Role of hydrogen bonding in solubility of poly(N-isopropylacrylamide) brushes in sodium halide solutions *

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(Received 5 September 2015; revised manuscript received 13 February 2016; published online 1 June 2016)

By employing molecular theory, we systematically investigate the shift of solubility of poly(N-isopropylacrylamide) (PNIPAM) brushes in sodium halide solutions. After considering PNIPAM–water hydrogen bonds, water–anion hydrogen bonds, and PNIPAM–anion bonds and their explicit coupling to the PNIPAM conformations, we find that increasing temperature lowers the solubility of PNIPAM, and results in a collapse of the layer at high enough temperatures. The combination of the three types of bonds would yield a decrease in the solubility of PNIPAM following the Hofmeister series: NaCl>NaBr>NaI. PNIPAM–water hydrogen bonds are affected by water–anion hydrogen bonds and PNIPAM–anion bonds. The coupling of polymer conformations and the competition among the three types of bonds are essential for describing correctly a decrease in the solubility of PNIPAM brushes, which is determined by the free energy associated with the formation of the three types of bonds. Our results agree well with the experimental observations, and would be very important for understanding the shift of the lower critical solution temperature of PNIPAM brushes following the Hofmeister series.

Keywords: molecular theory, PNIPAM brushes, anion effect, hydrogen bonds

PACS: 47.27.eb, 05.65.+b **DOI:** 10.1088/1674-1056/25/7/074703

1. Introduction

During the last decade, poly(N-isopropylacrylamide) (PNIPAM) as a prototype of thermally responsive polymer was extensively studied by many authors.[1–13] PNIPAM exhibits a lower critical solution temperature (LCST) $T_c \approx 32$ °C in water. That is, at temperatures lower than T_c, the polymer is swollen or soluble, while at temperatures higher than T_c, a deswelling or precipitation takes place.[7] Thus, it was identified as a particularly useful protein proxy.[14–17]

In particular, recent experimental studies[7,18] revealed a decrease in the LCST of PNIPAM brushes following the Hofmeister series: NaCl>NaBr>NaI in sodium halide solutions. Despite considerable efforts, the underlying cause of this effect is still far from being understood because of the complexity of ion-specific interactions between PNIPAM and ion. Zhang *et al.*[18] found that water molecules can associate with amides by hydrogen bonding, and anions may bond directly to polyamides, which leads to salting-out and salting-in effects of polymers, thereby lowering the LCST. By performing a molecular dynamics simulation, Du *et al.*[19] found that direct interaction between salt cations and amides plays a key role in the shift of LCST. In contrast, the anion interaction is considered to play a dominant role in the shift of LCST by Algaer *et al.*[20] A recent experiment carried out by Naini *et al.*[7] implied that sodium halides can couple directly to the PNIPAM chain. Okur *et al.*[21] specifically displayed that the interaction between metal cations and amides is far weaker than the analogous binding of weakly hydrated anions. Liu *et al.*[22–26] have investigated the specific anion effect on the LCST behavior of PNIPAM. They have demonstrated that the anion effect can be amplified by adding methylated urea, ethylene glycol, and alcohols.[23–25] These results provide an essential reference on the way to unpuzzling the molecular driving forces involved in the decrease in solubility of PNIPAM brushes. Heyda *et al.*[27] performed a detailed study on the nonlinear thermodynamic changes of the collapse transition occurring at the LCST of the role-model PNIPAM induced by salts. However, up to now, few theories have been devoted to a molecular-level understanding of the shift of solubility of PNIPAM brushes in sodium halide solutions. Thus, it is necessary to include more molecular details to properly describe the shift of the solubility of PNIPAM brushes.

In this work, motivated by some intriguing experiment results,[7,18,21] a molecular theory[28–32] aimed at investigating the shift of the solubility of PNIPAM brushes in solutions of sodium halides will be presented. Our theory model takes the three types of bonds into consideration. The formation of hydrogen bonds and PNIPAM–anion bonds will be introduced following the ideas of Tamai, Dormidontova, Ren,[33–36] Zhang and Okur.[18,21] Here, our main purpose is to

*Project supported by the National Natural Science Foundation of China (Grant Nos. 21264016, 11464047, and 21364016) and the Joint Funds of Xinjiang Natural Science Foundation, China (Grant No. 2015211C298).

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explore how the three types of bonds influence the conformations in sodium halide solutions, and to explain the mechanism for the shift of the solubility of PNIPAM brushes following the Hofmeister series. The reminder of this paper is organized as follows. The molecular theoretical model is described in Section 2. The results and discussions focusing on the effects of the three types of bonds and their explicit coupling to PNIPAM conformations are given in Section 3. The conclusions are presented in Section 4.

2. Molecular theoretical model

Our theoretical model considers the size, shape, and conformation of every PNIPAM molecular type with an explicit inclusion of the three types of bond. In order to create a PNIPAM brush system, we assume that PNIPAM chains are immersed in sodium halide solutions, and are homogeneously grafted onto the substrate surface, defined as the x–y plane at $z = 0$. The PNIPAM brush system contains $N_{\rm P}$ PNIPAM chains, which are tethered onto the substrate surface, and can be allowed only in the $z \geq 0$ half space. The number of tethered chains per unit area is $\sigma = N_{\rm p}/A$. Each PNIPAM chain has N segments, and each segment has a volume of $v_{\rm p} = 0.16$ nm^3. The numbers of water molecules and anions are $N_{\rm w}$ and $N_{\rm a}$, respectively. The volumes of each water molecule and each anion are $v_{\rm p} = 0.03$ nm^3 and $v_- = 0.03$ nm^3, respectively. We assume that the only inhomogeneous direction is the one perpendicular to the substrate surface that is the z direction. The free energy per unit area of PNIPAM brush system in sodium halide solutions has the following form:

$$\frac{\beta F}{A} = -\frac{S_{\rm p}}{k_{\rm B}A} - \frac{\sum S_i}{k_{\rm B}A} + \frac{\beta F_{\rm int}}{A} + \frac{\beta F_{\rm assoc}}{A} + \frac{\beta U_{\rm rep}}{A} + \frac{\beta}{A}\int [\mu_+\rho_+(z) + \mu_-\rho_-(z)]\,{\rm d}z + \frac{\beta F_{\rm e}}{A}. \quad (1)$$

