPMA with 1′-[1-[[(methacryloylglycyl)glycyl]oxy]ethyl]-3′,3′-dimethyl-6-nitrospiro[2*H*-1-benzopyran-2,2′-indoline] (MA-GG-SP) in acetone for 24 h at 50 °C using 2,2′-azobis(isobutyronitrile) as initiator.[8] The content of spirobenzopyran-containing side chains was calculated using UV spectrometry. The weight-average molecular weight of the copolymers was estimated by FPLC using a Superose 6 column (calibrated with poly(HPMA) fractions) and a 0.01 M Tris, 0.1 M NaCl, 30% CH_3CN buffer as an eluent. The chemical composition of the copolymers used in the present study together with their molecular parameters are shown in Table 1.

In order to obtain homogeneous copolymer solutions, increasing amounts of a copolymer solution in ethanol (0.02 g mL^{-1}) were irradiated for 5 min with a green light (Ar laser, $\lambda = 514.5$ nm, 100 mW) before mixing and added dropwise to a particular solvent with stirring. The copolymer solutions were incubated for 24 h at room temperature, and then the actual copolymer solubility was checked by dynamic light scattering spectroscopy. The final concentration of copolymers was $c = 5 \times 10^{-4}$ g mL^{-1} unless stated otherwise.

Dynamic light scattering (DLS) measurements were performed using a standard laser light multiangle Brookhaven Instruments spectrometer with a He−Ne and Ar ion laser and 78 channel BI 2030 (Brookhaven Instruments) multi-τ autocorrelator at 22 °C.

The autocorrelation functions were analyzed using the method of cumulants (a quadratic fit) with measured baseline options by assuming homodyne detection.[9] 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 apparent hydrodynamic diameter, D_H, was calculated from the Stokes-Einstein equation: $D_H = 2kT/6\pi\eta\, D_c$, where k is the Boltzmann constant, T is the absolute temperature, η is the solvent viscosity. The second cumulant, $\mu_2(q)$, measures the width of the diffusion coefficient distribution of the observed scatterers. The polydispersity index $P_D = \mu_2/\Gamma^2$ is used throughout as a qualitative estimation of polydispersity.

Photoirradiation was produced with a 200 W high-pressure mercury lamp. The collimated beam was filtered with the Oriel band ($\lambda = 350 \pm 50$ nm) and cutoff ($\lambda \geq 450$ nm) filters. The light intensity at $\lambda \approx 350$ nm was 2.9 mW. Spectral measurements were performed with a Lambda 7 Perkin-Elmer spectrometer at 22 °C. Isomerization was detected by monitoring changes in the absorbance at the absorption maximum, λ_m (~550 nm), of the open form of SPB molecules. The kinetics of the thermal isomerization of the copolymers were evaluated using the kinetics relationship for the first-

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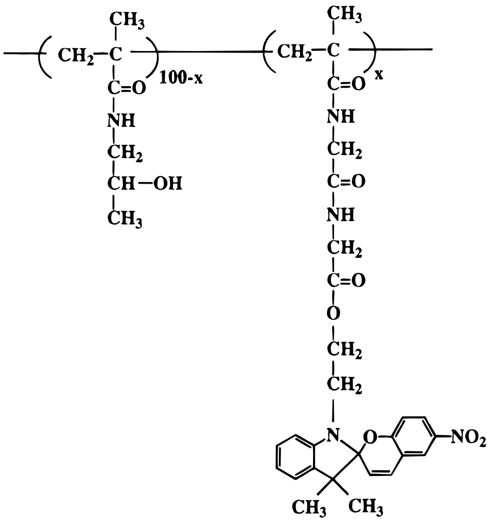
Chart 1



Copolymer	x mol %
1	5.2
2	11.4

order reactions. The concentration of the chromophores in solutions used for spectroscopic measurements was adjusted to approximately 2.7×10^{-4} mol L^{-1}.

