Volume Phase Transition of Polyelectrolyte Gels with Different Charge Distributions

Etsuo Kokufuta,*,† Benlian Wang,† Ryo Yoshida,† Alexei R. Khokhlov,‡ and Mitsuo Hirata§

Institute of Applied Biochemistry, University of Tsukuba, Tsukuba, Ibaraki 305, Japan, Physics Department, Moscow State University, Moscow 117334, Russia, and Department of Industrial Chemistry, College of Industrial Technology, Nihon University, Narashino, Chiba 275, Japan

Received October 27, 1997; Revised Manuscript Received July 11, 1998

ABSTRACT: Four polyelectrolyte gels consisting of acrylic acid (AA) and *N*-isopropylacrylamide (NIPA) were prepared using the following methods: (i) the usual redox polymerization of an aqueous solution containing NIPA, AA, and *N*,*N*′-methylenebis(acrylamide) (cross-linker) which was initiated by a pair of ammonium persulfate and *N*,*N*,*N*′,*N*′-tetramethylethylenediamine; (ii) the same method as employed in (i) except for the use of poly(acrylic acid) (PAA) instead of the AA monomer; (iii) the gelation of an aqueous solution containing the polymer of NIPA (PNIPA) and PAA with γ-ray irradiation from ^{60}Co; (iv) the same method as used in (iii) except for the use of an AA/NIPA copolymer instead of the PAA/PNIPA mixture. The gels prepared by (i) and (iv) contain the AA residues randomly distributed within the network, while the AA residues in the gels prepared by (ii) and (iii) are localized along the PAA chain within the network. This difference in the AA distribution between the former and latter gels was found to result in two clearly different sets of swelling curves when the degree of swelling was examined at pHs 3 and 10 as a function of temperature. At pH 10, at which a complete dissociation of the COOH groups takes place, the gels prepared by (ii) and (iii) underwent a volume phase transition at around 33 °C, whereas the gels obtained via (i) and (iv) were in a swollen state over the temperature range measured (25−50 °C). At pH 3, at which most of the COO^- ions are protonated, all the gels collapsed at temperatures >33 °C. However, the locally distributed AA residues reduced the gel volume in both the swollen (<33 °C) and the collapsed states (>33 °C), which suggests that hydrogen bonding, in addition to hydrophobic interaction, plays an important role in the gel collapse. The possibility that hydrogen bonding occurs under acidic conditions was supported by studying the effects of pH and urea on the complexation between PNIPA and PAA using the dynamic light scattering technique. In conclusion, the present study suggests a strong influence of the "distribution" of ionic groups in the network on the volume phase transition of ionic gels, the nature of which can no longer be explained in terms of the concept of osmotic pressure arising from mobile counterions within the gel phase.

Introduction

In 1978, Tanaka discovered the discontinuous volume change (i.e., volume phase transition) of a covalently cross-linked acrylamide gel in an acetone/water mixture when varying the temperature or composition of the mixture.[1] This phenomenon was interpreted theoretically in terms of the Flory−Huggins mean-field equation of state consisting of four principal terms: the rubber elasticity, the interactions among polymer segments and solvents, the mixing entropy, and the osmotic pressure. At present, it is well-known that volume phase transition occurs in various kinds of gels made of synthetic and natural polymers. In particular, gels consisting of *N*-isopropylacrylamide (NIPA) have attracted much attention because they undergo an "abrupt" volume collapse when heated at around 33 °C. Several theoretical studies[2−9] have attempted to describe the volume phase transition of NIPA gels based on the previously mentioned four principal terms, most of which were summarized in a recent review by Schild.[10] He pointed out that the expressions of the three contributions to the free energy other than the osmotic pressure vary from theory to theory with tenuous connections with reality in some cases. In addition, several arguments regarding the use of the Flory−Huggins theory were presented in his critical review.

In the above theoretical studies, on the other hand, there was little disagreement regarding the description of osmotic effects which exist when there are ionic charges in the system; in other words, Donnan equilibria were consistently used. Nevertheless, it is preferable to verify experimentally whether the "concept" of osmotic pressure is adequate or not, especially in view of both the scientific interest and the technological significance of polyelectrolyte gels. This is, however, a rather difficult problem with respect to experimental techniques; thus, to our knowledge, there has not been any comprehensive study dealing with this subject so far.

In our previous studies[11−13] on ionic NIPA gels with bound anionic surfactants, we have demonstrated that an inhomogeneous binding of surfactants brings about a different swelling behavior from that of the usual ionic gels prepared via random copolymerization of NIPA and acrylic acid (AA). Taking this into account, we decided to examine the effect of the charge distribution (i.e., the distribution of AA residues in the network) on the swelling behavior of NIPA/AA gels. If the concept of osmotic pressure is correct, one might not observe any difference in the swelling curves between the two kinds of ionic NIPA/AA gels into which the AA residues were homogeneously or inhomogeneously introduced. The

† University of Tsukuba.
‡ Moscow State University.
§ Nihon University.

