# Temperature-Dependent Conformational Change of PNIPAM Grafted Chains at High Surface Density in Water

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## Introduction

Poly(*N*-isopropylacrylamide) (PNIPAM) exhibits a lower critical solution temperature (LCST) of ~30 °C in water that is attributed to alterations in the hydrogen-bonding interactions of the amide group.[1−4] PNIPAM in various forms has been explored for a variety of applications including controlled drug delivery,[5,6] solute separation,[7,8] tissue culture substrates,[9,10] and controlling the adsorption of proteins,[11] blood cells,[12] and bacteria.[13] Grafting PNIPAM onto surfaces is a promising strategy for creating responsive surfaces, since the physical properties of PNIPAM are readily controlled by changing the temperature.

Considerable effort has been devoted to studying variations in chain conformations with temperature ($T$) in PNIPAM-based materials. Kubota et al. studied conformational changes of PNIPAM free chains with temperature for molecular weights ranging from 1.63 $\times 10^6$ to 2.52 $\times 10^7$ g/mol ($M_w/M_n > 1.3$) in water using laser light scattering.[14] They reported a decrease in the radius of gyration ($R_g$) as the solution temperature increased above the LCST. The magnitude of the effect was more pronounced with increasing molecular weight, ranging up to a factor of two for the highest molecular weight sample. In a similar study, Wu et al. observed a decrease in $R_g$ of a factor of seven for a high molecular weight PNIPAM sample with very low polydispersity ($M_w = 1.3 \times 10^7$ g/mol, $M_w/M_n < 1.05$).[15,16] Regarding grafted PNIPAM chains, Kidoaki et al. recently employed an iniferter-based graft polymerization method to generate a dense, high molecular weight brush and reported changes in the thickness measured by AFM.[17] The thickness of the grafted layer was obtained from AFM images of the boundary between grafted and nongrafted (ablated by laser light) regions. They found that the swollen film thickness decreased by a factor of ~2 with increasing temperature from 25 to 40 °C for samples with a range of dry film thickness from 250 to 1500 Å. More recently, Balamurugan et al. used surface plasmon resonance (SPR) to probe conformational changes in a PNIPAM brush grafted onto a gold layer by atom transfer radical polymerization (ATRP).[18] For a sample with a dry film thickness of 517 Å, the SPR measurements indicated a significant contraction (ex-

tension) of the layer with increasing (decreasing) temperature through the transition. Quantification of the change in profile characteristics was not reported, but it was noted that the change in the SPR signal occurred over a much broader range of temperature (15−35 °C) than is typical of the transition for free chains in bulk solution.

No systematic study of detailed PNIPAM chain conformations has yet been reported as a function of the two critical brush parameters, the surface density and molecular weight. A recent theoretical analysis by Baulin and Halperin[19] has identified the surface density as a critical parameter demarcating different regimes of behavior. This arises from the concentration dependence of the Flory $\chi$ parameter as obtained from a recent phase behavior study of free chains in solution.[20] Little attention has been paid to the surface density in previous experimental studies of grafted PNIPAM chains.

We have begun a systematic study of the temperature-dependent conformational changes of PNIPAM grafted chains in water as a function of surface density and molecular weight using neutron reflection (NR). In previous work,[21] we investigated the conformational changes of PNIPAM chains tethered to silicon oxide using two methods. The first was the "grafting from" method in which *N*-isopropylacrylamide monomers were polymerized from the silicon surface with a chain transfer, free-radical technique. In the second method, preformed PNIPAM chains with carboxylic acid end groups associated with terminal hydroxyl groups of a mixed self-assembling monolayer. Detailed concentration profiles of the PNIPAM brushes were determined in $D_2O$ as a function of temperature and also in *d*-acetone at room temperature. Profiles were obtained in the two solvents in order to investigate the role of the solvent in mediating interactions. The profiles in $D_2O$ were bilayers, composed of a very thin layer with higher concentration at the surface and a low concentration layer extending well into the subphase. The very thin, higher concentration surface layer was attributed to attractive segment−surface interactions. The profiles in acetone were smoothly decaying single-layer profiles. The low segment concentration at the surface in acetone indicated that the surface density of these brushes was rather low. The dry film thicknesses were less than 40 Å, much lower than in the study of Kidoaki et al. On the basis of the molecular weights and dry film thicknesses, the surface density ($\sigma$, chains/Å$^2$) ranged from $1 \times 10^{-4}$ to $2 \times 10^{-4}$ for those samples. For these low surface density brushes, the conformational changes with temperature in $D_2O$ were very subtle. No coil-to-globule transition was observed. This contrasted with the studies cited above and with a number of previous reports in which mechanisms were proposed for various effects based on such a conformational change.[4,6,12,22]