The first term on the right side of Eq. (1) denotes the conformational entropy of PNIPAM chains, which is given by

$$-\frac{S_{\rm p}}{k_{\rm B}A} = \sigma \sum_{\alpha} P(\alpha)\ln P(\alpha), \quad (2)$$

where $P(\alpha)$ is the probability distribution function of finding one PNIPAM chain in conformation α. Given a probability distribution function, we can calculate any average thermodynamical structural quantity of polymers.[36–38] The PNIPAM volume fraction profile is determined by

$$\langle\phi_{\rm p}(z)\rangle {\rm d}z = \sigma \sum_{\alpha} P(\alpha) v_{\rm p}(z;\alpha){\rm d}z, \quad (3)$$

where $v_{\rm p}(z;\alpha)$ denotes the volume that one PNIPAM chain in conformation α between z and $z + {\rm d}z$ of the brush contributes.

The second term on the right side of Eq. (1) describes the translational entropy of water molecules, anions, and cations in the system,

$$\frac{-\sum S_i}{k_{\rm B}A} = \int \sum_{i={\rm w},-,+} \rho_i(z)[\ln(\rho_i(z)v_i) - 1]{\rm d}z, \quad (4)$$

where $\rho_i(z)$ $(i = {\rm w},-,+)$ denotes the local particle number density of the i-th species (the signs of "w", "−", and "+" are for water molecule, anion, and cation, respectively), and v_i denotes the volume of the corresponding molecule. The local volume fractions of water molecules, anions, and cations can be given by $\phi_i(z) = \rho_i(z)v_i$.

The third term on the right side of Eq. (1) describes effective intermolecular interaction of PNIPAM in solutions, which accounts for the solvent quality, and is expressed as

$$\frac{\beta F_{\rm int}}{A} = \frac{\chi}{v_{\rm w}} \int \langle\phi_{\rm p}(z)\rangle(1 - \langle\phi_{\rm p}(z)\rangle){\rm d}z, \quad (5)$$

where χ is the Flory interaction parameter. A PNIPAM chain contains amide and hydrophobic groups. Dissolved electrolytes have a pronounced influence on this collapse transition, due to the ion-specific interactions among amide and hydrophobic groups on macromolecules.[20] Thus, we only consider the interaction parameter with the form of $\chi = B/T$ $(B > 0)$. The reason for this choice is that apart from PNIPAM–water hydrogen, water–anion hydrogen bonds and PNIPAM–anion bonds, hydrophobic interactions can be described as is done in general, and as being used in Dorminotova and Ren.[34,35] In order to capture the main quantitative features observed in Ref. [7], we take the values $B = 145$, $B = 152$, and $B = 172$ for NaI, NaBr, and NaCl solutions, respectively.

The fourth term on the right side of Eq. (1) is the contribution from the formation of the three types of bonds. In pure water, only PNIPAM–water hydrogen bonds need to be considered. When salts are added, additional bonds including amide–anion (PNIPAM–anion), water–ion, and ion–ion bonds should be taken into account. As reported in the previous studies,[18,20,21] Hofmeister anions can be bound directly to polyamide. Ion–ion pairs do not provide donors/acceptors, and contribute only to excluded volume interactions. Thus, PNIPAM–anion bonds and water–anion hydrogen bonds in a sodium halide solution should be taken into consideration, while ion–ion bonds can be ignored. According to Refs. [34] and [36], the contributions to free energy arising from the formation of the three types of bonds can be written as

$$\frac{\beta F_{\rm assoc}}{A} = \sum_j \int a_j\rho_j(z)\Big\{\sum_i x_{ij}(z)\ln[x_{ij}(z)] + [1 - x_{ij}(z)]\ln[1 - x_{ij}(z)] - \sum_i \beta F_{ij}x_{ij}(z)\Big\}{\rm d}z + \sum_i \int d_i\rho_i(z)\left[1 - \frac{\sum_j a_j x_{ij}(z)\rho_j(z)}{d_i\rho_i(z)}\right] \times \ln\left[1 - \frac{\sum_j a_j x_{ij}(z)\rho_j(z)}{d_i\rho_i(z)}\right]{\rm d}z$$

$$-\sum_j \int a_j \rho_j(z) \left\{ \sum_i x_{ij}(z) \ln \left[\frac{d_i \rho_i(z) v_w}{e} \right] \right., \quad (6)$$

where i and j denote a donor and an acceptor (for a specific type of molecule, it is assumed to provide d_i donors and a_j acceptors), respectively; $-\beta F_{ij}$ is the gain in free energy of forming a single bond, which includes the energetic gain and entropic loss: $-\beta F_{ij} = \beta E_{ij} - \Delta S_{ij}$; E_{ij} is the binding energy by which a donor i and an acceptor j are associated in pairs; and ΔS_{ij} is the entropic loss.[34,36]

The PNIPAM–water hydrogen bond energetic gain is chosen as $E_{pw}/k_B = 985$ K, and the entropic loss related to PNIPAM–water hydrogen bond is given by $\Delta S_{pw} = -26$ J·K^{-1}·mol^{-1}. The entropic losses related to water–anion hydrogen bonds I^-, Br^-, and Cl^- are given by $\Delta S_{wI^-} = -43$ J·K^{-1}·mol^{-1}, $\Delta S_{wBr^-} = -51$ J·K^{-1}·mol^{-1}), and $\Delta S_{wCl^-} = -67$ J·K^{-1}·mol^{-1}, respectively. According to the experimental observations,[7,18] we choose the energetic gains of $E_{wI^-}/k_B = 1052$ K, $E_{wBr^-}/k_B = 1063$ K, and $E_{wCl^-}/k_B = 1175$ K for water–I^- bond, water–Br^- bond, and water-Cl^- bond, respectively, and the energetic gains of $E_{pI^-}/k_B = 352$ K, $E_{pBr^-}/k_B = 325$ K, and $E_{pCl^-}/k_B = 292$ K, for PNIPAM–I^- bond, PNIPAM–Br^- bond, and PNIPAM–Cl^- bond, respectively. The entropic losses related to PNIPAM–anion bond I^-, Br^-, and Cl^- are given by $\Delta S_{pI^-} = -36$ J·K^{-1}·mol^{-1}, $\Delta S_{pBr^-} = -59$ J·K^{-1}·mol^{-1}, and $\Delta S_{pCl^-} = -75$ J·K^{-1}·mol^{-1},[18] respectively. In Eq. (6), $x_{ij}(z)$ denotes the average fraction of different bonds, which is defined as[36]

$$x_{ij}(z) = \frac{n_{ij}(z)}{d_j N_i(z)}, \quad (7)$$

where $n_{ij}(z)$ is the number of position-dependent bonds, and $d_j N_i(z)$ is the number of donors provided by species i.