S0024-9297(97)01565-9 CCC: $15.00
Published on Web 09/03/1998

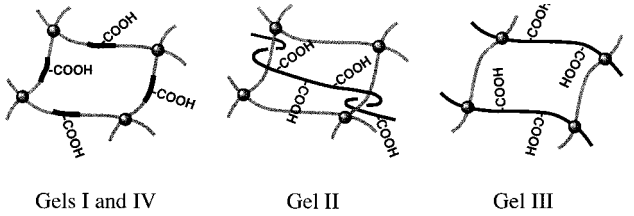


Figure 1. Schematic illustration of four polyelectrolyte gels consisting of NIPA and AA residues.

reason for this is that counterions to the ionized groups should move freely within the gel phase surrounded by the Donnan potential barrier and thereby increase the osmotic pressure acting to swell the gel.

The object of the present study is to examine the swelling behavior of NIPA/AA gels with the same amount but a different distribution of AA; through this examination we intend to discuss the validity of the concept of osmotic pressure on the molecular level. In addition, we also attempted to examine the obtained results in comparison with another concept[14] established by Kokufuta et al. in order to account for the volume phase transitions of various kinds of polymer gels on the molecular level. In the present study, dynamic light scattering (DLS) and measurements of lower critical solution temperature (LCST) for aqueous solutions containing homopolymers of NIPA and AA (respectively abbreviated as PNIPA and PAA) were employed in order to examine the formation of a PNIPA/PAA complex at an acidic pH, in addition to the usual swelling measurements of NIPA/AA gels.

Design of NIPA/AA Gels with Different Charge Distributions

For the present purpose, we designed four ionic gels (gels I−IV) composed of NIPA and AA residues. The AA distributions within the polymer network of these gel samples may be classified into three schemes, as shown in Figure 1. The preparation methods considered are as follows: (i) for gel I, the redox polymerization of an aqueous solution containing NIPA, AA, and *N,N′*-methylenebis(acrylamide) (MBA, cross-linker) which can be initiated by a pair of ammonium persulfate (APS) and *N,N,N′,N′*-tetramethylethylenediamine (TMED); (ii) for gel II, the physical entrapment of PAA by an MBA-cross-linked NIPA gel, the performance of which is based on the same method employed in (i) except for the use of PAA instead of the AA monomer; (iii) for gel III, the gelation of an aqueous solution containing PNIPA and PAA by γ-rays from ^{60}Co under conditions where no complexation occurs between PNIPA and PAA; (iv) for gel IV, whose AA distribution may be expected to be similar to that of gel I, the γ-ray irradiation of an aqueous solution of a copolymer of NIPA and AA, i.e., copoly(NIPA, AA).

Experimental Section

Materials. The NIPA monomer (kindly supplied by Kojin Chemical Co., Tokyo, Japan) was recrystallized in *n*-hexane before use in order to remove a polymerization inhibitor (*p*-methoxyphenol). The AA monomer was commercially obtained from Wako Chemical Co. (Tokyo, Japan) and purified by vacuum distillation. MBA, TMED, and APS were all used as received.

Three PAA samples (nominal $\bar{M}_w = 9 \times 10^4$, 4.5×10^5, and 1.25×10^6) were commercially obtained from Aldrich Chemical Co. (Milwaukee, WI). These polymers were purified by reprecipitation (three times) from methanol with *n*-hexane and then dried in a vacuum.

PNIPA ($\bar{M}_w = 7.6 \times 10^5$) was synthesized by radical polymerization using benzene as the solvent and α,α′-azobis(isobutyronitrile) as the initiator in the same manner used in a previous study.[11] Copoly(NIPA, AA) was also synthesized in a way similar to that employed for PNIPA; i.e., the copolymerization of a benzene solution containing NIPA and AA monomers at 75 °C for 20 min under nitrogen. In both cases, the resulting reaction mixture was slowly poured into *n*-hexane to precipitate PNIPA or copoly(NIPA, AA), which were then separated by filtration, washed with *n*-hexane, and dried in a vacuum. Purification was carried out by dialyzing an aqueous polymer solution against distilled water for 1 week. The dialyzed solution was lyophilized and finally dried under reduced pressure at 50 °C for 3 days. The NIPA:AA ratio of the copolymer was found to be 10:1.7 by moles of the monomer units, as estimated by means of colloid titration.[15]

