

Synthesis and Volume Phase Transition of Poly(methacrylic acid-*co*-*N*-isopropylacrylamide) Microgel Particles in Water

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A series of lightly cross-linked, nearly monodisperse, and random copolymerized microgel particles, based on methacrylic acid (MAA) and *N*-isopropylacrylamide (NIPAM) of various content, were synthesized in aqueous solution with sodium dodecyl sulfate at pH = 3.1 ± 0.2 and 70 °C. The polymerization kinetics, the colloidal stability, and the size of the microgel particles varied with the comonomer composition. The volume phase transitions of the MAA/NIPAM copolymer microgel particles with different PMAA contents in very dilute aqueous solution ($C < 1 \times 10^{-5}$ g/mL) were investigated by laser light scattering (LLS), as a function of both pH at 25 °C, and temperature at two different pH values of 3.4 and 7.5. To our knowledge, the volume phase transition of such submicron-sized hydrogels sensitive to multiple environmental changes was studied for the first time by LLS. The equilibrium swelling ratio, the critical transition pH, and the critical transition temperature (T_c) were strongly dependent on the comonomer composition. For the pH-sensitive transition, an increase in the PMAA content increased the swelling extent and enhanced the critical transition pH. For the thermal sensitive transition, an introduction of PMAA enabled us to adjust the hydrophobicity of the microgel network chains by varying the solution pH. At low pH, an increase in the highly collapsed hydrophobic PMAA content decreased the T_c , reduced the collapsing extent, and made the transition less sharp. At higher pH (7–10), an increase in the strongly hydrophilic, highly charged PMAA content raised T_c but unexpectedly reduced the collapsing extent and broadened the transition temperature region, which are contrary to the results observed in other weakly charged PNIPAM gels. The possible explanation related to a shell-enriched PMAA with a high charge density and a core-enriched in neutral PNIPAM for the MAA/NIPAM copolymer microgel with low PMAA content is presented.

Introduction

Polymer gels can undergo a volume phase transition in response to chemical or physical stimuli such as pH,^{1,2} temperature,^{3–5} solvent composition,^{6,7} ions,^{8,9} light,¹⁰ and electric field.¹¹ Such a volume phase transition has obtained very strong interest in the past 20 years from both scientific and technological viewpoints. Theoretically, a detailed examination of this critical phase behavior can provide us with a deeper insight into the polymer–polymer, polymer–solvent interactions so that some general and fundamental concepts in polymer physics can be clarified. Technologically, this special transition might be applied in very diverse end uses,¹² such as controlled release of drugs, bioseparation, enzyme or cell bioreactors, super absorbents, electrophoresis, and chemical transducers.

Most of the studies have, so far, been limited to the bulk gels by measuring the dimension or weight change of cylindrically shaped gel disks mainly in the final equilibrium state.^{2,5,13–15} Experiments based on macroscopic dimension measurements have been difficult to reproduce. Furthermore, the bulk gel pieces need a long time to reach the swelling equilibrium, i.e., of the order of a few days or even weeks. Tanaka et al.¹⁶ showed that the response to the equilibrium of a micron-sized gel particle could be achieved within the millisecond range and that the volume change of a polymer gel was proportional to the square of the gel size. Therefore, the preparation and investigation of submicron-sized gel particles with a rapid

response to an infinitesimal environmental change can be very important in high-technology applications.

Laser light scattering (LLS) is a powerful method to study the volume phase transition of submicron-sized polymer gel particles. A few LLS studies on volume phase transition of microgel particles, such as thermal-sensitive poly(*N*-isopropylacrylamide) (PNIPAM) microgels in water^{17,18} or in surfactant solution¹⁹ and pH-sensitive methyl methacrylate microgels copolymerized with a small amount of acrylic acid,²⁰ have been reported. To our knowledge, however, no LLS study has ever been reported on the microgel particles that can couple both temperature and pH responsive volume phase transitions due probably to the difficult preparation.

It is well-known that poly(methacrylic acid) (PMAA) can undergo a marked pH-induced conformation transition.^{21,22} At low pH, PMAA chains adopt a highly compact form in order to minimize the hydrophobic interaction. At a high degree of ionization and in the absence of electrolytes, PMAA chains open to an expanded coil. Correspondingly, the swelling/collapsing of PMAA gels are also highly pH dependent.^{13,23} With increasing pH, PMAA gels can swell and show a maximum swelling in a pH range of 7–10. On the other hand, PNIPAM is a reversible thermal-sensitive polymer. A PNIPAM single chain undergoes a coil-to-globule transition at 31.8 °C,²⁴ while the PNIPAM gel undergoes a volume phase transition around 33.8 °C.²⁵ The small amount of acrylic acid comonomer in the PNIPAM bulk gels not only make the gel undergo a discontinuous transition but also make the gel show a higher

critical transition temperature T_c and a larger volume change.^{5,15,26} A continuous volume change of these bulk gels was also observed at higher pH = 9.5.¹⁵

Recently, Peppas et al.¹⁴ prepared a series of random copolymer bulk gels of methacrylic acid (MAA) with *N*-isopropylacrylamide (NIPAM). The pH- and thermal-sensitive volume phase transition of MAA/NIPAM bulk gels were characterized by weighing the gel disk in both the swollen and the dried state. Long equilibrium times were required. Moreover, the coarse experimental results led to confused conclusions, especially about the effects of copolymerized PMAA contents on the T_c of the bulk gels. It is noted that the volume phase transition of hydrogels depends on the competition of hydrophilic/hydrophobic interactions between the network chains and the solvent. To clarify the effects of MAA content on the T_c of MAA/NIPAM copolymer gels, the interactions between the PMAA chains and water which are strongly pH dependent, namely, hydrophobic at low pH, and hydrophilic at higher pH (7–9), due to the ionization of the carboxylic group should be considered.

The objectives of this study are to synthesize “monodisperse” submicron MAA/NIPAM copolymer microgel particles covering a wide range of comonomer composition and to investigate the volume phase transition of these microgels over a range of pH and temperature changes by means of LLS. The coupling of both pH- and thermal-sensitive volume phase transition could rapidly induce a huge volume change. Moreover, the critical transition temperature and the extent of swelling/collapsing can be controlled by varying the solution pH and the copolymer composition. The coupling effects of hydrophobic/hydrophilic interactions among PMAA, PNIPAM, and water on the behavior of volume phase transition are presented.