In the present work we used NR to study the conformational change of a PNIPAM brush synthesized by ATRP with much higher surface density than in our previous study. For this brush a large change in conformation with temperature was observed. This is the first report of a strong conformational change with temperature for a PNIPAM brush detected by NR, which enables detailed profiles to be obtained. We report the data below and discuss the results in the context of

our previous data and the notion of a concentration-dependent $\chi$ parameter for this system.

## Experimental Section

**Materials.** 1-Dodecanethiol, 11-mercapto-1-undecanol, 2-bromopropionyl bromide, CuBr, Me4cyclam (1,4,8,11-tetramethyl-1,4,8,11-tetraazacyclotetradecane), *N*-Isopropylacrylamide (NIPAM), $D_2O$ (99.9 atom %), anhydrous dimethylformamide (DMF), and anhydrous tetrahydrofuran (THF) were purchased from Aldrich Chemical Co.[23] NIPAM was recrystallized from hexane; all other materials were used as received.

**Grafting of PNIPAM onto the Gold Surface.** The PNIPAM brush was synthesized using atom transfer radical polymerization (ATRP), where an alkyl halide was employed as an initiator and a transition-metal complex as a catalyst to create a polymer radical. The detailed synthetic procedure is described elsewhere.[18] Thin layers of chromium (30 Å) and gold (110 Å) were sequentially sputtered onto a silicon wafer. The gold-coated wafer was cleaned by placing it into a UV/ozone cleaner for 20 min and was then submerged overnight in an ethanol solution containing a mixture of 1-dodecanethiol and 11-mercapto-1-undecanol (10/90, v/v). After an ethanol rinse, the self-assembled monolayer (SAM) was treated with 2-bromopropionyl bromide (0.1 M) in the presence of triethylamine (0.12 M) for 2–3 min to convert to a bromo-terminated ester. The initiator-modified sample was placed into a DMF solution containing the NIPAM monomer and CuBr/Me4cyclam catalyst (0.2 M) and allowed to react for 20 min. The sample was rinsed with DMF and ethanol to terminate the reaction and then rinsed with deionized water and methanol to remove unbound polymer.

**Instrumentation.** The neutron reflectivity (NR) measurements were performed on the NG7 reflectometer at NIST. A fixed wavelength of 4.75 Å was used. Reflectivity data from the protonated PNIPAM layers in deuterated water were obtained using a liquid cell over a range of temperature from 20 to 41 °C. Neutron reflectivity probes the scattering length density (SLD) profile normal to the surface, which is determined by the density and atomic composition. The SLD profiles were converted to volume fraction profiles assuming additivity of volumes. The SLD profiles were composed of a stack of slabs, where each slab was assigned an SLD, a thickness, and a roughness. The data were analyzed using a small number of unconstrained layers (one or two) to represent the grafted PNIPAM profile and also using a large number of layers (2 Å thickness) in which the SLD values were constrained to follow various functional forms, such as a parabola with an exponential tail or the sum of two parabolas. The reflectivity was calculated from the stack of slabs using the optical matrix method.[24] Best-fit profiles are determined by minimization of least squares. X-ray reflectivity (XR), which determines the electron density profile normal to the surface,[25] was performed both at Sandia National Labs and at NIST.