Structure and Spectral Changes. SBP undergoes ring opening on ultraviolet irradiation (C−O bond scission) with the production of a zwitterionic structure (red merocyanine form).[1,10] Merocyanine (m) on exposure to visible light or in the dark converts back to the nonpolar (hydrophobic) yellow spiro (s) form.[10] The UV−vis absorption spectra of HPMA−SBP copolymer solutions in water and dioxane ($c = 5 \times 10^{-4}$ g mL^{-1}) are shown in Figure 1a,b, respectively. At room temperature and in the dark, SBP chromophores are expected to essentially exist in the more stable spiro form, showing a major absorption band at 340 nm only.[1,10] This is true for dioxane (Figure 1b) and acetone solutions (not shown) but in water (Figure 1a) and ethanol (not shown) a small absorption was observed in the region of $\lambda \approx 550$ nm. This means that a small equilibrium amount of the merocyanine form exists in highly polar solvents even in the dark. Upon irradiation at 350 nm, the weak absorption band around 550 nm becomes more intensive. At the same time, the UV absorption band becomes larger and shifts to 370 nm. The latter effect is more pronounced in water and ethanol solutions than in dioxane and acetone. Irradiation for 20 and 5 min was sufficient to achieve the photostationary state in aqueous and acetone solutions, respectively. A longer UV irradiation ($>$45 min) results in a small decrease of the merocyanine absorption probably due to a radiation degradation of SBP. The photostationary state in dioxane solutions could not be achieved because of the phase separation problem. Equivalent irradiation (45 min for water, 20 min for acetone, and 5 min for dioxane) with visible light ($\lambda \geq$ 450 nm) produced a back-conversion of the absorption spectra. In water (Figure 1a) and ethanol solutions after visible light irradiation, the absorption around 550 nm is lower than in the dark, demonstrating that the visible light irradiation is more effective in m−s conversion than the thermal process for highly polar solvents. The relaxation time for the thermal isomerization was found to decrease with decreasing polarity of the solvent to be nearly 2 orders of magnitude shorter in dioxane ($\sim$40 s) than in deionized water ($\sim$4000 s).

Association Properties. The solubility of HPMA−SBP copolymers in deionized water was found to be a function of the molar content of the SBP moieties x attached to the HPMA copolymer. Whereas copolymer 1 with $x = 5.2$ mol % was water-soluble, copolymer 2 with $x = 11.4$ mol % only dissolved in water using a stepwise increase in the copolymer concentration. The resulting hydrodynamic diameters of copolymers in deionized water measured after 24 h incubation are given in Table 1. Both the hydrodynamic diameters and polydispersity indexes are higher than those in ethanol (Table 1), indicating that in addition to thermodynamic expansion of chains, a very low amount of aggregates (clusters) is present.

The effect of UV irradiation ($\approx$350 nm) on solution properties of copolymers was only observable with copolymer 2, which is close to the solubility limit in deionized water. In this case, the formation of large clusters by random association of copolymers is indicated in light scattering experiments (Figure 2a). The initial growth of cluster diameters in water at short irradiation times is followed by a plateau after the photostationary state of SBP moieties is achieved (20 min). The aggregation found is due to the zwitterionic structure of the m-form of SBP moieties that are formed on UV irradiation. The driving force of this association is attractive electrostatic forces among ion pairs (dipoles) of zwitterion SBP moieties. Random association of water-soluble copolymers containing zwitterionic moieties at side chain termini has already been observed several times in aqueous solutions.[6,7]

The thermal recovery process, the spontaneous conversion of the m-form of SBP to the more stable s-form, was not directly reflected in dissolution of clusters because it was a slower process. The clusters are probably stabilized by hydrophobic interactions of SBP moieties and/or hydrophobic side chains. Thus, the hydrodynamic sizes of clusters have changed only slightly during 1 week.