Preparation of Gels. The NIPA:AA ratio of the feeds was adjusted to 10:1 by moles of the monomers or repeating units throughout all of the preparations, except for the case of gel IV. The pH of the feeds was also adjusted to ca. 9 in order to avoid formation of a complex between NIPA and AA or between PNIPA and PAA (the complexation will be described in detail in the later section). Gels I−IV were prepared as follows. (i) Gel I: an aqueous monomer solution (9.5 mL) containing NIPA (0.791 g; 7 mmol), AA (50.4 mg; 0.7 mmol), MBA (14 mg; 0.091 mmol), and TMED (94 μL) was prepared using distilled water as the solvent, degassed with N_2 at 0 °C for 10 min, and finally mixed with 0.5 mL of an aqueous solution including APS (10 mg). After that, 3 mL of the above solution was quickly transferred into a test tube (total volume, 5 mL; inner diameter, 9 mm) into which glass capillaries with an inner diameter of 0.3 mm had previously been inserted. The polymerization was carried out under an N_2 atmosphere at 1 °C. (ii) Gel II: the above monomer solution containing PAA (50.4 mg) instead of the AA monomer was prepared and gelated in the same manner used for gel I. (iii) Gel III: PNIPA (0.791 g) and PAA (50.4 mg) were dissolved in 10 mL of distilled water. The aqueous polymer solution was transferred into a test tube in which the same glass capillaries used in the preparation of gels I and II had previously been inserted. The test tube was sealed after degassing the solution under a vacuum. The gelation was then carried out at ca. 1 °C for 12.8 h at a dose rate of 0.156 Mrad/h, using γ-rays from a ^{60}Co source (see ref 16 for γ-ray irradiation techniques). (iv) Gel IV: the preparation was carried out in the same manner employed in gel III except for the use of an aqueous solution (10 mL) containing 0.841 g of copoly(NIPA, AA) (NIPA:AA ratio = 10:1.7). After the gelation was completed, all the gel samples were taken out of the capillaries, thoroughly washed with either an NH_4Cl/HCl buffer (50 mM, pH 3) or an NH_4Cl/NH_4OH buffer (50 mM, pH 10), cut into cylinders of approximately 2 mm length, and then stored at 3 °C before use.

Measurements of Gel Diameter. The gel sample obtained was inserted into a water-jacketed microcell together with either of the following buffer solutions: 50 mM NH_4Cl/HCl, pH 3; 50 mM NH_4Cl/NH_4OH, pH 10. The gel diameter was then determined as a function of temperature by using a microscope with a calibrated scale. During the measurements, the temperature was controlled by circulating thermostated water through the water-jacket around the cell. For gel II with physically entrapped PAA, special care was taken in measuring its diameter; that is, total organic carbon (TOC) analysis[17] with a Beckman TOC analyzer (model 915 B) was employed in order to confirm that there was no release of the entrapped polymer during the measurements.

DLS and LCST Measurements. To study the formation of a PNIPA/PAA complex via hydrogen bonding, the effects of pH and urea on the size distributions of PNIPA and PAA in their separated and mixed solutions were examined by DLS. We used here a 0.1 M NaCl solution instead of the 50 mM ammonium buffer, because the former was easier to handle than the latter in the preparation of 4 M urea solutions at pH

3 and 10 (we believe from our experience that although there is some good evidence for specific ion-binding of Na^+ to polycarboxylates (not "counterion condensation"), which would not be exhibited by NH_4^+, this does not lead to serious errors in the present experiments). The PNIPA and PAA solutions were thus prepared by dissolving a desired amount of the polymer (0.5 g/dL for PNIPA and 0.16 g/dL for PAA) in aqueous 0.1 M NaCl solutions containing or not containing 4 M urea, followed by an adjustment of the pH to 3 with 0.1 M HCl or to 10 with 0.1 M NaOH. The polymer solutions were filtered through 0.45 μm filters (Sartorius) to remove dust, and then mixed in PNIPA:PAA = 2:1 (unit mole ratio). Since it was found that urea shifts the LCST of the PNIPA solution to a low temperature range, the PNIPA solutions and the PNIPA/PAA mixtures were subjected to LCST measurements prior to the DLS experiments. The measurements were carried out using a Shimazu spectrophotometer (Model UV-240) equipped with an electronically controllable thermoregulator. The transmittance (%) of the solution at 500 nm was then recorded by raising or lowering the temperature at a rate of 1 °C/min.

The DLS experiments were performed at 15 °C after taking into account the results of the LCST measurements. The scattering angle was then fixed at 90°. We employed an Otsuka laser light scattering apparatus (Model DLS-7000) equipped with an argon ion laser (Spectra-Physics, Model 2060-4S; multiline type; 1.2 W when $\lambda_0 = 488$ nm). The time correlation function was then evaluated by the histogram method, from which we obtained the size distribution curve. The DLS measurements for several samples were also performed by using a Brookhaven system (Holtsville, NY) equipped with a 256-channel digital auto-correlator (BI-2030 AT) and a 2 W Ar laser (Stabilite 2017, Spectra-Physics Lasers). In the latter case, we used the CONTIN program to obtain the size distribution curve as previously reported in the study on the complexation between protein and polyelectrolyte molecules.[18]

Results and Discussion

Swelling Curves for Gels I−IV. Figure 2 shows the temperature dependence of the normalized equilibrium diameters (d/d_o) at pHs 3 and 10 for gels I−IV. The normalization of each observed equilibrium diameter (d) was performed using the inner diameter (d_o) of the capillary utilized in the gel preparation. It was found that gels I and IV, with a random distribution of the AA residues, exhibited a similar volume phase transition when varying the temperature at pHs 3 and 10. A similarity was also observed in gels II and III with the locally distributed AA residues. Therefore, the volume phase transitions for gels I−IV are divided into two different classes when taking into account the distribution of the AA residues. In particular, at pH 10 at which the COOH groups bound to the AA residues are ionized ($COOH \rightarrow COO^- + H^+$), there is a marked difference due to the AA distribution; the localized COO^- ions are not effective in preventing the thermally induced gel collapse at temperatures above the volume-phase transition temperature (T_v). This indicates an effect of the "charge distribution" in the network on the volume transition of ionic gels.