Experimental Section

Materials. MAA monomer (Aldrich, 98.5%) was vacuum distilled. NIPAM monomer (ARCOS, 99%) was purified by recrystallization in a toluene/hexane mixture. Methylenebisacrylamide (BIS) (Ultragrade, Pharmacia LKB; as a cross-linker), ammonium persulfate (APS) (Aldrich, 98+%; as an initiator), and sodium dodecyl sulfate (SDS) (Fisher Scientific, 98.8%) were used as received. Deionized water was distilled before use.

Synthesis of Copolymer Microgel Particles. The microgel particles were prepared by dispersion polymerization in aqueous solution. A 1.5 g sample of comonomer in different MAA/NIPAM molar ratios, 1.0 mol % (of total monomer) BIS, and 0.040 g of SDS were added to 100 mL of dust-free deionized water. A 250 mL glass reactor fitted with a nitrogen bubbling tubing, a glass stirring rod containing a 6 cm Teflon paddle, and a reflux condenser was used. To remove oxygen, the solution heated to 70 °C in a water bath was stirred at 300 rpm for 40 min while being purged with nitrogen. Then, 0.065 g of APS dissolved in 0.3 mL of water was added to start the reaction. The reaction mixture was stirred for a time period varying from 0.5 to 4 h depending on the feed composition. A portion of the polymerized lattices was purified to remove SDS and other impurities by four successive centrifugations, decantations, and redispersions in deionized water (pH ~ 5.6), which were used for LLS measurements. The other part of the lattices from the reaction mixture was centrifuged, decanted, and vacuum-dried to constant weight at 45 °C, before the compositional determination by titration.

Characterization of Copolymer Microgels. The PMAA content in the copolymer microgel was determined by acid–

base titration using 0.01–0.05 M standard NaOH solution as the titrant and bromophenol blue as the indicator. The dried MAA/NIPAM copolymer microgel of known weight (0.1 g) was immersed in 30 mL of deionized water. After reaching equilibrium swelling, two drops of the indicator were added. The solution was titrated slowly with NaOH solution, shaking thoroughly after each NaOH addition until a light purple color indicated the end point.

The pH- and thermal-sensitive volume phase transitions were performed by following the hydrodynamic radius of microgel particles as functions of solution pH and temperature. All the microgel stock solutions under synthesis conditions (collapsed states) were dust-free by filtration through 0.45–0.8 μ m Millipore filters. The dust-free stock microgel solutions were added to a dust-free aqueous solution of either HCl or NaOH of appropriate concentration in order to reach the desired pH and solution concentration ($\sim 1 \times 10^{-5}$ g/mL). Once mixed, the resulting pH was not further adjusted. For the pH-sensitive transition, the LLS measurements were carried out at 25.0 °C and different fixed pH values. For the thermal-sensitive transition, two solutions with pH = 3.4 and pH = 7.5 were measured at various temperatures.

Instrumentation. A standard laboratory-built light-scattering spectrometer capable of both time-averaged scattered intensity and photon correlation spectroscopy measurements over an angular range of 15°–135° was used for the light-scattering experiments. The scattering cell was held in a brass thermostat block filled with a refractive index matching silicone oil. The temperature was controlled to within ± 0.05 °C. A Spectra-Physics argon ion laser (Model 165) with a wavelength of 488 nm and a Lexel argon ion laser with a wavelength of 514.5 nm were used as light sources.

Photon Correlation Spectroscopy. The intensity–intensity autocorrelation function $G^{(2)}(q, t)$ in the self-beating mode was measured with a Brookhaven BI2030AT 64-channel digital correlator.

$$G^{(2)}(q, t) = A[1 + \beta |g^{(1)}(q, t)|^2] \quad (1)$$

where $q = (4\pi n/\lambda_0) \sin(\theta/2)$ with n , λ_0 , and θ being the solvent refractive index, the wavelength of light in vacuo, and the scattering angle, respectively; t is the delay time, A a measured baseline, β , the coherence factor, and $g^{(1)}(q, t)$ the normalized electric field time correlation function.

$$g^{(1)}(q, t) = \int_0^\infty G(\Gamma) e^{-\Gamma t} d\Gamma \quad (2)$$

with $G(\Gamma)$ being the normalized line width distribution function at infinite dilution and as $q \rightarrow 0$, the linewidth Γ can be expressed as $\Gamma/q^2 = D$ with D being the translational diffusion coefficient. $G(\Gamma)$ can be obtained from the Laplace inversion of $g^{(1)}(q, t)$. Furthermore, $G(\Gamma)$ can be converted to the translational diffusion coefficient distribution $G(D)$ and to the hydrodynamic radius distribution $F(R_h)$ by using the Stokes–Einstein equation

$$R_h = k_B T / 6\pi\eta D \quad (3)$$

where k_B , T , and η are the Boltzmann constant, the absolute temperature, and the solvent viscosity, respectively.

Results and Discussion

Synthesis of Copolymer Microgels. Both MAA and NIPAM are water-soluble monomers. However, PMAA chains at low pH and PNIPAM chains at high temperature (above the lower

TABLE 1: Preparation Conditions^a and Partial Properties of MAA/NIPAM Copolymer Microgels

MAA in feed (mol %)	reaction time (h)	colloidally stable	MAA in copolymer (mol %)	$\langle R_h \rangle_c / \text{nm}^b$ (pH = 3.4; 40 °C)	$\langle R_h \rangle_s / \text{nm}^b$ (pH = 7.5; 25 °C)	swelling ratio _c V_s/V_c
0.0	4	yes	0.0	50.0	139.9	21.9
4.3	4	yes	2.4	83.5	377.6	92.5
10.8	4	yes	8.7	64.1	383.4	214.0
24.7	0.5	no	23.0	95.5	425.0	88.1
37.1	0.8	no	33.6	90.0	372.5	70.9
50.2	0.8	no	47.2	88.0	298.5	39.0
62.0	1	yes	64.7	80.0	279.6	42.7
75.0	1	yes	79.1	71.0	253.2	45.4
86.5	4	yes	85.7	30.3	171.4	181.0

^a Total volume 100 mL; reaction temperature 70 °C; $n_{\text{BIS}}/(n_{\text{MAA}} + n_{\text{NIPAM}}) = 1.0\%$; $C_{\text{SDS}} 4 \times 10^{-4}$ g/mL. ^b $\langle R_h \rangle_c$ and $\langle R_h \rangle_s$ are the hydrodynamic radius of particles at collapsed and swollen states, respectively.

critical solution temperature (LCST)) are in highly hydrophobic compact conformation.^{24,27} According to the precipitation polymerization mechanism, the effective nucleation of MAA/NIPAM copolymer microgel particles could be expected in water at low pH and high temperature.

