

Synergistic depression of volume phase transition temperature in copolymer microgels

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Abstract Microgels consisting of poly-*N,N*-diethylacrylamide (PDEAAM) and copolymer microgels consisting of *N,N*-diethylacrylamide-co-*N*-isopropylacrylamide (PDEAAM-co-PNIPAM) have been synthesized via free radical polymerizations. The volume phase transition of the microgels in aqueous solution was investigated by means of dynamic light scattering. All samples revealed a volume phase transition upon heating and the size change was fully reversible. An unusual dependence of transition temperature on the composition of the copolymer microgels was observed and samples were obtained with a transition temperature that was lower than that of both corresponding homopolymer particles. This synergistic behavior could be caused by strong hydrogen bonding between the mono- and the disubstituted acrylamide repeating units at nearly equimolar composition of the microgel.

Keywords Microgels · PNIPAM · PDEAAM · Temperature sensitive · Smart polymer · Dynamic light scattering · Phase transition

Introduction

Hydrogels and microgels of thermoresponsive polymers have promising potential as materials for technical applications especially in the biomedical field, e.g., for drug delivery or sensors [1–6]. A prominent example is poly(*N*-isopropylacrylamide) (PNIPAM). Aqueous solutions of PNIPAM undergo a reversible phase transition at ca. 32 °C.

The phase transition of the thermosensitive polymers is attributed to the balance between the hydrophobic interaction and hydrogen bonding. One important aspect is to find means for tuning the volume phase transition temperature (VPTT) of such polymer systems as this allows tailoring them for specific needs in technical applications. A common way to change the VPTT is the copolymerization with different monomers that can either be hydrophilic, hydrophobic, or even sensitive to a different stimulus as, e.g., pH. Copolymerization with a monomer that also affords a temperature sensitive polymer is of special interest because relevant information on mechanisms that lead to phase separation in the first place can be obtained.

Random linear copolymers of NIPAM and *N*-isopropylmethacrylamide (NIPMAM) were investigated by Djopke and Vogt [7]. They observed that the transition temperature of the copolymers changes linearly between the transition temperatures of the two homopolymers and is thus proportional to the molar composition of the copolymer. Our group recently showed that core-shell microgels based on these two monomers reveal different behavior: two transition temperatures correlated with collapse of core and shell were found [8–10].

Several other *N*-substituted poly(acrylamides) such as poly-*N,N*-diethylacrylamide (PDEAAM) or *N*-ethylacrylamide, exhibit thermosensitive behavior as well. The copolymer microgel series examined in this study comprises samples containing different portions of the two monomer units *N*-isopropylacrylamide (NIPAM) and *N,N*-diethylacrylamide (DEAAM).

In the last few years, *N,N*-diethylacrylamide became an interesting alternative to the PNIPAM system because of the better biocompatibility [11]. Mainly, hydrogels, linear macromolecules, or block copolymers were synthesized [12–15]. To the best of our knowledge, PDEAAM micro-

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gels have not been investigated yet. The transition temperature of linear PDEAAM in water is close to that of PNIPAM [12, 14].

The aim of this study was to investigate the effect of copolymerizing a mono substituted acrylamide (NIPAM) with a disubstituted acrylamide (DEAAM) on the transition temperature.

Experimental

N-isopropylacrylamid (NIPAM: Acros Organic), *N,N*-diethylacrylamide (DEAAM: Polyscience), sodium dodecyl sulfate (SDS: Fluka), potassium peroxodisulphate (KPS: Merck KGA), and crosslinker *N,N'*-methylenebisacrylamide (BIS: Merck KGA) were used as received. Water for all purposes was bidistilled Milli-Q-water.

The crosslinked copolymer microgels were synthesized via free radical emulsion polymerization. Polymerization was performed in a 250-ml vessel equipped with a mechanical stirrer, thermometer, a reflux condenser, and a nitrogen inlet. The two monomers (NIPAM and DEAAM, details Table 1), BIS and SDS, were dissolved in 90 ml water at 70 °C and purged with nitrogen at least for 1 h. Polymerization was initiated by adding KPS (dissolved in 10 ml degassed water) and added to the monomer mixture. Polymerization was carried out for 6 h at a constant temperature, a constant gas stream, and constant stirring of 330 rpm. The reaction mixture was allowed to reach room temperature under stirring over night. The dispersion was filtered through glass wool and was purified three times by repeated ultra centrifugation (30 min 50,000 rpm), decantation of the supernatant, and redispersion in bidistilled water. A Sorvall Discovery 90SE ultracentrifuge with a T865 rotor was used for the centrifugation at 20 °C.

The sample composition is indicated in the sample name, for example, PD-5/95, where the first number denotes the mass percentage of the DEAAM monomer and the second

number gives the percentage of NIPAM in the monomer feed.