The fifth term on the right side of Eq. (1) represents repulsive interaction of the system, which can be given by

$$\frac{\beta U_{rep}}{A} = \int \beta \pi(z) [\langle \phi_p(z) \rangle + \sum_{i=w,-,+} \rho_i(z) v_i] dz, \quad (8)$$

where $\pi(z)$ is the position-dependent repulsive interaction field, which is determined by packing constraints

$$\langle \phi_p(z) \rangle + \sum_{i=w,-,+} \rho_i(z) v_i = 1. \quad (9)$$

The quantities of μ_- and μ_+ in the sixth term of Eq. (1) represent the chemical potentials of anions and cations, respectively.

The last term of Eq. (1) accounts for the electrostatic contribution to the free energy. The closest distance between an anion and a cation is usually larger than the Bjerrum length,[36] though ions have net charges. Hence, the electrostatic interactions are ignored here. In reality, the electrostatic contributions are partly included in the three types of bonds. Minimization of the free energy with respect to $P(\alpha)$ yields

$$\begin{aligned} P(\alpha) = \frac{1}{q} \exp \Bigg\{ & -\beta \int \pi(z) n(\alpha; z) v_p dz \\ & - \frac{\chi_{eff}}{v_w} \int [1 - 2\phi_p(z)] n(\alpha; z) v_p dz \\ & - \int 2 n(\alpha; z) \ln \left[1 - \sum_i x_{ip}(z) \right] dz \Bigg\}, \end{aligned} \quad (10)$$

where q is a normalization constant ensuring that $\sum_\alpha P(\alpha) = 1$, and $n(\alpha; z)dz$ is the number of PNIPAM segments located at z when a PNIPAM chain has the conformation α. The volume fraction of water molecules $\phi_w(z)$ is

$$\begin{aligned} \phi_w(z) = \exp \Bigg[& -\beta \pi(z) v_w - 2 \ln \left(1 - \sum_i x_{iw}(z)\right) \\ & - 2 \ln \left(1 - \frac{\sum_j a_j x_{wj}(z) \rho_j(z)}{d_i \rho_w(z)} \right) \Bigg]. \end{aligned} \quad (11)$$

The volume fractions of anions and cations are given by

$$\begin{aligned} \phi_-(z) = \exp \Bigg[& -\beta \pi(z) v_- - \ln \left(1 - \sum_i x_{i-}(z)\right) \\ & - \ln \left(1 - \frac{\sum_j x_{-j}(z) \rho_j(z)}{d_i \rho_-(z)} \right) \Bigg], \end{aligned} \quad (12)$$

and

$$\begin{aligned} \phi_+(z) = \exp \Bigg[& -\beta \pi(z) v_+ - \ln \left(1 - \sum_i x_{i+}(z)\right) \\ & - \ln \left(1 - \frac{\sum_j x_{+j}(z) \rho_j(z)}{d_i \rho_+(z)} \right) \Bigg], \end{aligned} \quad (13)$$

respectively. The bulk values of ions can be obtained from the ions concentration: $\phi_{bulk,\mp} = c_\mp N_a v_\mp$. The quantities of $x_{pw}(z)$ and $x_{pa}(z)$ in Eq. (6) are determined by

$$\begin{aligned} x_{ij}(z) = & \phi_{bulk,i} d_i \exp(\beta F_{ij}) \left[1 - \frac{\sum_j a_j x_{ij}(z) \rho_j(z)}{d_i \rho_i(z)} \right] \\ & \times \left[1 - \sum_i x_{ij}(z) \right] \phi_i(z). \end{aligned} \quad (14)$$

The equation above indicates that the average fractions of different bonds relating to the species density offer donors or acceptors. Thus, the densities of different species for PNIPAM–salt solutions and the average fractions of hydrogen bonds are coupled in a nonlinear way. This equation in fact belongs to the "chemical-equilibrium" type of equation.[34] From Eq. (14), it is easy to obtain the following connection between PNIPAM–water hydrogen bonds, $x_{pw}(z)$, and water–anion hydrogen bonds, x_{w-}:

$$\frac{x_{pw}(z)}{x_{w-}(z)} = \exp(\beta F_{pw} - \beta F_{w-}) \frac{1 - x_{pw}(z)}{1 - x_{w-}(z)}. \quad (15)$$

The difference between two local fractions of $x_{pw}(z)$ and x_{w-} originates from the difference in the free energy associated with the formation of single PNIPAM–water hydrogen bond and single PNIPAM–anion bond. If $\exp(\beta F_{pw} - \beta F_{w-}) > 1$, then $x_{pw}(z)$ is larger than x_{w-}, which implies that the formation of PNIPAM–water hydrogen bonds is more favorable than that of water–anion bonds. Conversely, if $\exp(\beta F_{pw} - \beta F_{w-}) < 1$, the association of PNIPAM–anion bonds is more favorable. These two types of bonds compete with each other because water is a common donor source. The completion also occurs between PNIPAM–water hydrogen and PNIPAM–anion bonds, because PNIPAM–amide is a common source of donors. The unknowns in equations above are the position-dependent repulsive fields and fractions of the three types of bonds. These quantities are obtained by substituting Eqs. (10)–(14) into the packing constraints of Eq. (9). A detailed numerical methodology can be found in Refs. [30], [35], and [36].