Table 1 summarized the preparation conditions and partial properties for a series of MAA/NIPAM copolymer microgel particles. The dissociation of a small amount of MAA monomer in deionized water produced a low pH (3.1 ± 0.2) solution. All the copolymerizations were performed in 100 mL of aqueous solution at 70 °C. Large particles with a broad distribution were obtained from the precipitation copolymerization. However, the addition of a small amount of SDS enhanced the colloidal stability of MAA/NIPAM copolymer microgel particles. Nearly monodisperse microgel particles could be synthesized in the presence of SDS. The effects could be attributed to the adsorption of SDS on the surface of coagulative nuclei during the sensitive nucleation stage so that the dispersed primary particles could be stable at fairly high concentrations.¹⁸ The small amount of dissociated (charged) MAA monomer did not improve the colloidal stability because they are too hydrophilic to be adsorbed on the surface of nuclei although they can play a role in the electrostatic repulsion.

Under our reaction conditions, the cross-linker density and the SDS and the APS concentrations were fixed. The only variable was the comonomer composition. When MAA was fed below 10 mol %, the particle formation was relatively slow, and colloidally stable lattices were obtained. No precipitation was observed after a 4 h reaction, which was very similar to the synthesis results of homo-PNIPAM microgels. Therefore, the addition of a small amount of MAA did not change the colloidal stability of PNIPAM microgel particles. However, when MAA was added greater than 25 mol %, the polymerization kinetics and the colloidal stability of MAA/NIPAM copolymer microgels were strongly dependent on the comonomer composition. It has been shown that the number and size of microspheres prepared by precipitation or dispersion polymerization depend on the frequency of particle nucleation and the stability of the nuclei,^{28,29} both of which are affected by the affinity of the MAA/NIPAM copolymer to water in our system. The solubility parameter of the oligo-radicals or/and the copolymer particles formed in the early stage of the polymerization process changed with the comonomer composition. Accordingly, the rate of polymerization and the stability of particles are comonomer composition dependent. The effects due to the difference in solubility parameter between polymer and dispersant on precipitation polymerization have been discussed elsewhere.^{30,31}

Figure 1 shows the polymerization kinetics of three typical MAA/NIPAM copolymer microgel particles at different MAA

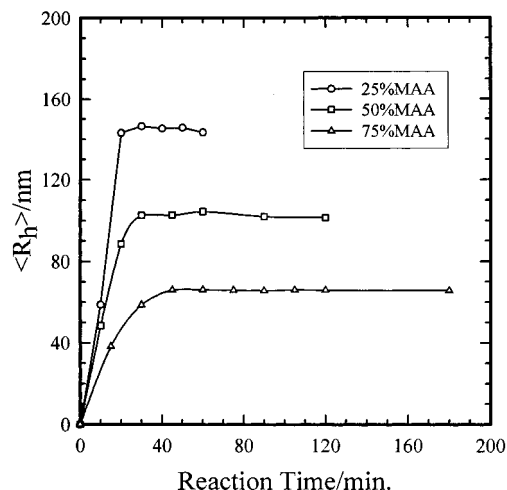


Figure 1. Polymerization kinetics of MAA/NIPAM copolymer microgels at different MAA concentrations, following $\langle R_h \rangle$ as a function of reaction time, in water at pH = 3.1 and $T = 25$ °C.

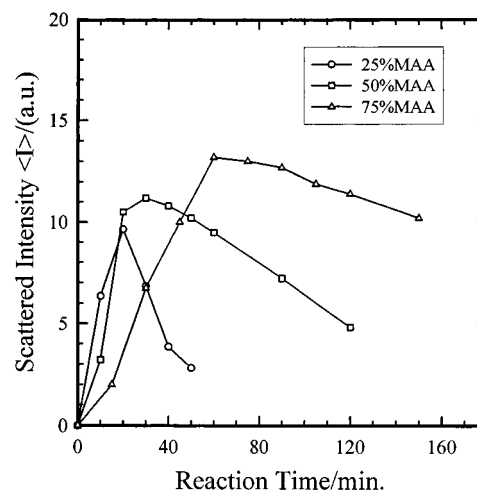


Figure 2. Scattered intensity $\langle I \rangle$ of MAA/NIPAM copolymer microgels taking from the reaction solution phase at different reaction times; $\langle I \rangle$ was measured at scattering angle $\theta = 45^\circ$ and $T = 25$ °C.

concentrations. The samples taken from the reaction solution at different reaction times were diluted to 1/1000 by using dust-free deionized water. Both hydrodynamic radius $\langle R_h \rangle$ and the scattered light intensity $\langle I \rangle$, as shown in Figures 1 and 2, respectively, were determined by using the diluted solution. In the case when precipitation is present, only the solution phase was analyzed. The $\langle R_h \rangle$ values were determined at pH = 3.1 and $T = 25$ °C. The polymerization was very fast. For the 25 mol % MAA feed, the particle size grew to a constant value in about 20 min. An increase in the MAA concentration slowed

the particle growth; i.e., particles grew to a constant size in about 30 min for 50 mol % MAA and in about 45 min for 75 mol % MAA feed. The fast polymerization rate can be explained by the heterophase polymerization mechanism.³² Precipitation of minute polymer droplets swollen with monomers occurs, and these newly formed polymer droplets provide loci for polymerization. In the droplets, single chain radicals may be isolated from others. Therefore, polymerization is likely to be faster than in a homogeneous system.