The phase separation of PNIPA in pure water at the LCST was generally understood by considering both hydrogen bonding and hydrophobic effects.[10] Since there was little disagreement between the T_v for the usual nonionic NIPA gels and the LCST for PNIPA when the measurements were performed in the same solvent, Schild has surmised a similar molecular mechanism for the phase separation and the volume transition (see page 211 of ref 10). For gels II and III composed of 90% (in unit mole base) cross-linked "pure" NIPA chains, it is predictable that their phase transition

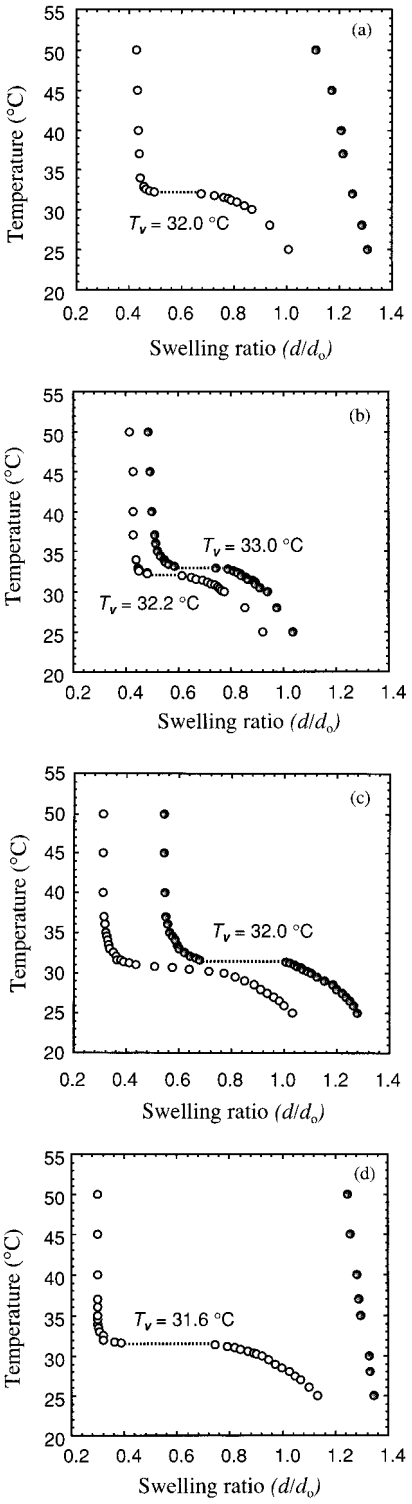


Figure 2. Temperature dependence of normalized equilibrium diameters (d/d_o) at pHs 3 (open circles) and 10 (shadowed circles) for four polyelectrolyte gels consisting of NIPA and AA residues: (a) gel I; (b) gel II; (c) gel III; (d) gel IV. PAA with $\bar{M}_w = 4.5 \times 10^5$ was used for the preparation of gels II and III. Dashed line indicates a discontinuous volume phase transition at a temperature (T_v) at which we observed a transient pattern in both swelling and shrinking processes and thereby were not able to measure d. Such a transient pattern was not observed in the measurements for gel III at pH 3, suggesting a continuous transition.

behaviors are not so different from those of nonionic NIPA gels or PNIPA, even at pH 10 where the incorporated PAA chains (10% in unit mole base) are

ionized. Indeed, at pH 10 gels II and III underwent a volume phase transition at temperatures near the T_v for nonionic NIPA gels or the LCST for PNIPA.

A more detailed interpretation could be made when taking into account the mechanism of microphase separation of weakly charged polyelectrolytes in poor solvents, which has been proposed by Borue et al.,[19] as well as by Dormidontova et al.[20] According to this, it appears that microphase separation takes place at T_v; i.e., the NIPA chains within gels II and III collapse to form hydrophobic "micromicelle-like" aggregates surrounded by water-rich domains including both the ionized PAA chains and their corresponding counterions (NH_4^+) at pH 10. The microphase separation mechanism also makes it possible for us to understand the results of gels I and IV. For both gels, the NIPA and AA monomer residues should be intermixed in the network; therefore, the dissociation of the COOH groups at pH 10 strongly hinders the formation of hydrophobic aggregates not only through an increase in the hydrophilicity due to the COO^- plus NH_4^+ ions, but also through the Coulomb repulsion between the COO^- ions. A similar molecular mechanism may be applied to explain the fact that at pH 10 copoly(NIPA, AA) does not undergo phase separation, even at 50 °C. Consequently, these discussions lead us to conclude that the volume transition of ionic gels, at least in our gels, is no longer explainable in terms of the concept of osmotic pressure.