## Results and Discussion

To constrain the fits to the NR data, it was important to determine the thicknesses and SLD values of the silicon oxide, Cr, Au, SAM, and dry PNIPAM films in separate experiments. To accomplish this, three preliminary experiments were performed: a sample containing the metal films only was measured with XR, a sample containing the metal films and the SAM but without PNIPAM was measured in the presence of $D_2O$ in the liquid cell by NR, and the sample with all layers was measured in a vacuum using NR. Using XR, the Cr and Au layers on the silicon substrate were determined to be 30 and 110 Å, respectively. The thickness of the SAM layer was 15 Å. In the second preliminary experiment described above, the SLD of the SAM layer was obtained in the presence of $D_2O$ to account for any $D_2O$ that penetrated into that layer. The dry PNIPAM film thickness was 215 Å, roughly five times greater
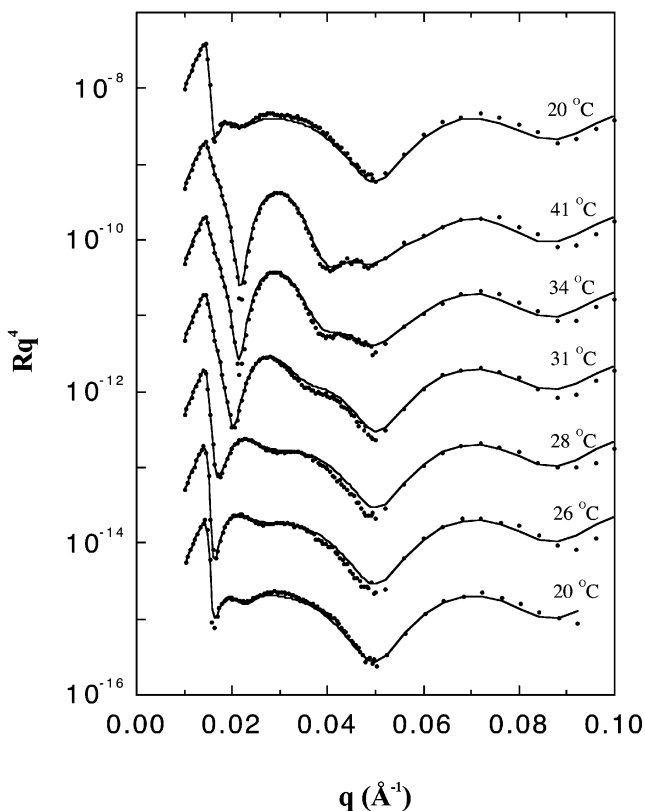
**Figure 1.** Neutron reflectivity data from the grafted PNIPAM sample for a series of temperatures in $D_2O$. The curves through the data correspond to best fits using model segment volume fraction profiles.

than the highest value for the samples in our previous study. The surface density was $\geq 2.5 \times 10^{-3}$ chains/Å² for this sample,[26] an order of magnitude greater than the samples in our previous study.

NR data for the PNIPAM sample in $D_2O$ for a sequence of temperatures beginning at 20 °C, after heating above the LCST, and then upon subsequent cooling are shown in Figure 1. The data are displayed as reflectivity × $q^4$ to compensate for the $q^{-4}$ decay due to the Fresnel law. The data are shifted on the *y*-axis for clarity. Large changes are observed as a function of temperature for $q < 0.06$ Å$^{-1}$, reflecting the change in the PNIPAM segment concentration profile. The reflectivity for $q > 0.06$ Å$^{-1}$ is mostly determined by the metal layers and showed little change with temperature. The best-fit profiles are shown in Figure 2.