3. Results and discussion

In this Section, we present some representative results of the anion effects on the LCST of PNIPAM brushes in sodium halide solutions.

To begin with, we analyze the distribution of the grafted PNIPAM segments at different temperatures. The average volume fraction of the grafted PNIPAM chains is a function of distance from the substrate surface, as shown in Fig. 1. Clearly, the grafted PNIPAM chains collapse with increasing temperature in pure water and 0.25 M sodium halide solutions.

The height of the grafted PNIPAM brushes H is defined as $H = \int \langle \phi_p(z) \rangle z \mathrm{d}z / \int \langle \phi_p(z) \rangle \mathrm{d}z$, which measures the amount of stretching of the grafted PNIPAM chains. Figure 2 shows a dependence of height on temperature. The height of the grafted PNIPAM brushes decreases with increasing temperature in pure water and in 0.25 M sodium halide solutions, which implies that the grafted PNIPAM brushes collapse with increasing temperature. From Fig. 2, the LCST at $H \approx 12$ nm in water and in 0.25 M sodium halide solutions can be obtained. The LCST shifts from ~ 32.8 °C in water to ~ 28.6 °C in 0.25 M NaCl solution, which is consistent with the experimental results.[7] In the previous experiments,[7,18] the PNIPAM chains were indeed reported to collapse rapidly with an increase in temperature. Evidently, the data of H in Fig. 2 shifts toward the lower temperatures following the typical magnitude of the Hofmeister series:[7] NaCl>NaBr>NaI.

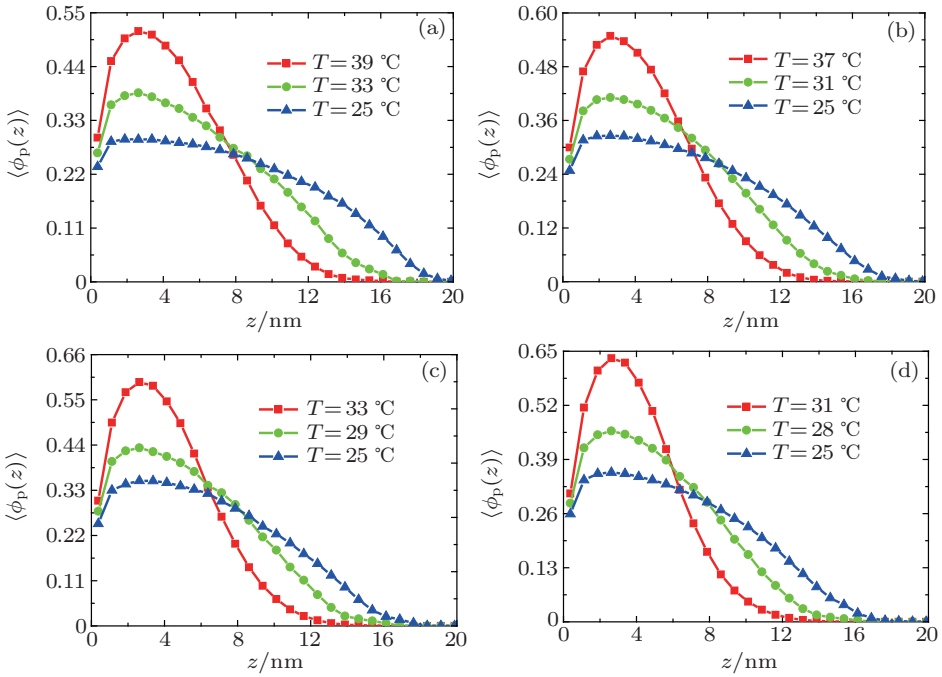


Fig. 1. (color online) The average volume fraction of the grafted PNIPAM chains as a function of distance from the substrate surface (a) in pure water, (b) in 0.25 M NaI solution, (c) in 0.25 M NaBr solution, and (d) in 0.25 M NaCl solution.

It is worth stressing that the molecular weight ($M_w = 22500\ \mathrm{g \cdot mol^{-1}}$) chosen in theoretical models is smaller than the experimental result ($M_w = 90000\ \mathrm{g \cdot mol^{-1}}$)[7] because of the limit of theoretical calculations, but the theoretical lower critical solution temperatures are consistent with the experimental data[10] when we choose E_{ij} and ΔS_{ij}, as mentioned above. Experimental results[39,40] also demonstrated that the LCST of PNIPAM is independent of molecular weight and concentration. The molecular weight ($M_w = 22500\ \mathrm{g \cdot mol^{-1}}$) chosen in theoretical models is thus enough to describe the shift of solubility of PNIPAM brushes in sodium halide solutions and to understand the physical origin of this behavior.

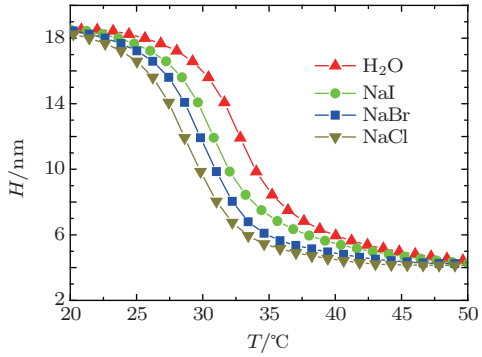


Fig. 2. (color online) The height of the grafted PNIPAM brushes as a function of temperature. The molecular weight of polymer chains is $M_w = 22500\ \mathrm{g\cdot mol^{-1}}$, and the surface coverage is $\sigma = 0.5\ \mathrm{nm^{-2}}$.