Figure 2 shows the precipitation kinetics of MAA/NIPAM copolymer microgel particles during the reaction. The scattered light intensity $\langle I \rangle$ of MAA/NIPAM microgels was followed by LLS at scattering angle $\theta = 45^\circ$ and $T = 25^\circ\text{C}$. The $\langle I \rangle$ first increased with increasing reaction time, then reached a maximum $\langle I \rangle$, and finally decreased due to the precipitation of particles. In comparison with Figure 1, it can be clearly noted that the increase in $\langle I \rangle$ during the first stage was due to the growth of particles, while the second stage with a maximum $\langle I \rangle$ and the third stage with decreasing $\langle I \rangle$ depended on the comonomer composition. For the 25 mol % MAA feed, the grown primary particles were not colloidally stable so that the coagulated particles, which were being precipitated from the solution to decrease the number of primary particles in solution, were formed over short time periods. However, when MAA in the feed was increased to 50 and 75 mol %, the time period exhibiting a maximum $\langle I \rangle$ value increased. The nearly constant values in $\langle I \rangle$ and $\langle R_h \rangle$ (Figure 1) during the second stage suggested that the formed primary particles were kinetically stable in the reaction solution. An increase in the MAA concentration increased the time period for the second stage and slowed the decreasing rate of $\langle I \rangle$ in the third stage, which could be viewed as another indication of an increase in the colloidal stability of the primary particles. This stabilization effect by increasing MAA content might be attributed to the increase of the difference in solubility parameter between copolymer and water and also to the electrostatic repulsive force of the weakly dissociated carboxylic group of copolymerized MAA, even though the amount was very small. It should be noted that the primary particle size $\langle R_h \rangle$ in the reaction solution phase remained unchanged although $\langle I \rangle$ decreased in the third stage. Therefore, the precipitation only decreased the number of kinetically stable primary particles in the reaction solutions.

On the basis of the polymerization and precipitation kinetics study, the copolymerization was controlled by using different reaction times (Table 1) for different feed compositions in order to obtain small microgel particles suspended in water with high concentrations. It is worthwhile to mention that the formed particle concentration was very low and broadly distributed in the reaction solution when the MAA in the feed was greater than 90 mol %. All of the obtained particles were titrated by NaOH to determine the PMAA content in the copolymer, which were also summarized in Table 1. At low MAA fraction in the feed, the content of PMAA in the copolymer microgels was a little lower than that in the feed composition. At high MAA fraction in the feed (>50 mol %), the PMAA content in the copolymer microgels was nearly equal to or a little higher than that in the feed. According to the reactivity ratio $r_1 = 1.13$ for MAA and $r_2 = 0.89$ for NIPAM,¹⁴ the copolymer microgels should be enriched in PMAA when compared with the feed comonomer composition, as has been observed experimentally for bulk MAA/NIPAM copolymer gels. The relatively low PMAA content in our MAA/NIPAM copolymer microgels might be attributed to the fact that the particles polymerized in the early stages have low absorbability of the dissociated MAA

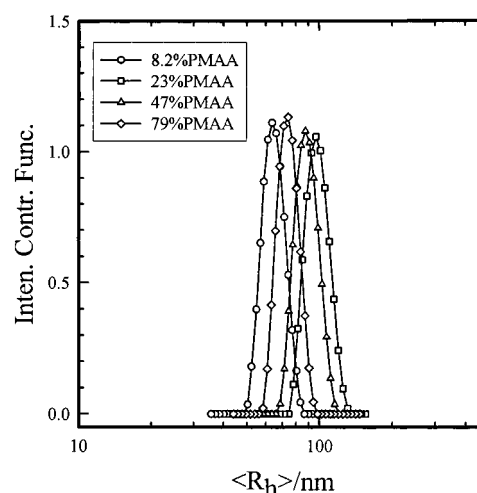


Figure 3. Hydrodynamic radius distributions of MAA/NIPAM copolymer microgels in water at pH = 3.4 and $T = 40.0^\circ\text{C}$, where all the particles are in the collapsed state.

monomers as well as MAA-enriched oligo-radicals in solution due to electrostatic repulsion. All the data in the following discussion reflect the titrated copolymer composition.

Figure 3 shows the hydrodynamic radius distributions $F(R_h)$ of a series of MAA/NIPAM copolymer microgels at pH = 3.4 and $T = 40^\circ\text{C}$, corresponding to the collapsed states for both pH- and thermal-sensitive volume change of the MAA/NIPAM microgels. To avoid the overlap of distribution curves, only four typical distributions with different PMAA content were shown. All the microgel particles are very narrowly distributed. The average hydrodynamic radius $\langle R_h \rangle (= \int_0^\infty F(R_h) R_h dR_h)$ for all the microgel particles are listed in Table 1. The particle size in collapsed state was very small, i.e., having a $\langle R_h \rangle$ of tens of nanometers. It should be mentioned that all the measured $F(R_h)$ were nearly independent of scattering angle θ in the range 20° – 135° . For microgel particles in the swollen state, another fast mode peak related to the dynamic behavior of microgel network appeared. However, the first peak corresponding to the translational diffusion of the swollen microgels was still independent of θ in the low scattering angle region. This angular independence of $F(R_h)$ indicated a spherical symmetry of the particles.

pH-Sensitive Volume Phase Transition. Figure 4 shows the reduced hydrodynamic radius, $\langle R_h \rangle / \langle R_h \rangle_c$, as a function of solution pH at 25°C for MAA/NIPAM copolymer microgel particles with different PMAA contents, where $\langle R_h \rangle_c$ is the hydrodynamic radius in collapsing limit under the measurement conditions. All the microgels underwent a similar continuous volume change in three stages with an increase in pH, namely, the equilibrium swelling ratio first increased greatly, then showed a maximum, and finally decreased when pH was gradually increased. This three-stage volume change with increasing pH was understandable. The pH increase first induced the dissociation of carboxylic acid groups on the network chains, thus increasing the charge density on the network. The concomitant increase in mobile counterion content of the network increased the internal osmotic pressure, which induced the swelling of microgels until the network chains reached a maximum of ionization. In the absence of electrolytes, the maximum expansion of network remained unchanged in a maximum degree of ionization. This is why all the microgels showed a maximum swelling around pH = 7–9, where the additional electrolyte concentrations were too low to affect the ionization of PMAA chains. Further increasing the