Nevertheless, one more aspect to be taken into account when analyzing the present results is the Manning-type condensation of counterions, which has been neglected in previous theories (see refs 2−9) as pointed out by Grosberg and Khokhlov.[21] For gels II and III at pH 10, many of the counterions are condensed around the charged PAA ions, and hence the osmotic pressure may not be generated to swell the gel. However, for gels I and IV, in which the charged AA residues are randomly distributed, many of the counterions are free from condensation and mobile at pH 10. Therefore, their substantial contribution to the osmotic pressure should allow the gel to swell over a wide temperature range; in other words, we can again conclude that the osmotic pressure plays an important role in the volume phase transition of ionic gels.

The above discussions have led to conflicting conclusions. When carefully examining the swelling curves in Figure 2, however, one should not forget the fact that the swelling curves at pH 10 for gels II and III are shifted to the right-hand side (i.e., high degree of swelling) over all the temperatures measured. This suggests the existence of a microphase within which the NIPA chains around the charged PAA fail to form hydrophobic aggregates via the collapse transition at temperatures $> T_v$. Thus, our attention will be focused on the effect of the charged or uncharged PAA chains incorporated into the NIPA gel on its volume transition.

Effect of the Molecular Weight of Entrapped PAA within Gel II. If the osmotic pressure due to mobile counterions plays an important role in the volume phase transition of NIPA/AA gels, one would expect to observe either one of the following: (a) little change in the gel volume caused by the molecular weight of the PAA ions entrapped within the cross-linked NIPA chain or (b) an increase in the molecular weight leading to the tendency for the gel to collapse due to a decrease in the entropy of the counterions.

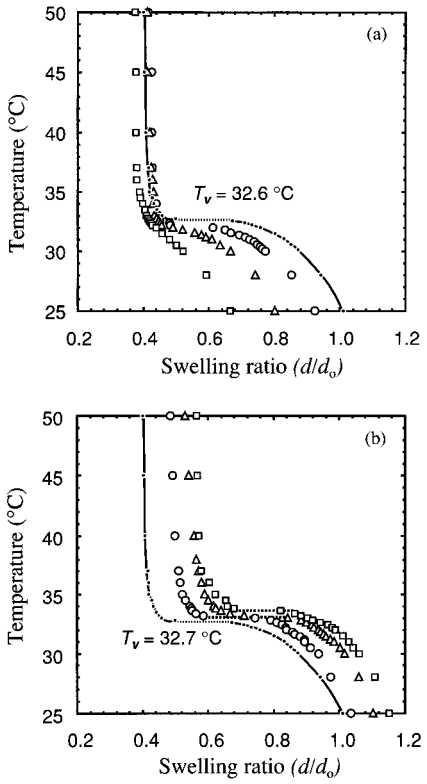


Figure 3. Effect of the molecular weight of the entrapped PAA on the normalized equilibrium diameters (d/d_o) for gel II at pHs 3 (a) and 10 (b). M_w: (○) 9×10^4; (△) 4.5×10^5; (□) 1.25×10^6. Swelling curves (small solid circles) for the neutral NIPA gel (T_v = 32.6 °C at pH 3 and 32.7 °C at pH 10) are shown in Figure 3a,b as the standard. The increase in the molecular weight alters the transition at pH 3 from a discontinuous to a continuous type accompanying a decrease in T_v, whereas at pH 10 it leads to a discontinuous transition with an increase in T_v.

Consequently, the study of the swelling behavior of gel II with entrapped PAAs of different molecular weights may provide a key to determining whether the volume phase transition of NIPA/AA gels is governed by microphase separation or by osmotic pressure.

Figure 3 shows changes in the swelling curves of gel II at pHs 3 and 10 caused by the molecular weights of the entrapped PAA chains. It can be seen that the increase in the molecular weight at pH 10 brought about an increase in the gel volume over the temperature range 25−50 °C. This result evidently suggests little contribution of the osmotic pressure to the swelling of a polyelectrolyte gel consisting of the NIPA/AA system. In other words, the observed results may be understood in connection with the microphase separation mechanism rather than the contribution of osmotic pressure; the increase in the molecular weight of the entrapped PAA ions leads to the formation of larger water-rich regions due to the COO^- ions around the water-unfriendly hydrophobic aggregates of the NIPA chains and, therefore, the swelling of the gel with high molecular-weight PAA ions should increase.