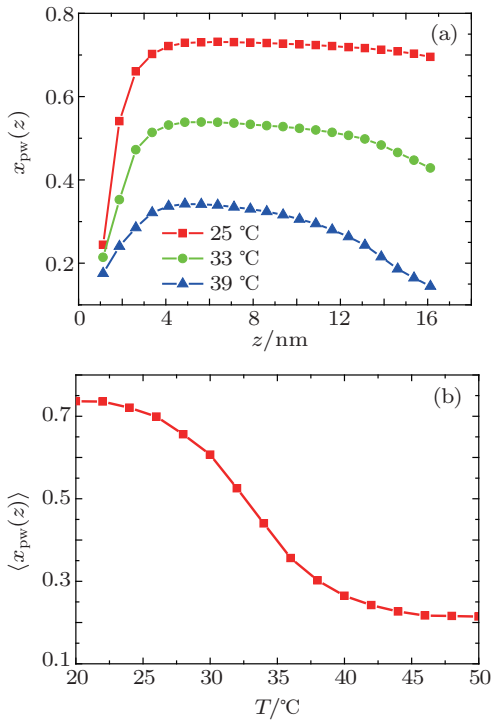


Fig. 3. (color online) (a) Local fraction of PNIPAM–water hydrogen bonds as a function of distance from the substrate surface in pure water. (b) The average fraction of PNIPAM–water hydrogen bonds as a function of temperature in pure water. The molecular weight of the polymer chain is $M_w = 22500\ \mathrm{g\cdot mol^{-1}}$, and the surface coverage is $\sigma = 0.5\ \mathrm{nm^{-2}}$.

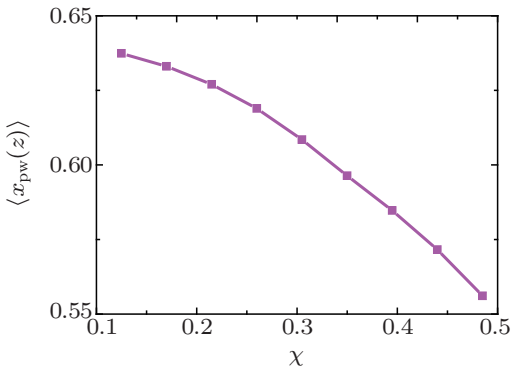


Fig. 4. (color online) The average fraction of PNIPAM–water hydrogen bonds as a function of χ for a temperature of $T = 25\ ^\circ\mathrm{C}$ in pure water. The molecular weight of the polymer chain is $M_w = 22500\ \mathrm{g\cdot mol^{-1}}$, and the surface coverage is $\sigma = 0.5\ \mathrm{nm^{-2}}$.

In the following, we will investigate the variations of fractions of PNIPAM–water hydrogen, water–anion hydrogen bonds, and PNIPAM–anion bonds. From Fig. 3(a), one can see that the local fractions of PNIPAM–water hydrogen bonds near the brush surface are lower. As discussed above, the PNIPAM–water hydrogen bonds are position dependent. Thus, in order to describe the overall behavior of PNIPAM brushes, we define an average fraction of PNIPAM–water hydrogen bonds, $\langle x_{pw}(z)\rangle = \int \langle \phi_p(z)\rangle x_{pw}(z)\,dz / \int \langle \phi_p(z)\rangle\,dz$, an average fraction of water–anion hydrogen bonds $\langle x_{w-}(z)\rangle = \int \langle \phi_w(z)\rangle x_{w-}(z)\,dz / \int \langle \phi_w(z)\rangle\,dz$, and an average fraction of PNIPAM–anion bonds, $\langle x_{p-}(z)\rangle = \int \langle \phi_p(z)\rangle x_{p-}(z)\,dz / \int \langle \phi_p(z)\rangle\,dz$. As a function of temperature, the average fraction of PNIPAM–water hydrogen bonds decreases with increasing temperature, as easily seen in Fig. 3(b).

Figure 3 also shows that the number of PNIPAM–water hydrogen bonds depends on temperature. The average fraction of free amide groups has a very low value at a lower temperature, so nearly all amide groups are employed to be in association through PNIPAM–water hydrogen bonds. With an increase in temperature, the disruption of PNIPAM–water hydrogen bonds enhances, and the number of hydrogen bonds decreases, which indicates that the temperature dependence of PNIPAM brush height H becomes stronger due to the existence of hydrogen bonds. The hydrogen bonding PNIPAM chains are more stretched than PNIPAM chains, which cannot form hydrogen bonds with the water, as shown in Fig. 2. This is because the energetically favorable hydrogen bonds between PNIPAM segments and water molecules can compensate the loss of entropy due to the chain stretching and the repulsive intermolecular interactions. PNIPAM chains tend to adopt more extended conformations for the formation of PNIPAM–water hydrogen bonds. This implies that the average fraction of PNIPAM–water hydrogen bonds and the Flory interaction parameter determine solvent quality, and the hydrogen bonds make a large contribution to the solubility of PNIPAM in a relevant temperature range.

By changing B and keeping T constant, we regulate the value of χ, and make a diagram of $\langle x_{pw}(z)\rangle$ vs. χ. Figure 4 indicates that there is a dependence of the number of PNIPAM–water hydrogen bonds on χ when the attractive interactions between polymers and solvents become less favorable. Increasing the number of PNIPAM–water hydrogen bonds leads to a gain in the free energy. Note that this gain is balanced by the loss of the chain conformational entropy, due to the chain stretching and an increase in the number of intermolecular repulsions. This additional cost to the free energy hinders a further PNIPAM–water association, which is shown in Fig. 4 ($\langle x_{pw}(z)\rangle$ decreases with increasing χ). On the other hand, over the range of investigated values of χ, the change in the number of PNIPAM–water hydrogen bonds is very low. These

results show that the behavior of PNIPAM brushes in pure water is determined by the conformational entropy of PNIPAM chains and the free energy associated with PNIPAM–water hydrogen bond formation.

Figure 5(a) shows that the number of PNIPAM–anion bonds depends on temperature, and all the average fractions of PNIPAM–anion bonds decrease with increasing temperature. Figure 5(b) demonstrates that PNIPAM–anion bonds contributes to the solubility of PNIPAM in sodium halide solutions. Therefore, the effect of PNIPAM–anion bonds is similar to that of PNIPAM–water hydrogen bonds, and both of the effects enhance the solubility of PNIPAM. The effect of PNIPAM–anion bonds could lead to the salting-in of PNIPAM. However, once anions bind to PNIPAM, the local water molecules tend to form hydrogen bonds with anions rather than to form PNIPAM segments. Compared to formations of PNIPAM–water hydrogen bonds (see Fig. 4), the hydrophobicity of PNIPAM increases. Similar results were obtained in previous studies,[36] which suggested that cations bind to PEO, whose hydrophobicity increases.