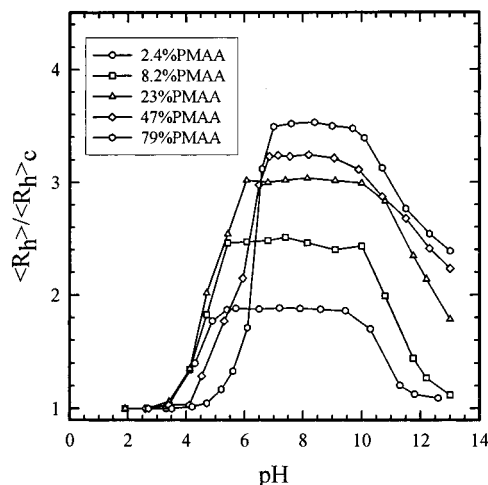


Figure 4. pH-sensitive volume phase transitions, the swelling ratio $\langle R_h \rangle / \langle R_h \rangle_c$ as a function of pH, for MAA/NIPAM copolymer microgel at different PMAA content and $T = 25^\circ\text{C}$. $\langle R_h \rangle_c$ represents the hydrodynamic radius in the collapsed limit over the studied pH range.

pH to 10, the ionic strength of added NaOH was not negligible. The high NaOH concentration caused fewer acid side groups to be dissociated due to the shield effect, decreasing the charge density on the network and the swelling ratio.

As can be seen in Figure 4, the equilibrium swelling behavior of the MAA/NIPAM microgels was also strongly influenced by the copolymer composition. As the PMAA content was increased in the copolymer microgels, two effects were observed: (1) the extent of the swelling transition was increased, and (2) the critical swelling transition shifted to higher pH values. When the PMAA content was below 23 mol %, broad pH intervals of the swelling transition from 3.4 to 5.5 were observed. With a PMAA content of 47 mol %, the pH interval for the swelling transition of microgels occurred from 4.0 to 6.0. By further increasing the PMAA content to 79 mol %, a relatively sharp swelling transition from 5.5 to 7.0 was observed. The first effect was attributed to an increase in the concentration of ionizable carboxylic groups on the network with increasing PMAA content. The higher the counterion concentration, the higher the osmotic pressure which led to the higher swelling extent of the network. The second one could be interpreted as an increase in the hydrophobicity of the copolymer network chains when the PMAA content was increased. A transition will occur only when a particular balance of osmotic and hydrophobic forces was achieved. With increasing network hydrophobicity, a greater degree of ionization was required to enable the transition. At the measurement temperature of 25°C , PNIPAM chains are always hydrophilic in the range of pH investigated. However, the hydrophobicity of PMAA chains varied with pH. At low pH (2–3), PMAA chains possess a hydrophobic compact impermeable form.²⁷ With increasing pH, the PMAA chain can open to form an extended coil. Fluorescence studies showed that the pH-induced change is not a homogeneous ionization of PMAA.²² Increasing pH ionizes a number of COOH groups on PMAA which leads to a hydrophobic core of PMAA surrounded by a more hydrophilic mantle or ionized sections of the polymer. Further increasing the pH value leads to a decrease in the ratio of hydrophobic PMAA core to ionized PMAA “mantle”. Eventually, at high enough pH (6.5), the PMAA chains become extensively uncoiled. The PMAA chain always presents some hydrophobic microdomains before it becomes completely extended. Therefore, an increase in the PMAA content in the MAA/NIPAM copolymer microgels

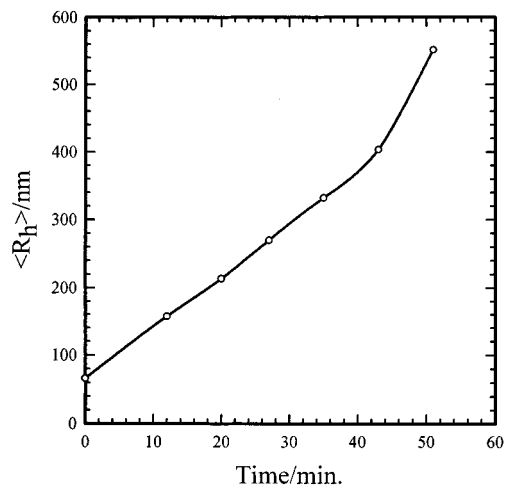


Figure 5. Aggregation kinetics of MAA/NIPAM copolymer microgel particles with 79 mol % PMAA inside the gel network at pH = 1.9 and $T = 25^\circ\text{C}$.

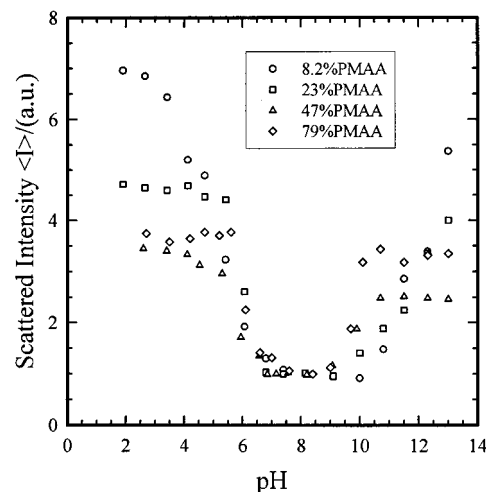


Figure 6. pH dependence of the scattered intensity $\langle I \rangle$ of MAA/NIPAM copolymer microgels with different PMAA content in fixed concentrations at $\theta = 45^\circ$ and $T = 25^\circ\text{C}$.

increased the overall hydrophobicity at pH < 6, which required a higher pH to induce the swelling transition of the microgels.