Dynamic light scattering measurements were performed with an ALV goniometer and a laser wavelength of 633 nm. The samples were highly diluted ($c < 0.01$ wt%) to prevent multiple scattering and filtered through a 0.8- μ m filter to remove dust. The scattered light was detected at a scattering angle of 40°, and hydrodynamic radius $R_h(T)$ have been calculated from second-order cumulant fits via Stokes–Einstein equation. Heating and subsequent cooling cycles have been performed. The particle size change is fully reversible.

Results and discussion

Copolymer microgels with different monomer composition were prepared and the temperature dependence of particle size was determined by means of dynamic light scattering.

Figure 1 shows results of the DLS experiments, the hydrodynamic radius R_h [normalized by the radius in the swollen state at 10 °C $R_h(10\text{ °C})$] is plotted vs temperature. For the sake of clarity, only data of three samples are shown; the VPTT of the microgel is influenced dramatically by the monomer composition and the values are given in Table 1 for all samples.

Samples with three comonomer compositions were chosen for this plot. The first microgel consists of an excess of NIPAM (PD-10/90), the second microgel exhibit an excess of DEAAM (PD-60/40), and the third curve shows the pure PDEAAM-microgel.

PDEAAM microgels do not reveal a sharp phase transition in contrast to PNIPAM microgels. A sharper transition was found for PD-60/40 resembling the shrinking behavior of a pure PNIPAM microgel, although the microgel still contains an excess of DEAAM.

The most striking result, however, is the observation that the transition temperature of the copolymer microgel PD-

Table 1 Composition of the copolymerization batches

Sample name	DEAAM (g)	NIPAM (g)	BIS (g)	SDS (g)	KPS (g)	Monomer composition DEAAM/ NIPAM (wt%)	VPTT (°C)
PNIPAM						0/100	32
PD-5/95	0.079	1.2973	0.1185	0.0781	0.08	5.7/94.3	31
PD-10/90	0.1626	1.2379	0.214	0.0963	0.0725	11.6/88.4	31
PD-25/75	0.3888	1.0702	0.0955	0.05998	0.08	26.6/73.4	25
PD-40/60	0.6222	0.9052	0.0976	0.0641	0.08	40.7/59.3	23
PD-50/50	0.7665	0.6819	0.0935	0.0601	0.0722	52.9/47.1	21
PD-60/40	0.9234	0.6032	0.096	0.063	0.0831	60.5/39.5	20
PD-75/25	1.0552	0.342	0.0918	0.0563	0.0713	75.5/24.5	22
PD-90/10	1.291	0.1495	0.098	0.058	0.078	89.6/10.4	23
PDEAAM	2.45		0.07	0.02	0.12	100/0	26

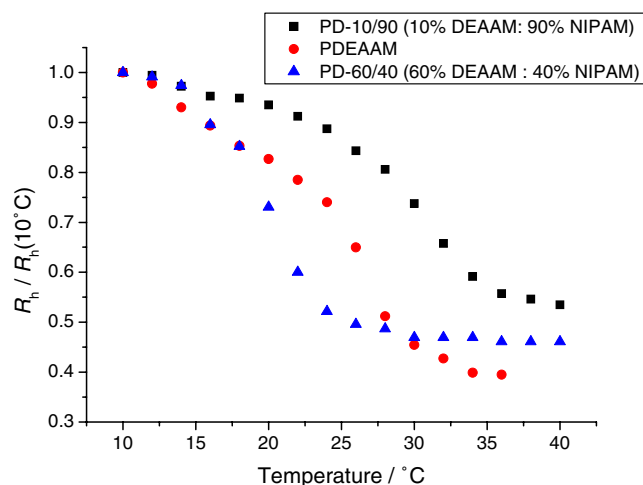


Fig. 1 Temperature dependence of hydrodynamic radius for three different microgels

60/40 is *lower* than that of both homopolymer microgels! The transition temperatures of all samples are displayed in Fig. 2. Obviously there cannot be a simple relationship between copolymer composition and transition temperature. These results indicate that specific interaction as hydrogen bonding might be the reason for the depression of transition temperature in the copolymer particles as compared to the homopolymer systems.

In the following, we will compare our results with literature reports on similar systems. To check whether the macromolecular architecture plays a role, we prepared a copolymer microgel containing the same amounts of NIPAM and *N*-isopropylmethacrylamide (Konate and Richter, unpublished results) and the transition temperature was in between that of the homopolymer microgels which is in perfect agreement with the results by Djopke and Vogt [7] on linear copolymers.