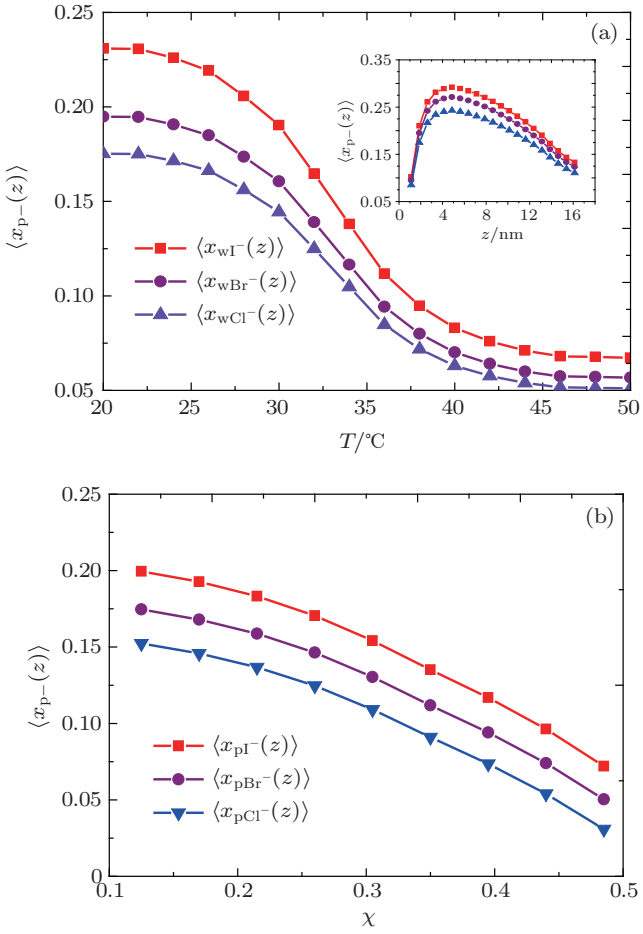


Fig. 5. (color online) (a) The average fraction of PNIPAM–anion bonds as a function of a temperature in sodium halide solutions. The inset shows local fraction of PNIPAM–anion bonds as a function of distance from the substrate surface. (b) The average fraction of PNIPAM–anion bonds as a function of χ for a temperature of $T = 25$ °C in sodium halide solutions. The molecular weight of the polymer chain is $M_w = 22500$ g·mol^{-1}, and the surface coverage is $\sigma = 0.5$ nm^{-2}.

In order to further investigate the shift of solubility of PNIPAM brushes in sodium halide solutions, we produce the diagrams of $\langle x_{pw}(z)\rangle$ versus T and $\langle x_{w-}(z)\rangle$ versus T, as shown in Fig. 6. It is obvious that both PNIPAM–water hydrogen and PNIPAM–anion bonds decrease with temperature. At low temperatures, nearly all amides are employed to be in association through PNIPAM–water hydrogen bonds and PNIPAM–anion bonds. The degree of associations between amides and water, amides and anions is higher, due to a larger energy of association between amide and water, amide and anions. With an increase in temperature, the fraction of free amide groups increases considerably due to the disruption of PNIPAM–water hydrogen bonds, anion–water hydrogen bonds, and PNIPAM–anion bonds, but the degree of association between PNIPAM and water remains rather high even at a temperature above the LCST. Since the entropic loss for PNIPAM–water hydrogen bonds and water–anion bonds formation is also large, the difference between $\langle x_{pw}(z)\rangle$ and $\langle x_{w-}(z)\rangle$ increases with temperature.

Insets in Fig. 5 show that the local fractions of PNIPAM–water hydrogen bonds and PNIPAM–anion bonds are functions of temperature in 0.25 M solutions of sodium halides. All the average fractions of PNIPAM–water hydrogen bonds decrease in 0.25 M sodium halide solutions, compared with those in pure water (see Fig. 3(b)). We find that both of the local fractions of PNIPAM–water hydrogen bonds and water–anion hydrogen bonds near the brush surface become larger at different temperatures.

The formations of PNIPAM–water hydrogen bonds and water–anion hydrogen bonds are often accompanied by a gain in free energy, which indicates that both $-F_{pw}$ and $-F_{wa}$ are negative. However, there are always $F_{pw} < F_{wI^-} < F_{wBr^-} < F_{wCl^-}$. Therefore, whenever possible, water would prefer to form water–anion hydrogen bonds, rather than to form PNIPAM–water hydrogen bonds. Due to the difference between the free energy associated with water–anion hydrogen bonds and the free energy associated with PNIPAM–water hydrogen bonds, the formation of PNIPAM–water hydrogen bonds is accompanied by more water–anion hydrogen bonds and PNIPAM–anion bonds. The fraction of PNIPAM–water hydrogen bonds is further affected by the addition of anions following the Hofmeister series: NaCl>NaBr>NaI. Figure 6 directly presents the competition interaction relation between PNIPAM–water hydrogen bonds and water–anion hydrogen bonds at a fixed temperature. The average fraction of water–anion hydrogen bonds follows the Hofmeister series: NaCl>NaBr>NaI. The influence of temperature on the properties of PNIPAM brush is caused by the competition interaction between PNIPAM–water hydrogen bonds and water–anion hydrogen bonds. Moreover, an increase in water–anion hydrogen bonds leads to the loss of water molecules bound di-

rectly to grafted PNIPAM chains. Dehydration of PNIPAM results in a decrease in the compatibility between PNIPAM and aqueous solution, which implies the decrease in LCST roots in the breaking of water-PEO hydrogen bonds and the increase in water–anion hydrogen bonds.

