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A quantitative analyses of the viscometric data of the coil-to-globule and globule-to-coil transition of poly(*N*-isopropylacrylamide) in water

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Abstract

The coil-to-globule and globule-to-coil transition of poly(*N*-isopropylacrylamide) in aqueous solution had been studied by heating and cooling the sample solution with conventional viscosity measurement. A single chain collapsed globule solution was prepared firstly by adding sodium *n*-dodecyl sulfate (SDS) into the polymer solution at room temperature, as the chain collapsed to compact globule at higher temperature and then the SDS was removed by electro-dialysis. The viscosity data were analyzed in a quantitative way, which permitted to elucidate the transition temperature and the amount of the water in the collapsed globule precisely.

Keywords: Poly(*N*-isopropylacrylamide); Globule-to-coil transition; Viscosity

1. Introduction

The reversible coil-to-globule transition of macromolecules in solutions have been extensively studied both theoretically and experimentally in the last 40 years, which is a fundamental problem related both to polymer and life sciences [1–7]. However, it was very difficult to investigate the region consisting isolated single-chain globules experimentally, since the coil contractions and intermolecular aggregations were competitive processes, when the solvent turned bad.

Poly(*N*-isopropylacrylamide) (PNIPAM) has lower critical solution temperature (LCST) in its aqueous solution. The coil-to-globule transition can take place within several degrees around 32 °C, and there are a great number of papers about its solution properties in water [8–13]. The nature of the coil-to-globule transition is revealed as the hydrophilic interaction changed to hydrophobic interaction. Wu et al. [14,15] reported that they observed the real thermodynamics stable compacted single chain globule firstly in the extremely dilute concentration, and studied the process of globule-to-coil transition by static and dynamic laser light scattering. However, Wu's experimental condition was very rigorous. Another interesting experiment was about the blend of a certain amount of the surfactant (especially for sodium *n*-dodecyl sulfate (SDS)) with PNIPAM water solution [16]. The surfactant would form a surface layer around the polymer globules and prevented the aggregation of the polymer chains, when the coil-to-globule transition takes place. It is proved to get a real single chain globule solution [17] if the concentration of the surfactant is higher than a critical number. That gives great convenience to prepare the single chain globule solution, although the existence of the surfactant may disturb.

Therefore, the spherical single chain particles solution of poly(*N*-isopropylacrylamide) were prepared successfully in a normal aqueous solution above its LCST with the addition of sodium *n*-dodecyl sulfate in our group [18]. The SDS molecules would be removed by dialysis after the coil having been transferred to compact particle, and the single chain particles have been observed clearly under transmission electron microscopy. In this paper, the process of globule to coil transition of the single-chain particles, prepared as above mentioned, was investigated by viscosity measurement with decreasing temperature. To compare with it, the entire process of coil-to-globule and globule-to-coil transition of an ordinary PNIPAM solution was measured also, and the resulted data were analyzed in a

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quantitative way to obtain more information about this transition.

2. Experimental

2.1. Materials

The poly(*N*-isopropylacrylamide) (PNIPAM) sample was prepared [19,20] in this laboratory by free radical polymerization in benzene with recrystallized azobisisobutyronitrile (AIBN) as initiator. The monomer was recrystallized three times in benzene/*n*-hexane mixture before use. The viscosity average molar mass [21] of PNIPAM was 4.4×10^5 g/mol as calculated from its intrinsic viscosity. The ratio of weight- to number-average molar mass was 1.85 as determined by size exclusion chromatography. Sodium *n*-dodecyl sulfate (SDS) surfactant was recrystallized three times from methanol solution before use.

2.2. Solution preparation

The de-ionized distilled water was used for preparing the normal and surfactant containing aqueous PNIPAM solutions. All solutions were prepared by weighing the sample and the resulting solution kept in a suitable vessel for at least 24 h at room temperature. The weight concentration was converted to weight-volume concentration (in g/ml) by applying the density correction. Before viscosity measurements, the solutions were filtered by Millipore filter with 0.45μ pore-diameter to remove dust.

The surfactant containing solution was prepared similarly as normal solution by mixing weighed PNIPAM, SDS and water at room temperature. After dissolution, the temperature was raised to 40 °C and kept the solution at that temperature for 12 h. Then, the solution was transferred into a bag of semi-permeable membrane placed in a dialysis water bath kept at 40 °C. An electrostatic field ($E = 2000$ V/m) was applied to the bath in order to accelerate the removal of SDS from the solution at that temperature. Both the solution and dialyzate were tested by aqueous $BaCl_2$ solution to check whether the SDS was removed thoroughly. This method was very efficient to remove SDS within a few days of dialysis. The final concentration of the solution was determined by weighing the remaining polymer after evaporation of water.

2.3. Viscosity measurement

An Ubellohde viscometer, which capillary with a diameter of 0.413 mm and length of 102.1 mm, was used to measure the change of the solution viscosity with the temperature. The same viscometer was modified to act as a sealed viscometer [22]. The viscometer was thoroughly cleaned by repeatedly rinsing and soaking for 2 days with deionized water and finally drying at 110 °C after every measurement.