The photoinduced random association of the copolymers can also be observed in mixed acetone/ethanol solvents, as demonstrated for solutions of copolymer 2 in acetone with 10 vol % of ethanol. The association behavior is similar to that in aqueous solutions. The maximum sizes of clusters ($D_H \approx 100$ nm) are again detected after the photostationary state of SBP moieties is achieved ($\sim$5 min) and then they are nearly independent of irradiation time (see Figure 2a).

HPMA−SBP copolymers are insoluble in dioxane, but good solubility of the copolymers is achieved by adding a small amount of ethanol. Thus, 7.5 vol % of ethanol is sufficient for copolymer 2. The response of copolymer 2 solutions of dioxane/ethanol and water/ethanol to UV irradiation is enormous, as demonstrated in Figure 2a where D_H is plotted as functions of the irradiation time, t. Compared to aqueous solutions, the formation of clusters is many times faster in dioxane/ethanol mixtures. This is due to stronger attractive dipole−dipole interactions in solvents with low permittivity, ϵ. These attractive forces are inversely proportional to ϵ. Since the permitivity, ϵ, in dioxane is 34.6 times smaller than that in water, then, naturally, a much smaller amount of zwitterionic merocyanine groups can form copolymer clusters than observed for aqueous solutions. The

Table 1. Molecular Characteristics of HPMA−SBP Copolymers[a]

copolymer no.	x, mol %	$10^{-3}M_w$, g mol^{-1}	M_w/M_n	D_H(EtOH), nm	P_D(EtOH)	$D_H(H_2O)$, nm	$P_D(H_2O)$
1	5.2	26.7	1.7	7.5	0.24	10.5	0.26
2	11.4	33.9	1.6	7.2	0.21	16.5	0.22

[a] x = content of SBP in mol %, M_w = weight-average molar mass, M_w/M_n = polydispersity, D_H = hydrodynamic diameter, P_D = polydispersity index.

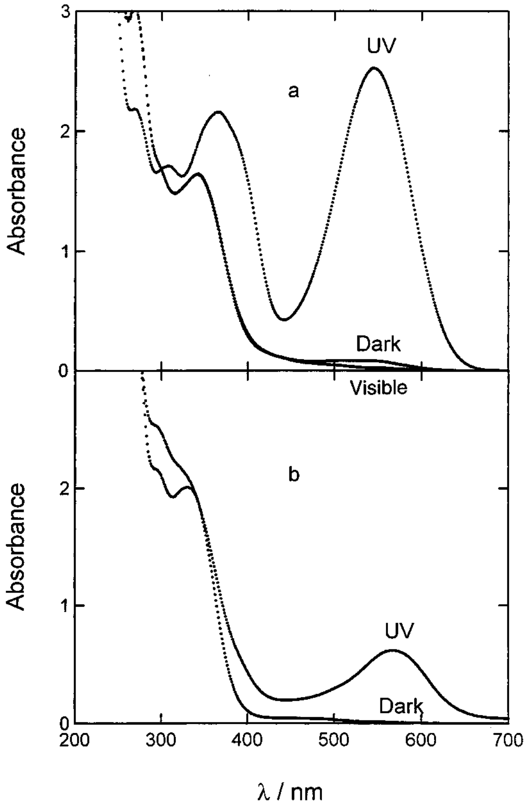


Figure 1. (a) Absorption spectra of SBP bound to HPMA copolymers in deionized water with 2.5 vol % of ethanol at different s−m conversions: dark, 0.5 h UV irradiation, 0.5 h irradiation with visible light ($\lambda \geq 450$ nm). (b) Absorption spectra of SBP bound to HPMA copolymers in dioxane with 7.5 vol % of ethanol at different s−m conversions: dark, 120 s UV irradiation.