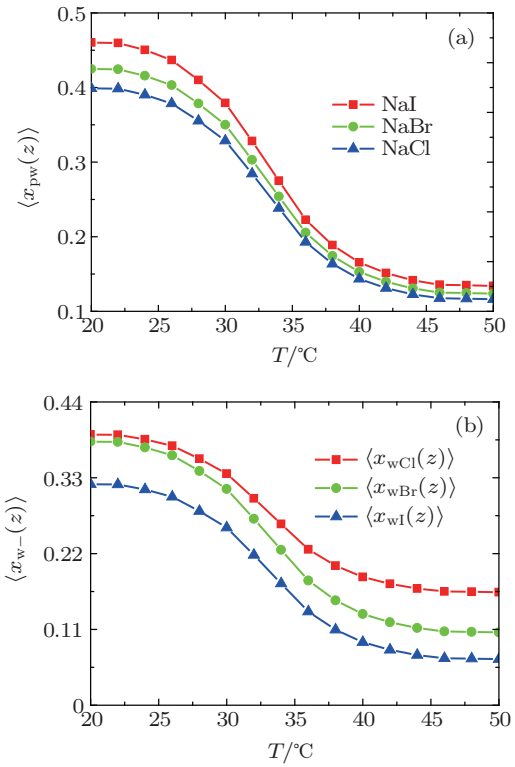


Fig. 6. (color online) (a) The average fraction of PNIPAM–water hydrogen bonds as a function of temperature in sodium halide solutions. Different curves represent PNIPAM–water hydrogen bonds in different solutions. (b) The average fraction of water–anion hydrogen bonds as a function of temperature in solutions of sodium halides. Different curves represent different water–anions hydrogen bonds in different solutions. The molecular weight of the polymer chain is $M_w = 22500\ \mathrm{g\cdot mol^{-1}}$, and the surface coverage is $\sigma = 0.5\ \mathrm{nm^{-2}}$.

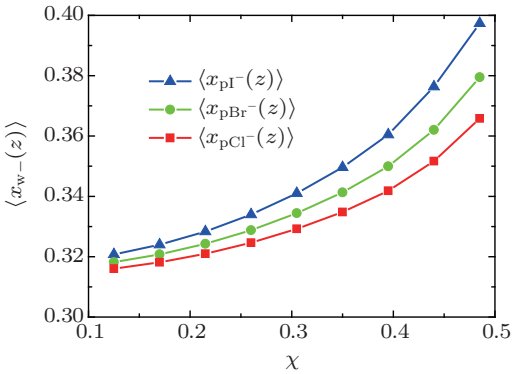


Fig. 7. (color online) The average fraction of PNIPAM–anion bonds as a function of χ for a temperature of $T = 25$ °C. The molecular weight of the polymer chain is $M_w = 22500\ \mathrm{g\cdot mol^{-1}}$, and the surface coverage is $\sigma = 0.5\ \mathrm{nm^{-2}}$.

To better quantify the coupling of two components determining the solvent quality, we plot the diagrams of $\langle x_{w-}(z)\rangle$ vs. χ, as shown in Fig. 7. We have altered $\chi = B/T$, and kept T constant. From Fig. 7, we find that there is a dependence of the number of water–anion hydrogen bonds on χ when water–anion hydrogen bonds become more favorable, and the numbers of PNIPAM–water hydrogen bonds and PNIPAM- anion bonds decreases. Consequently, the solubility of PNIPAM decreases, and PNIPAM brush becomes more compact. With respect to the formation of water–anion hydrogen bond, increasing the fraction of water–anion hydrogen bonds makes the solvent poorer, thus the polymer brush collapses easily. This implies that the quality of solvent is determined by the competition between PNIPAM–water hydrogen bonds and water–anion hydrogen bonds. In particular, the experimental studies[18] revealed that hydrophobic hydration is altered by the addition of salts. The effect of PNIPAM–water hydrogen bonds and PNIPAM–anion bonds is to make the solvent (water) better as temperature decreases. However, water–anion hydrogen bonds have the opposite effect and result in a decrease in the LCST of PNIPAM following the Hofmeister series: NaCl>NaBr>NaI.[7,18] These results show that the shift of LCST of PNIPAM brushes in solutions of sodium halides is determined by the free energy associated with the formations of PNIPAM–water hydrogen bonds, water–anion hydrogen bonds, and PNIPAM–anion bonds.

Combining Fig. 3 with Fig. 6, it is clear that the addition of anion affects the phase transition of thermo-responsive PNIPAM brushes, and results in the shift of solubility of PNIPAM brushes. The behaviors above are related to unbinding of water molecules from the PNIPAM by the presence of anions, and are thermodynamically favored because they increase the system entropy by letting water molecules escape into the solution. According to Ref. [18], the anions may be associated with amide groups in PNIPAM. The average fraction of water–anion hydrogen bonds are determined by the free energy associated with the formation of water–anion hydrogen bonds.

The relation between the chemical potential of PNIPAM brushes and surface coverage in pure water and sodium halide solutions is shown in Fig. 8. The chemical potential is given by $\mu = -(\partial F/\partial N_P)_{A,T}$, which provides the thermodynamic stability of PNIPAM brushes. From Fig. 8, it is obvious that the chemical potential following the Hofmeister series increases monotonically at $T = 25$ °C, which implies that tethered brushes are stable in the presented regime of temperatures and surface coverages.

The chemical potentials in Fig. 8(a) show a following tendency of the Hofmeister series for PNIPAM brushes, which is similar to that observed in structural properties, and reflects the changes in the quality of solvent with PNIPAM–water hydrogen bonds and PNIPAM–anion for each case. The chemical potential of PNIPAM measures the amount of work required to bring a PNIPAM from the bulk solution to the surface. Since the system is actually incompressible, the chemi-

cal potential is exchangeable,[35] and the insertion of PNIPAM molecules requires a removal of water molecules and ions. If PNIPAM molecules are inserted, the free energy cost associated with the formation of PNIPAM–water hydrogen bonds and water–anion hydrogen bonds also needs to be overcome. Consequently, the exchange chemical potential presents a tendency of NaI>NaBr>NaCl.