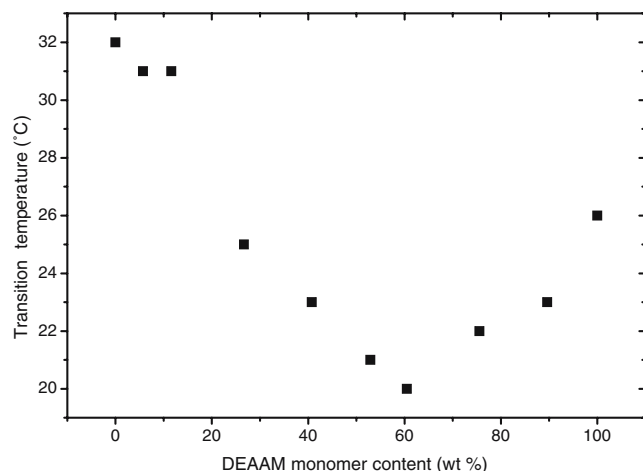


Fig. 2 The influence of composition on the transition temperature for all samples. A minimum at ca. 60 wt% DEAAM (corresponding to 55 mol%) is observed which is clearly below the transition temperatures of the homopolymers

Liu et al. [16] reported on properties of random copolymers of *N*-substituted acrylamide monomers in aqueous solutions. The lower critical solution temperature (LCST) of these copolymers was always in between the LCST of the two corresponding homopolymers; however, copolymers of DEAAM and NIPAM were not investigated. A monotonic decrease of the LCST was observed when DEAAM was copolymerized with very hydrophobic bile salt derivatives [17]. It is interesting to note that Cai et al. [18] observed that the LCST is also reduced when the hydrophilic acrylic acid is employed as comonomer. At low acrylic acid content, the LCST first increased as could be expected when a hydrophilic component is added. However, acrylic acid contents higher than ca. 7% lead to a LCST decrease as compared to pure PDEAAM and at acrylic acids contents above 25% the polymers became insoluble in water unless the pH was in the alkaline region. These results indicate that strong hydrogen bonding at certain composition lead to coil collapse.

The presence of strong binding forces is further supported by the complex formation that was observed when linear poly(acrylic acid) (PAAc) and PDEAAM were mixed [14]. Such complexation processes have been interpreted in terms of ladder structures and zipping models.

Liu et al. [19] prepared linear random copolymers by copolymerization of DEAAM and methacrylic acid (MAAc). In contrast to the DEAAM-acrylic acid copolymers, the transition temperature increase monotonically with the MAAc content and a maximum was not observed.

Shibayama et al. [20] investigated the influence of *N,N*-dimethylacrylamide (DMAAM) content on the volume phase transition temperature of PNIPAM hydrogels. Poly (*N,N*-dimethylacrylamide) itself is water soluble and does not display a LCST in aqueous solutions. An increasing DMAAM content in the copolymer gels lead to an increasing transition temperature.

The phase transition upon heating that is observed with polymers and gels based on *N*-substituted acrylamides is caused by hydrophobic interaction and hydrogen bonding. Our results on copolymer microgels of NIPAM and DEAAM as well as the literature reports discussed above clearly show that little changes in the molecular structure lead to big changes in solubility. These cannot be attributed to “simple” changes in terms of hydrophilicity or hydrophobicity as can be seen by the differences between, e.g., NIPAM vs NIPMAM or DEAAM vs DMAAM. Instead, a full understanding of the underlying forces must consider hydrogen bonding both between repeating units and water molecules as well as hydrophobic interaction and the conformation of the polymer backbone.

One can speculate why the NIPAM–DEAAM copolymer system displays this peculiar synergistic behavior of

transition temperature as function of composition. The observation that the minimum of the volume phase transition temperature as shown in Fig. 2 is close to an equimolar composition suggests strong hydrogen bonding between the two repeating units. DEAAAM seems to be a strong hydrogen-bonding acceptor and presumably the combination of a di- and a mono-*N*-substituted amide leads to the synergistic behavior similar to a zipper model. Recently reported calorimetry data from PNIPAM–PNIPAM core-shell microgels also indicated an influence of microgel architecture on the formation of hydrogen bonds [21, 22].

Obviously, a model system is needed for a comprehensive understanding of the phase separation of nonionic macromolecules in aqueous mixtures and we believe that copolymers based on NIPAM and DEAAAM are suited as model system. First of all, both monomers yield polymers with similar transition temperatures. They are nonionic and special effects caused by electrostatic interaction are not important in contrast to copolymers with acrylic acid. Both monomers lead to the same polymer backbone and differences in chain stiffness that occur, e.g., in copolymers of NIPAM and NIPMAM can be neglected.

Conclusions

We described the synthesis of poly(*N,N*-diethylacrylamide) microgels, PDEAAAM, which exhibit a slightly lower volume phase transition temperature as compared to PNIPAM. PDEAAAM-co-PNIPAM microgels reveal a non-monotonic dependence of transition temperature on composition. A strong depression of the VPTT as compared to both homopolymer microgels is observed with a minimum close to equimolar composition.

The copolymer-PDEAAAM-microgel seems to be a good model system for investigating the influence of hydrogen bonding on phase transition. Further experiments are in progress and will be reported later.

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