Figure 5 shows the aggregation kinetics of MAA/NIPAM copolymer microgel particles containing 79 mol % PMAA after the microgel solution pH was adjusted from 2.6 to 1.9 by adding HCl at 25°C . A very fast aggregation process was observed, in which the particle size increased 10-fold within 1 h. The fast aggregation of the microgels was induced by the strong hydrophobic interaction among the particles at low pH. As discussed above, the lower the pH of the aqueous solution, the more hydrophobic the PMAA chains became. Over a pH range of 2.6–4.2, the microgel particles with 79 mol % PMAA were in the collapsed limit with a constant $\langle R_h \rangle_c$ of ~ 70 nm (Figure 4). No aggregation was observed in 2 weeks. Reducing the hydrophobic PMAA content in the copolymer microgels could also increase the thermodynamical stability of the collapsed microgel particles, since the copolymerized PNIPAM chains were in the hydrophilic extended coil state at 25°C . For copolymer microgels with PMAA content below 47 mol %, no aggregation was observed at pH = 1.9, even for 1 month.

Figure 6 shows the scattered light intensity $\langle I \rangle$ as a function of solution pH at 25°C with fixed microgel concentration, but different PMAA contents in the microgel. As a general trend, an increase in the pH first decreased $\langle I \rangle$ and then showed a

lowest plateau in the pH range 7–9. By adding more NaOH to the solution, $\langle I \rangle$ increased with a further increase in pH. Qualitatively, this trend could be explained by a change in the compressional osmotic modulus K_{os} due to the change in the degree of ionization. In the limit of $q = 0$, the excess light intensity scattered from concentration fluctuations in the gel is given by³³

$$I(q \rightarrow 0) = A_0 k_B T (dn/dC)^2 C^2 / M \quad (4)$$

where q is the scattering wave vector, A_0 an apparatus constant, $k_B T$ the thermal energy, dn/dC the refractive index increment with polymer concentration C , and M the longitudinal modulus. M can be further written as $M = K_{os} + (4/3)\mu$ with μ , the shear modulus. The ionization of polymer chains in the gel network reduces slightly the shear modulus but enhances strongly the compressional osmotic modulus due to the osmotic contribution of the free counterions.³⁴ The higher the ionization degree, the higher the K_{os} and thus the lower the scattered light intensity. For MAA/NIPAM copolymer microgels, the ionization degree of network chains first increased with increasing pH as a result of dissociation of MAA units, then reached a maximum at pH 7–9, and finally decreased with increasing pH due to the screening effect of NaOH. Therefore, the scattered light intensity of microgels showed an opposite trend.

Thermal-Sensitive Volume Phase Transition. Homopolymer NIPAM gels undergo a volume phase transition in water from a swollen state to a shrunken state by increasing the temperature. The driving forces for the thermal-sensitive volume phase transition were generally considered to be a subtle balance between the ability of the polymer to form hydrogen bonds with water and the inter- and intramolecular hydrophobic forces.^{5,33} The hydrophobic/hydrophilic atmosphere is expected to be controlled by the property changes of the backbone chains or the pendent groups. Thus, the behavior of the thermal volume phase transition is expected to be altered by external stimuli. The MAA/NIPAM copolymer microgels, synthesized in this work, could provide insight into how the hydrophobic/hydrophilic interactions affect the phase transition behavior, since the hydrophobicity/hydrophilicity of copolymerized PMAA on the backbone chains can be controlled by changing the solution pH.

Figure 7 shows the reduced hydrodynamic radius $\langle R_h \rangle / \langle R_h \rangle_c$ as a function of solution temperature for MAA/NIPAM copolymer microgel particles with different PMAA contents at pH = 3.4, where all the particles were in the collapsed state based on the pH-sensitive transition of PMAA, and $\langle R_h \rangle_c$ represents the hydrodynamic radius in the collapsed limit over the measured temperature range. The thermal sensitive volume phase transition was strongly copolymer composition dependent. Three features should be noted. First, the shrinking extent of the microgels was reduced with increasing PMAA content. It was known that PMAA chains showed a Θ temperature of 30 °C in 0.002 M HCl aqueous solution (pH = 2.7).²⁷ Therefore, at low pH, the PMAA chain in a highly collapsed hydrophobic compact conformation will expand to coil conformation when the temperature was increased above its upper critical solution temperature (UCST). However, our results showed that the MAA/NIPAM copolymer microgel with 79 mol % PMAA did not present any temperature-sensitive volume change over our studied temperature range (<50 °C) at pH = 3.4. An increase in the PMAA content relatively reduced the content of thermal-sensitive PNIPAM chains inside the copolymer microgels, thus reducing the extent of shrinkage by the microgels. Second, the critical collapsing transition temperature T_c decreased with increasing PMAA content. T_c depends on the balance of

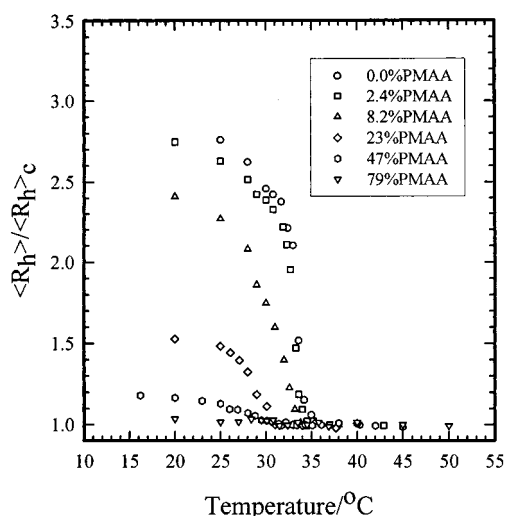


Figure 7. Thermal-sensitive volume phase transition plot of $\langle R_h \rangle / \langle R_h \rangle_c$ as a function of solution temperatures at pH = 3.4, where based on the pH-sensitive volume transition all the MAA/NIPAM copolymer microgels were in the collapsed state, and $\langle R_h \rangle_c$ represents the hydrodynamic radius in the collapsed limit over the studied temperature range.