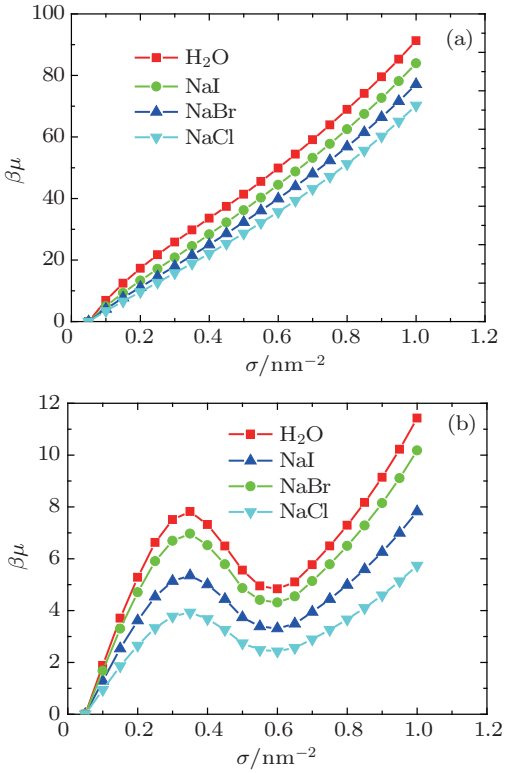


Fig. 8. (color online) The relation between chemical potential and surface coverage of PNIPAM brushes in pure water, 0.25 M NaI solution, 0.25 M NaBr solution, and 0.25 M NaCl solution at (a) $T = 25$ °C and (b) $T = 35$ °C. The molecular weight of the polymer chain is $M_w = 22500$ g·mol^{-1}, and the surface coverage is $\sigma = 0.5$ nm^{-2}.

The chemical potentials in Fig. 8(b) show a clear Van der Waals loop that is an important characteristic of a phase-separated system at $T = 35$ °C. This behavior is qualitatively different from the chemical potential discussed above at $T = 25$ °C. Obviously, the addition of these salts strongly affects the stability of swelling and/or deswelling PNIPAM brush, and enhances the driving force of water released from the grafted PNIPAM chains. The phase separation presented at these critical temperatures is driven by the variation of the three types of bonds. This helps to understand Fig. 8(b), in which the chemical potential of PNIPAM brush in pure water is larger than that in sodium halide solutions, and sodium halides affect the chemical potential following the Hofmeister series.

4. Summary and conclusions

In this work, we have employed a molecular theory to systematically study the shift of the solubility of PNIPAM brushes following the Hofmeister series in sodium halide solutions, and the switching of PNIPAM brushes in pure water and sodium halide solution. Firstly, we investigate the switching behavior of PNIPAM brushes as a function of temperature in pure water, which discloses the characteristics of microscopic structures and the role of PNIPAM–water hydrogen bonds. Our results show that the height of PNIPAM brushes depends sensitively on temperature, due to the fact that hydrogen bonding is entropically dominated. Secondly, in order to elucidate the effects of different sodium-halide salts on the solubility of PNIPAM brushes, we perform a theoretical investigation on PNIPAM brushes in 0.25 M NaI, NaBr, and NaCl solutions, and consider PNIPAM–water hydrogen bonds, water–anion hydrogen bonds and PNIPAM–anion bonds, and their explicit coupling to the switching of PNIPAM conformations. We find that, at moderate grafting densities, the combination of the three types of bonds results in a sensitive temperature dependence of the height of PNIPAM brushes. Naini *et al.*[7] emphasized that enthalpy and entropy are essential to unpuzzle the molecular driving forces shifting the solubility. Our results show that the shift of LCST of PNIPAM brushes is caused by the competition between PNIPAM–water hydrogen bonds and water–anion hydrogen bonds, and the coupling with the polymer conformations is determined by the free energy associated with the formation of the three types of bonds. Finally, we analyze the chemical potential of PNIPAM brushes, and give a further explanation for the effect of PNIPAM–water hydrogen bonds, water–anion hydrogen bonds, and PNIPAM–anion bonds. As to the accuracy of the model, a fixed salt concentration (0.25 M) should be considered here, because cloud-point temperatures showed a large difference at different salt concentrations,[36] which are not included in the present model. In particular, we will extend this approach to study the effect of the three types of bonds at different salt concentrations.

It is worth mentioning that, in the present model, we have only considered the effects of the three types of bonds on the shift of solubility of PNIPAM brushes in sodium halide solutions. In reality, there are additional bonds (including ion–ion bonds) and additional interaction between Na^+ and amide O at temperatures above or below the LCST.[19] Molecular dynamics and theoretical results also suggest that ion–ion bonds do not affect cloud points of PEO electrolyte solutions.[36] Based on our theoretical model, the shift of solubility of PNIPAM brushes in sodium halide solutions originate from the competition among PNIPAM–water hydrogen bonds, water–anion hydrogen bonds, and PNIPAM–anion bonds. Yang *et al.* found that the ion–ion bonds have a small effect on water dynamics.[41] In fact, Na^+ would not form contact ion pairs with I^-, Br^-, and Cl^- in sodium halide solutions.[42,43] According to Okur *et al.*,[21] the interactions

between metal cations and amides are far weaker than the binding of weakly hydrated anions. The anions may bind directly to the polyamide of PNIPAM, and destabilize hydrogen bonding interaction between the amide group and water, thus affecting the LCST of PNIPAM.[18] Earlier researchers also suggested that anions play a critical role in the conformational transitions for the LCST of PNIPAM.[14,44–47] Therefore, we believe that the main anion effects on the shift of solubility of PNIPAM brushes in solutions of sodium halides are captured by our model approach that considers the formation of the three types of bonds. Our theoretical results agree well with the experimental observations.[7,18] Such an agreement suggests that PNIPAM–water hydrogen bonds, water–anion hydrogen bonds, and PNIPAM–anion bonds may become key elements inducing the shift of LCST of PNIPAM by anions (I^-, Br^-, Cl^-). Despite the fact that other contributions (e.g., according to a recent experiment,[48] Na^+ can induce the switching of PSS brushes) certainly operate, they are unlikely to play a pivotal role in changing the LCST of PNIPAM brushes in sodium halide solutions. Our theoretical results may be helpful in providing the most fundamental understanding of the anion effects on the LCST of PNIPAM brushes. It is expected that the theoretical advances[49–54] combined with experimental observations will enable us to modify the designs of PNIPAM in biological applications.

Acknowledgment

We would like to thank Dr. Chun-Lai Ren for her valuable advice and suggestions.

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