The profiles show that the PNIPAM chains contract significantly upon heating from 20 to 41 °C. Specifically, the maximum extent of the layer, defined arbitrarily as the distance at which the volume fraction drops to 0.02, decreases from ~670 to ~420 Å over this temperature range. The first moment of the segment volume fraction distribution decreases from 210 to 149 Å. The reflectivity returned to that of the original curve as the temperature was lowered back to 20 °C. At 20 °C, a single step profile with roughness or a parabola with an exponential tail is not able to describe the data precisely. Much better agreement with the data is obtained with a bilayer function in which the foot of the profile is more pronounced. At 41 °C, the profile is steplike with a small roughness. These profiles are very different than those obtained in our previous study involving PNIPAM films with much lower dry film thickness. In particular, the segment volume fraction at the surface is much higher
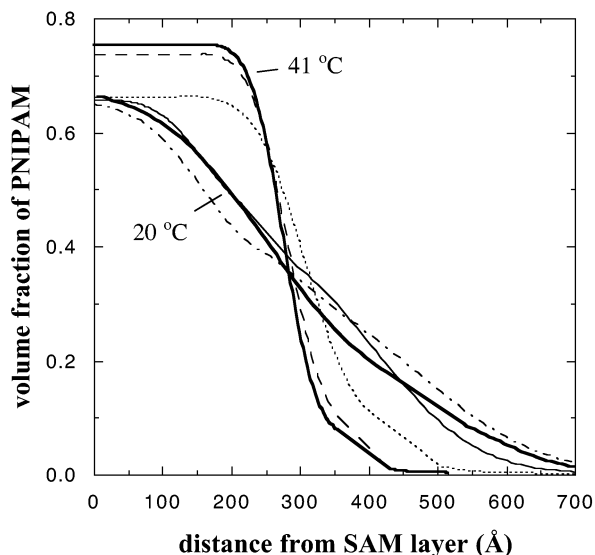
**Figure 2.** Best-fit segment volume fraction profiles from the grafted PNIPAM sample in $D_2O$ at 20 °C (—) after heating to 41 °C (—) and then upon cooling to 34 °C (− −), 31 °C (· · ·), 28 °C (−), and 26 °C (− · −).
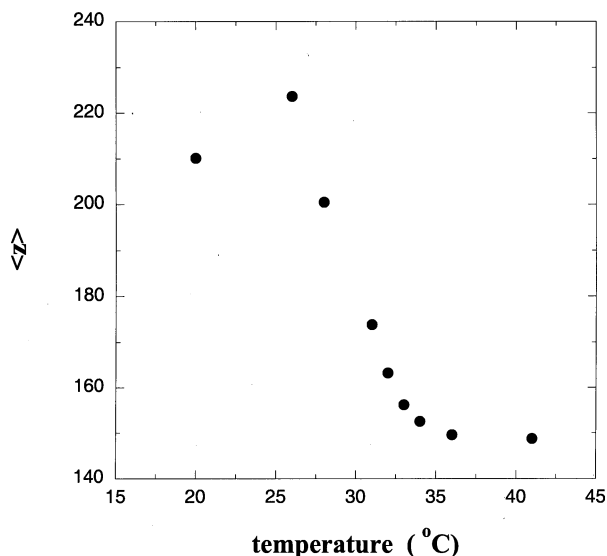


**Figure 3.** Variation of the first moment of the segment volume fraction distribution with temperature upon cooling from 41 °C.

a subtle change in profile shape near the transition temperature. This will be discussed in a future publication involving data for additional samples.

The large conformational change with $T$ reported here is in contrast to our previous study, in which only very modest conformational changes were observed for PNIPAM chains end-tethered by other methods. Following the theoretical arguments of Baulin and Halperin for the PNIPAM system, this is likely due to the fact that the surface density is at least an order of magnitude higher in the present case. However, we note that the grafted PNIPAM layer in the present study from the ATRP method should also have much lower polydispersity than the grafting-from sample in our previous study synthesized with the chain-transfer free radical method.[27] For the preformed PNIPAM chains at low surface density in the previous study, our data showed evidence of segmental adsorption in the form of distinct bilayer profiles. This would lead to a polydisperse distribution of loops and tails. Thus, polydispersity could also contribute to the difference observed in the magnitude of the conformation change with $T$ since a sharper and more pronounced change is expected for samples with lower polydispersity. To resolve this, we are currently undertaking a systematic study of the effect of molecular weight and surface density on the conformational change of PNIPAM chains grafted using the ATRP method.