Another important feature of Figure 3 is that, at pH 3 and at temperatures $< T_v$, the gel volume decreased with increasing molecular weight of the entrapped PAA with the nonionized COOH groups. A possible interpretation of this result could be the increase in the cross-linking points by the formation of hydrogen bonds between the NIPA and AA residues. To confirm this assumption, we attempted to examine the temperature-

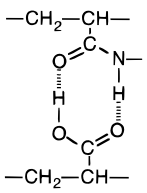
Table 1. Effects of pH and 4 M Urea on the LCST for Aqueous 0.1 M NaCl Solutions Containing PNIPA or PNIPA/PAA Mixture

sample[a,b]	pH	4 M urea	LCST[c]
PNIPA	3	absence	31.3 ± 0.2
PNIPA	3	presence	26.1 ± 0.3
PNIPA	10	absence	31.4 ± 0.3
PNIPA	10	presence	25.9 ± 0.3
PNIPA/PAA mixture	3	absence	*d*
PNIPA/PAA mixture	3	presence	26.2 ± 0.3
PNIPA/PAA mixture	10	absence	31.1 ± 0.2
PNIPA/PAA mixture	10	presence	26.4 ± 0.3

[a] Concentrations of PNIPA ($\bar{M}_w = 7.6 \times 10^5$) and PAA ($\bar{M}_w = 4.5 \times 10^5$) in the sample solutions were adjusted to 0.5 and 0.16 g/dL, respectively. [b] The same volumes (10 mL each) of the PNIPA and PAA solutions were mixed; thus, the ratio of PNIPA:PAA in the mixed sample was 2:1 by unit mole base and the total polymer concentration was 0.33 g/dL. [c] Denotes the average of five measurements. [d] The measurement could not be performed because the solution was turbid even at 1 °C.

induced swelling changes for gels I and III in the presence and absence of 4 M urea at pH 3. However, we found that urea shifts both the LCST of aqueous NIPA solutions and the T_v of NIPA gels to a low-temperature range. We therefore discontinued this experiment and tried to find another approach to study the formation of hydrogen bonds between the NIPA and AA chains (see below).

Complexation of PNIPA and PAA at pH 3. Our preliminary experiments showed that a mixed solution of PNIPA and PAA was transparent under alkaline pH conditions but became turbid under acidic conditions where most of the PAA-bound COO^- groups are protonated. Moreover, the acidic mixture turned from opaque to transparent by the addition of 4 M urea and upon cooling, while such a change did not take place in the absence of urea. These results suggest the complexation of PNIPA with PAA via hydrogen bonding between −COOH and −CONH− groups; for example,



We thus assumed that DLS would be an appropriate approach in order to carry out a quantitative study on this kind of complexation.

As mentioned above, however, a decrease in the LCST was observed when urea was added to an aqueous PNIPA solution. We thus tried to determine the LCSTs of both the PNIPA solution and the PNIPA/PAA mixture in the presence of 4 M urea (Table 1). It is generally believed that urea breaks up the hydrogen bonds between solute molecules and also disrupts the cluster structure of water molecules ("structure breaking effect"). The latter brings about a weakening of the hydrophobic interaction between solute molecules (e.g., see ref 22). In the case of an aqueous PNIPA system, however, the addition of urea shifted the LCST to a low-temperature range. Therefore, we cannot simply state that hydrophobic interaction between NIPA residues is weakened by the addition of urea.

Taking the above into account, we initially examined the effect of 4 M urea on the size distributions of PNIPA and PAA at pHs 3 and 10 (Figure 4). It was found that there was little influence of urea on the size distributions of PNIPA and PAA. Thus, urea can be used in order to break the hydrogen bonds between PNIPA and PAA. Figure 5 shows the size distributions in the presence and absence of urea for the 2:1 (unit mole base) mixtures of PNIPA and PAA at pHs 3 and 10. At pH 10, at which PAA is completely ionized, no urea effect was observed. In contrast, the results at pH 3 revealed that a large PNIPA/PAA complex was formed in the absence but not in the presence of urea. It should be noted that the size distribution of PNIPA or PAA observed in the mixture containing 4 M urea is the same as the distribution of each original polymer (see Figure 4). As a result, we can say that the formation of hydrogen bonds between the NIPA and AA residues plays an important role in the volume collapse of gels II and III at pH 3.

General Concept of Swelling−Deswelling of Polyelectrolyte Gels. We attempted to establish a simple concept[14] for interpreting the volume phase transition of gels in the studies on the construction of "functional" immobilized biocatalysts using polymer gels,[23−25] in particular in the studies on the construction of "biochemo-mechanical systems", which convert the energy arising from biochemical changes (such as enzyme reactions) into mechanical work through a swelling−deswelling change of the gel with immobilized biocatalysts. In this regard, we accounted for the volume phase transitions by hypothesizing a balance between the repulsion and attraction among functional groups attached to the cross-linked polymers that arise from a combination of four intermolecular forces (see ref 14): ionic, hydrophobic, van der Waals, and hydrogen bonding. When a repulsive force, usually electrostatic in nature, overcomes an attractive force such as hydrogen bonding or hydrophobic interaction, the gel volume should increase discontinuously in some cases and continuously in others. The variables that trigger the transition influence these intermolecular forces and thereby the balanced state of the attractive and repulsive forces.

Although this concept was extremely useful in the preparation of biochemically driven gel systems,[23−25] there were arguments against accepting it in order to understand the nature of the volume phase transitions of gels.[10] The major reason for the reluctance to accept our concept seems to be the general assumption that a simple concept cannot be used to explain complex systems. Indeed, the mechanism suggested in ref 14 was criticized in ref 10 (see pp 214−217) as being overly simplistic. However, the present study regarding the effects of the distribution of the AA residues on the swelling behaviors of NIPA/AA gels provides experimental evidence supporting the validity of our previous concept.