hydrophobic/hydrophilic interactions between the polymer chains and water. The hydrophobic interaction lowers T_c , while the hydrophilic interaction raises T_c . In the past, a few systems have been designed to check the hydrophobic effects on T_c . A decrease in T_c was observed in bulk gels by increasing the hydrophobicity of pendent groups, such as changing the isopropyl group to a diethyl group or an azobenzene group.^{35,36} In this study, the decrease in T_c with increasing PMAA content indicated that the PMAA chains at low pH and low temperature (<50 °C in the studied range) were more hydrophobic than the PNIPAM chains, as disclosed here for the first time. Therefore, by copolymerizing MAA with NIPAM in the microgels, the hydrophobic interaction was forced at low pH. The higher the PMAA content in the microgels, the more hydrophobic the copolymer backbone chains became and thus the lower the T_c ; i.e., when the PMAA content was increased from 0 to 23 mol % in the microgels, the T_c decreased from 33.5 to 28 °C. Third, the transitions became broader with increasing PMAA content. The broader transition might be attributed to the PNIPAM chain inhomogeneity in the microgel network. It is known that for a given polymer concentration the polymer chains with different lengths undergo a phase transition at different temperatures. For the MAA/NIPAM random copolymer microgels, the PNIPAM chains inside the microgel network have a broad molecular weight (length) distribution. With increasing PMAA content, the molecular weight (chain length) distribution of the thermal-sensitive PNIPAM chains that have been copolymerized randomly inside the microgel are broadened. The higher the MAA/NIPAM molar ratio in the feed composition, the larger the PNIPAM chain length difference inside the microgels, and thus the broader the phase transition temperature range, until the PNIPAM chain inhomogeneity reaches a maximum at a MAA/NIPAM molar ratio of 1.

Figure 8 shows the reduced hydrodynamic radius $\langle R_h \rangle / \langle R_h \rangle_c$ as a function of solution temperatures for MAA/NIPAM copolymer microgel particles at different PMAA contents and pH = 7.5, where all the particles were in the maximum swollen state corresponding to a pH-sensitive transition, and $\langle R_h \rangle_c$ represents the hydrodynamic radius in the collapsed limit over the measured temperature range. In comparison with the collapsed PMAA chains in Figure 7, the ionized PMAA chains

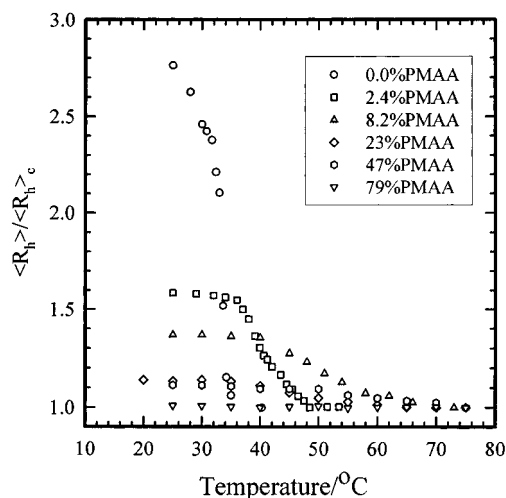


Figure 8. Thermal-sensitive volume phase transition plot of $\langle R_h \rangle / \langle R_{hc} \rangle$ as a function of solution temperature at pH = 7.5, where based on the pH-sensitive transition all the MAA/NIPAM copolymer microgels were in the maximum swollen state, and $\langle R_{hc} \rangle$ represents the hydrodynamic radius in the collapsed limit over the studied temperature range.

affected the thermal-sensitive volume phase transition of microgels in a very different way. As expected, the ionized hydrophilic PMAA chains copolymerized in the microgels raised T_c . The higher the PMAA content, the higher the T_c . When the PMAA contents were over 10 mol %, T_c was too high to be observed in the studied temperature range ($\leq 75^\circ\text{C}$). However, the sharp (or discontinuous) and large volume changes from the swollen state to the shrunken state, usually observed in weakly charged PNIPAM bulk^{5,26} or submicron¹⁷ gels, were absent for the MAA/NIPAM copolymer microgels. Very broad temperature change accompanied by small shrinkage in volume was unexpectedly observed for the copolymer microgel with PMAA content below 10 mol %. The higher the PMAA content, the broader the temperature transition range and the smaller the extent of shrinkage. In the beginning, we were astonished by this strange volume phase transition behavior of MAA/NIPAM copolymer microgels, since in other weakly charged PNIPAM gels, the higher the charged comonomer concentration, the sharper (or discontinuous) the transition range in temperature and the larger the volume change.^{5,17,26} We speculated that the broad temperature and small volume transition might be related to the inhomogeneous distribution of the comonomers in the MAA/NIPAM copolymer microgels with low PMAA content, namely, a core enriched by PNIPAM chains and a shell enriched by PMAA chains. With low MAA content in the feed, the MAA-containing oligo-radicals formed in the early stage of polymerization mainly consist of the hydrophobic PNIPAM oligomer. A small amount of MAA units in the oligo-radicals is relatively hydrophilic due to the dissociation of partial carboxylic groups. In other words, these MAA-containing oligo-radicals have an amphiphilic property. When these oligo-radicals further polymerize to form insoluble polymer particles in water, it is likely that the MAA units are located on the outer shell of the particles due to the presence of charged groups. These charged groups can also stabilize the formed particles. Therefore, at a higher pH value of 7.5, the surface layer of the spherical copolymer microgels will have a relatively higher charge density than that inside the microgel. The core enriched in neutral PNIPAM will collapse at a lower temperature, while the shell enriched in PMAA with a higher charge density will collapse at a higher temperature, which led to a broader temperature region in the volume transition. With

the microgels being collapsed, the particle size was reduced, but the surface charge density was increased. When the charge density in the shell was increased high enough, the shell of the microgel would not collapse further in our studied temperature range, explaining why the weakly charged MAA/NIPAM copolymer microgel showed a lower extent of shrinkage. Hirotsu³⁷ even observed a dimension dependence on the volume phase transition of weakly charged bulk PNIPAM gels. The smaller the gel, the lower the T_c and the lower the swelling ratio, which were possibly explained according to the surface tension effect induced by the surface charge. Further study is needed to understand how the surface state of the ionized gel alters the behavior of the volume phase transition.