## Conclusions

Neutron reflectivity has been applied to study the temperature-dependent conformational change of PNIPAM chains grafted at high surface density to the surface of a gold-coated silicon wafer using the ATRP method and immersed in $D_2O$. A strong contraction was observed as the temperature passed through the LCST. This is the first measurement of the detailed segment volume fraction profiles for a PNIPAM brush undergoing a significant conformational change with temperature. The large change with temperature in this work contrasts with the results of our previous study involving PNIPAM chains tethered at lower surface density by other methods. Combined with the previous data, the present results support the notion of a concentration-dependent $\chi$ parameter for PNIPAM in water, although polydispersity has not yet been ruled out as a contributing factor.

in the present case. Furthermore, most of the segment density is in the surface layer, and the tail is a small fraction of the total segment density. By contrast, in the previous work the surface layer was very thin, and most of the segment density was in a lower density layer that extended into the subphase.

Upon cooling, most of the conformational change occurred between 33 and 27 °C, as shown by the variation in the first moment in Figure 3. This range of temperature is much smaller than that in the SPR study reported by Balamurugan et al. However, we note that preliminary NR data for samples with varying surface density and molecular weight to be reported elsewhere indicate that the change in the first moment with temperature varies greatly as a function of these parameters. So a detailed comparison awaits the full characterization of this dependence. We also note that the variation in the profile shape with temperature is not continuous through the transition. Rather, there is

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(26) We estimated the range of surface density in two ways. First, a polymerization of free chains in the bulk was performed

for conditions identical to those that yield a dry film thickness of $500 \pm 20$ Å in a surface polymerization. The number-average molecular weight of $1.15 \times 10^5$ from gel permeation chromatograhy for the bulk polymerization and the dry film thickness of the surface polymerization correspond to a surface density of $2.6 \times 10^{-3}$ chains/Å². The surface polymerization was performed for a sample in which 32% of the molecules in the SAM could react with the initiator.[18] For the present case 90% of the molecules in the monolayer were hydroxyl-terminated and able to react to form initiator sites; therefore, the surface density in the present case must be $\geq 2.6 \times 10^{-3}$ chains/Å². This method assumes that the characteristics of the chains for the surface polymerization are similar to those for free chains polymerized in the bulk. This was confirmed previously in a recent study involving ATRP.[28] The second method of estimating the surface density was to compare the NR profiles at 20 °C with the extensive database for tethered polystyrene chains in good solvent conditions.[29,30] In that case the variation in profile characteristics with surface density and molecular weight were described by the relations $h = 0.16\sigma^{0.22}M_w^{0.86}$ and $\phi_s = 14\sigma^{0.78}M_w^{0.14}$, where $h$ and $\phi_s$ are the parameters defining a parabolic profile of the segment volume fraction $\phi = \phi_s[1 - (z/h)^2]$. In the present case the values $h = 538$ Å and $\phi_s = 0.60$ define the best parabola approximating the profile at 20 °C in Figure 2 having an integral of 215 Å. Using the aforementioned relations from ref 30, these parameters correspond to a molecular weight of 59 000 g/mol and a surface density of $2.5 \times 10^{-3}$ chains/Å². The data in ref 30 were obtained for a lower range of reduced surface density $\sigma\pi R_g^2$, so there is undoubtedly some error in the extrapolation to higher $\sigma\pi R_g^2$ as the exponents should gradually increase toward the limiting scaling values for the brush regime.

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