The effect of the distribution of the NIPA residues on the swelling of terpolymer gels consisting of NIPA, AA, and 2-hydroxyethyl methacrylate (HEMA) has been studied by Vakkalanka and Peppas.[26] They prepared two sorts of terpolymer gels: (i) gel with cross-linked random terpolymer chains and (ii) gel with cross-linked chains consisting of blocks of NIPA (continuous NIPA segments) in a random copolymer of AA and HEMA. It was demonstrated that there is a marked difference in swelling behaviors between the block and random terpolymer gels when temperature was varied at a

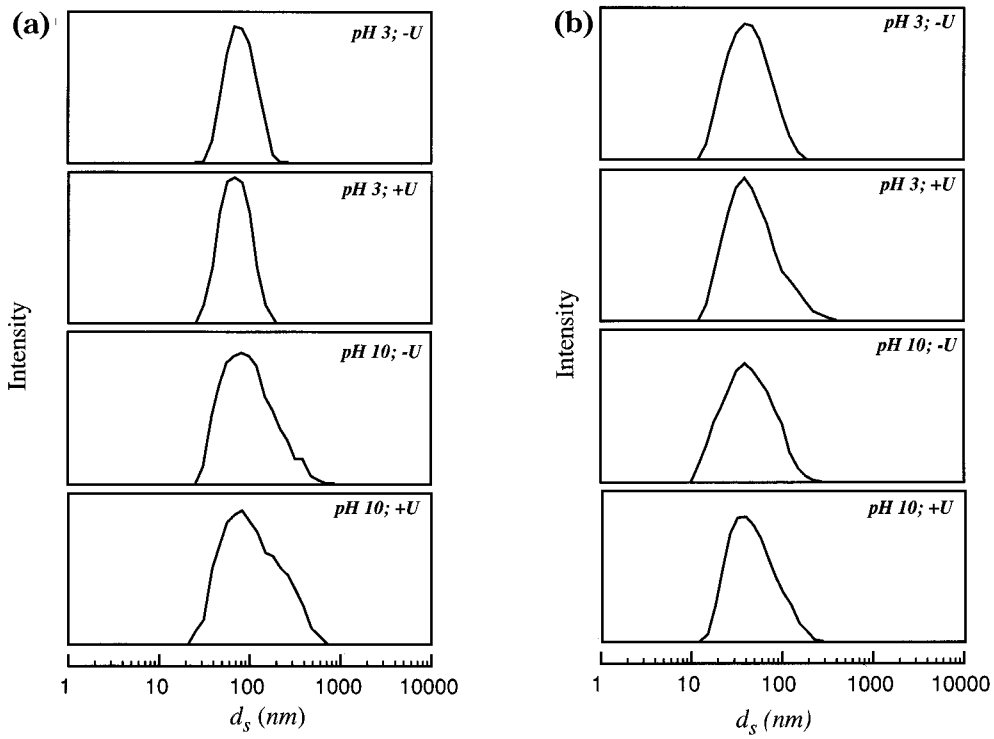


Figure 4. Effects of pH and 4 M urea on the size distribution of PAA (a) and PNIPA (b) examined by DLS at 15 °C. The samples were the same as the those in Table 1. +U and −U represent the presence and absence of 4 M urea, respectively.

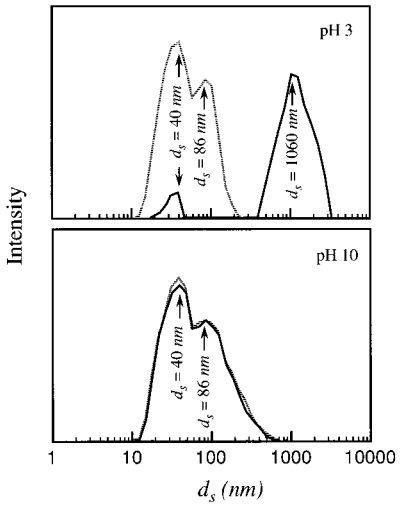


Figure 5. Effects of pH and 4 M urea on the size distribution of the PAA/PNIPA mixture examined by DLS at 15 °C. Full lines and dashed lines respectively denote the absence and presence of 4 M urea. From the results of Figure 4, we can assign the peak appeared at $d_s \sim 40$ nm to PNIPA and the peak at $d_s \sim 86$ nm to PAA. A complex with the average Stokes diameter ~1060 nm was observed in the PNIPA/PAA mixture at pH 3 in the absence of urea.

constant pH. This appears to be more evidence supporting the validity of our concept in ref 14.