A combination of Figures 7 and 8 clearly indicated that the copolymer composition altered the thermal-sensitive volume phase transition of the MAA/NIPAM microgels in a very different way; namely, the hydrophobicity of the PMAA chain can be adjusted by varying the solution pH. It should also be noted that the decrease in T_c was observed in Figure 3 of ref 14 for the bulk MAA/NIPAM copolymer gel in deionized water (pH = 6.5) when the MAA content was over 25 mol %. However, no explanation for the decrease in T_c was given because an increase in T_c was also observed when the MAA content was below 16 mol %. The hydrophobicity of PMAA chains are strongly pH dependent. At low pH, the PMAA chains are in a highly compact hydrophobic conformation. Figure 7 shows that even the presence of 2.4 mol % PMAA in the MAA/NIPAM copolymer microgel could decrease the T_c at pH = 3.4. Assuming pH = 6.5 was correct in ref 14, the observed T_c for all the bulk MAA/NIPAM copolymer gels should be increased since at such a high pH value, nearly all of the PMAA chains would be ionized. Thus, the hydrophilic effects should be observed. One possible reason for the results in ref 14 (T_c increased with MAA content below 16 mol %, while T_c decreased with MAA content above 25 mol %) could be the wrong pH value (6.5) of the deionized water used. As shown in Figure 4, the pH-sensitive critical swelling transition was copolymer composition dependent. The microgels with a high PMAA content swelled at higher pH values than those with a lower PMAA content. By taking pH ~ 5 in Figure 4, we would find that the microgels with a low PMAA content (i.e., <10 mol %) were already in the hydrophilic swollen state which increased the T_c , while the microgels with a high PMAA content (i.e., >25 mol %) were still in the (partially) hydrophobic collapsed state which decreased the T_c . Only at such pH values in the transition region were similar results as observed in ref 14 possible. Therefore, the conclusions on the effect of the MAA content on T_c of bulk MAA/NIPAM gels in ref 14 should be reexamined since the hydrophobicity of PMAA chains are strongly pH dependent.

Figure 9 shows the temperature dependence of the scattered light intensity $\langle I \rangle$ for nearly neutral MAA/NIPAM copolymer microgels with different PMAA contents at pH = 3.4. For microgels with low PMAA contents, and with increasing temperatures, $\langle I \rangle$ showed a slight increase at temperatures far below T_c and a strong increase near T_c . After reaching T_c , $\langle I \rangle$ increased dramatically. For microgels with high PMAA contents which showed no T_c in the studied temperature range, $\langle I \rangle$ increased only very slightly with increasing temperature. According to eq 4, an increase in $\langle I \rangle$ could be induced by an increase in T and dn/dC or/and a decrease in M at fixed C . However, the effects of T and dn/dC were very small. The dominant contribution could only be the decrease in $M = K_{os} + (4/3)\mu$. Experimental evidence for the bulk neutral PNIPAM gel showed that K_{os} decreased strongly with increasing tem-

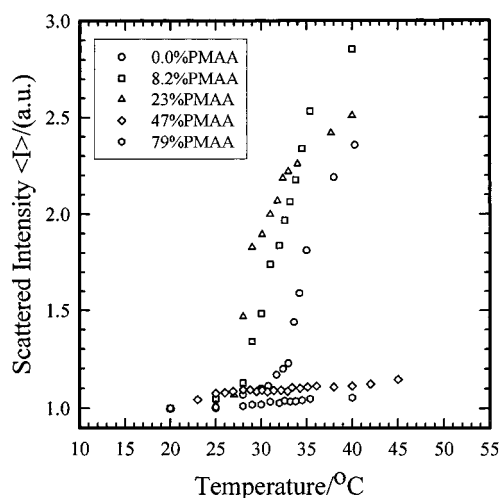


Figure 9. Temperature dependence of scattered intensity $\langle I \rangle$ of MAA/NIPAM copolymer microgel particles during thermal volume phase transition at $\theta = 45^\circ$ and $\text{pH} = 3.4$.

perature around T_c and that the critical volume phase transition occurred at the point of $K_{os} = 0$, while μ increased only slightly at T_c .³⁸ Thus, when temperatures were increased near or to T_c , M decreased strongly, leading to a dramatic increase in $\langle I \rangle$.

Conclusions

Lightly cross-linked, nearly monodisperse, and submicron-sized MAA/NIPAM random copolymer microgel particles can be synthesized in water by dispersion polymerization. With MAA in the feed below 10 mol %, the particle formation was relatively slow and the lattices were colloidally stable for a long time. With MAA in the feed greater than 25 mol %, the polymerization became very fast, and only kinetically stable particles that precipitated from solution with increasing time were obtained. An increase in the MAA content increased the colloidal stability of the particles in solution.

The MAA/NIPAM copolymer microgels can undergo a pH-sensitive volume phase transition at 25 °C, in which the PMAA content has two effects: (1) an increase in the PMAA content increased the equilibrium swelling ratio due to the electrostatic repulsion of ionized MAA units; (2) an increase in the PMAA content enhanced the critical transition pH, which could be explained by the inhomogeneous ionization of PMAA chains, namely, a hydrophobic core surrounded by a more hydrophilic ionized mantle. At 25 °C and low pH (<2), the collapsed microgels with high MAA content aggregated very fast to produce a phase separation due to the strong hydrophobic interaction.

The MAA/NIPAM copolymer microgels can also undergo a thermal-sensitive volume phase transition. The behavior of the volume phase transition could be controlled by changing the hydrophobicity/hydrophilicity of copolymerized PMAA chains in different pH solutions. At low pH, PMAA chains are in a highly collapsed hydrophobic state. An increase in the PMAA content decreased T_c , reduced the extent of collapse, and broadened the transition temperature region. At higher pH (7–10), the PMAA chain expanded to form a strongly hydrophilic coil with high charge density. An increase in the PMAA content raised the T_c , but unexpectedly reduced the extent of collapse of the swollen microgels, and made the transition flatter. The thermal-sensitive volume change of weakly charged MAA/NIPAM copolymer microgel, synthesized in this work, might be related to the inhomogeneous distribution of the comonomers

inside the gel network, namely, a core enriched in neutral PNIPAM and a shell enriched in PMAA with a high charge density.

All the observed pH- and thermal-sensitive volume phase transitions for the MAA/NIPAM copolymer microgels were continuous and reversible. The coupling of pH and temperature variables could induce a hydrodynamic volume change as large as 10–100-fold of the collapsed microgel particles by adjusting the PMAA content (see Table 1). For both pH, and temperature-sensitive volume transitions, the collapse of microgels from the swollen state to the shrunken state increased the scattered light intensity, which could be explained by a change in the longitudinal modulus.

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