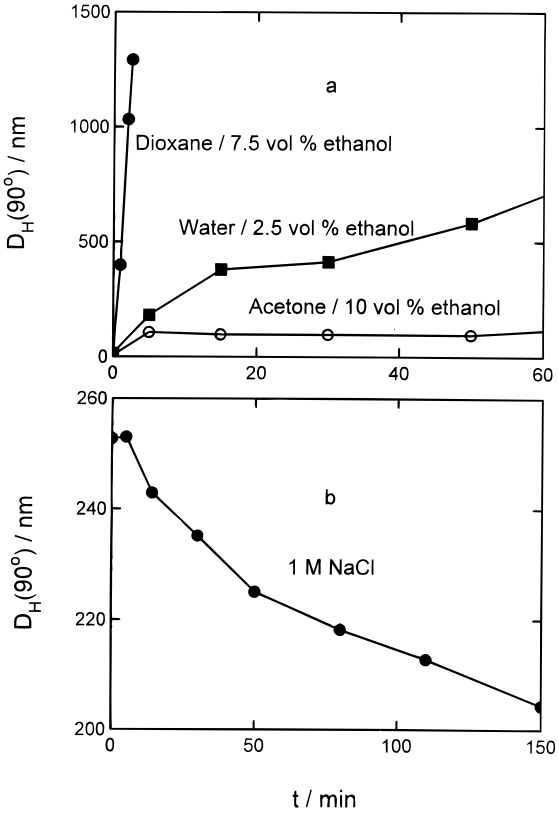


Figure 2. (a) Dependence of cluster diameter, D_H, on UV irradiation time, t, in deionized water/2.5 vol % of ethanol, acetone/10 vol % of ethanol and dioxane/7.5 vol % of ethanol solutions of copolymer 2. (b) Dependence of cluster diameter, D_H, on UV irradiation time, t, in aqueous 1 M NaCl solutions of copolymer 2.

dissolution process of clusters in the dark is also fast but slower than corresponding m−s conversion. The delay of dissolution after the m−s conversion of the m-form of SBP moieties is due to kinetics of cluster dissolution. The association process in dioxane is very sensitive to the content of ethanol, which increases the thermodynamic quality of the mixed solvent for the copolymers. At higher volume contents of ethanol, the dissolution successfully competes with association and suppresses cluster formation; for example, 12.5 vol % of ethanol is sufficient to suppress the random association in solutions of copolymer 2. In order to achieve a maximum association response to UV irradiation, the copolymer solutions must be close to the solubility limit of copolymers.

In order to prove the decisive role of electrostatic dipole−dipole interactions in the cluster formation, analogous irradiation experiments were performed with copolymer solutions in 1 M NaCl, where electrostatic forces are effectively screened by co-ions. Since the solubility of copolymers in the electrolyte is generally lower than in deionized water, copolymer 2 with x = 11.4 mol % of SBP only dissolved in the cluster form ($D_H \approx 250$ nm). UV irradiation, contrary to solutions in deionized water, accelerates the dissolution process, as demonstrated in Figure 2b. This is probably due to an increase in solubility of the m-form of SBP groups formed upon irradiation at suppressed electrostatic attractive interactions.

In conclusion, experimental evidence was found for photoinduced association in solvents with different polarities (water, acetone, dioxane). The common feature of all association processes is a fast initial growth of cluster diameters at short irradiation times followed by a plateau after the photostationary state of SBP moieties is achieved. The driving forces of this association are electrostatic dipole−dipole interactions between zwitterionic merocyanine forms of SBP molecule formed upon UV irradiation. The intermolecular association is only possible in solvents with a low thermodynamic quality for copolymers close to their solubility limit. An increase in solvent quality or screening by co-ions can successfully suppress the photoassociation. The dissolution of clusters in the dark was very slow in aqueous solutions and relatively fast in dioxane solutions. Since solutions of HPMA−SBP copolymers are an ideal system for an investigation of kinetics of the random association, time-resolved laser light scattering and absorption experiments, particularly in dioxane solutions, are in progress.

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