Conclusions

To understand the nature of the volume phase transitions of polyelectrolyte gels on the molecular level, we prepared four different gels consisting of NIPA and AA either randomly distributed or localized within the network. Their swelling curves, i.e., the temperature dependence of the degree of swelling, were studied at pHs 3 and 10. We observed a strong effect of the charge distribution on the swelling behaviors of these NIPA/AA gels. This result was no longer explainable in terms of the concept of osmotic pressure which had been consistently used in previous theoretical descriptions of the swelling behaviors of ionic gels. In contrast, the swelling behaviors of the present NIPA/AA gels could be interpreted well by taking into account the microphase separation of the cross-linked NIPA chains due to hydrophobic interaction. The reason is that the distribution of the charged groups exhibits a different inhibition effect on the microphase separation that may take place not only through an increase in the hydrophilicity but also through the Coulomb repulsion. In addition, our results also suggest that hydrogen bonding between −COOH and −CONH− groups plays an important role in the gel collapse at pH 3. Thus, the present study supports the concept we established previously for interpreting the volume phase transitions of various kinds of gels.

Acknowledgment. We thank Professor T. Tanaka at MIT, Cambridge, MA, for his stimulating discussions and valuable suggestions. This research was supported by a grant to E.K. from the Ministry of Education of Japan (#08558092).

References and Notes

(1) Tanaka, T. *Phys. Rev. Lett.* **1978**, *40*, 820.
(2) Lundberg, R. D. *Encyclopedia of Polymer Science and Engineering*; Wiley-Interscience: New York, 1987; Vol. 8, p 393.
(3) Hirotsu, S.; Hirokawa, Y.; Tanaka, T. *J. Chem. Phys.* **1987**, *87*, 1392.
(4) Yamamoto, I.; Iwasaki, K.; Hirotsu, S. *J. Phys. Soc. Jpn.* **1989**, *58*, 210.
(5) Prange, M. M.; Hooper, H. H.; Prausnitz, J. M. *AIChE J.* **1989**, *35*, 803.
(6) Marchetti, M.; Prager, S.; Cussler, E. L. *Macromolecules* **1990**, *23*, 1760, 3445.
(7) Lee, K. K.; Cussler, E. L.; Marchetti, M.; McHugh, M. A. *Chem. Eng. Sci.* **1990**, *45*, 766.

(8) Otake, K.; Inomata, H.; Konno, M.; Saito, S. *J. Chem. Phys.* **1990**, *91*, 1345.
(9) Hirotsu, S. *Adv. Polym. Sci.* **1993**, *110*, 1 and references therein.
(10) Schild, H. G. *Prog. Polym. Sci.* **1992**, *17*, 163 and references therein.
(11) Kokufuta, E.; Zhang, Y.-Q.; Tanaka, T.; Mamada, A. *Macromolecules* **1993**, *26*, 1053.
(12) Kokufuta, E.; Nakaizumi, S.; Ito, S.; Tanaka, T. *Macromolecules* **1995**, *28*, 1704.
(13) Kokufuta, E.; Suzuki, H.; Sakamoto, D. *Langmuir* **1997**, *13*, 2627.
(14) Ilmain, F.; Tanaka, T.; Kokufuta, E. *Nature* **1991**, *349*, 400.
(15) For the colloid titration method, see: Kokufuta, E. *Macromolecules* **1979**, *12*, 350.
(16) (a) Kokufuta, E.; Tanaka, T.; Hirasa, O.; Fujishige, S.; Yamauchi, A. *Phase Transitions* **1993**, *44*, 217 (b) Wang, B.; Mukataka, S.; Kodama, M.; Kokufuta, E. *Langmuir* **1997**, *13*, 6108.
(17) For TOC analysis of water soluble polymers, see: Kokufuta, E.; Fujii, S.; Hirai, Y.; Nakamura, I. *Polymer* **1982**, *23*, 452.
(18) Tsuboi, A.; Izumi, T.; Hirata, M.; Xia, J.; Dubin, P. L.; Kokufuta, E. *Langmuir* **1996**, *12*, 6295.
(19) Borue, V. Yu.; Erukhimovich, I. Ya. *Macromolecules* **1988**, *21*, 3240.
(20) Dormidontova, E. E.; Erukhimovich, I. Ya.; Khokhlov, A. R. *Makromol. Chem., Theory Simul.* **1994**, *3*, 661.
(21) Grosberg, A. Yu.; Khokhlov, A. R. *Statistical Physics of Macromolecules*; American Institute of Physics: New York, 1994.
(22) Dubin, P.; Strauss, U. P. *J. Phys. Chem.* **1973**, *77*, 1427.
(23) Kokufuta, E. *Prog. Polym. Sci.* **1992**, *17*, 647.
(24) Kokufuta, E. *Adv. Polym. Sci.* **1993**, *110*, 159.
(25) Kokufuta, E. Functional immobilized biocatalysts prepared using stimulus-sensitive polymer gels. In *The Polymeric Materials Encyclopedia − Synthesis, Properties and Applications*; Salamone, J. C., Ed.; CRC Press: New York, 1996; Vol. 4, pp 2615−2621.
(26) Vakkalanka, S. K.; Peppas, N. A. *Polym. Bull.* **1996**, *36*, 221.

MA971565R