3. Results and discussion

The temperature dependences of the intrinsic viscosity of PNIPAM in water at different temperatures for heating the normal solution, cooling the normal and dialyzed solutions are shown in Fig. 1. One could clearly see from the figure that there are three distinct temperature regions according to the change of the chain conformation, namely a coiled region I, a transition region II and a globule region III. The data for each temperature region could be equally well fitted by both the linear equation

$$\ln[\eta] = A + BT \qquad (T \text{ in } ^\circ\text{C}) \tag{1}$$

and Andrade equation

$$\ln[\eta] = C + Q/T \quad (T \text{ in } ^\circ\text{C}) \tag{2}$$

as shown in Figs. 2 and 3. Both the equations described the relationship between the viscosity and temperature. The coefficients A, B, C and Q evaluated by linear regression for each region were listed in Table 1.

Though the fitted lines were only applicable to the data in the specified temperature region as shown in Fig. 4, the evaluated coefficients pairs $A-B$ and $C-Q$ permitted us to determine the boundary temperatures between the two adjacent regions precisely as the intersecting points of the fitted curves by solving Eqs. (1) or (2) with known coefficients. The calculated boundary temperatures were listed in Table 2.

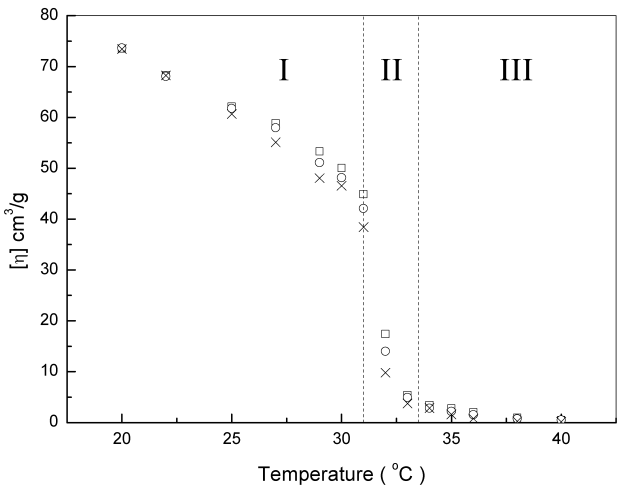

Fig. 1. The plot of the calculated intrinsic viscosity $[\eta]$ to the temperature. The concentration of the normal PNIPAM solution was 6.65×10^{-4} g/ml, and that of the 'single chain' globule particle solution was 5.30×10^{-4} g/ml. The intrinsic viscosity was calculated according to the formula [24]: $[\eta] = \sqrt{2(\eta_{sp} - \ln(\eta_r))}/C$. □: The variation of $[\eta]$ of the normal PNIPAM solution with the temperature from 20 to 40 °C; ○: the variation of $[\eta]$ of the normal PNIPAM solution with the temperature from 40 to 20 °C after heating; ×: the variation of $[\eta]$ of the dialyzed PNIPAM and SDS solution with the temperature from 40 to 20 °C.

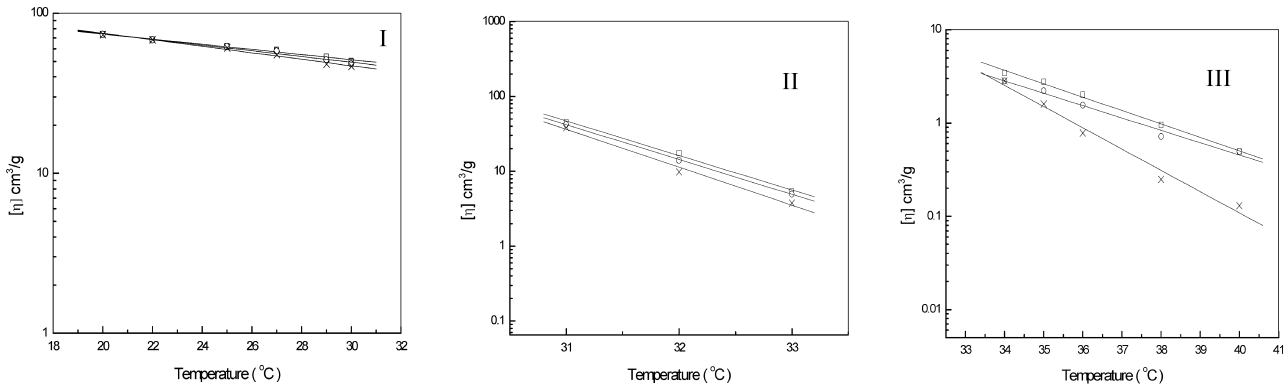

Fig. 2. The $[\eta]$ for each temperature region satisfies the linear function, $\mathrm{Ln}[\eta] = A + BT$ (T in °C). The □, ○, × are the same as in Fig. 1.

Table 1
The fitted viscosity coefficients of each temperature region for aqueous PNIPAM solutions with various treatment process

Treatment process	Temperature region	Linear function		Andrade equation	
		A	*B*	*C*	*Q*
Heating normal solution	I	5.039	−0.037	−6.819	3.26E + 03
Heating normal solution	II	36.766	−1.062	−321.102	9.88E + 04
Heating normal solution	III	12.589	−0.332	−102.605	3.19E + 04
Cooling normal solution	I	5.134	−0.041	−8.144	3.65E + 03
Cooling normal solution	II	36.936	−1.071	−324.07	9.97E + 04
Cooling normal solution	III	11.408	−0.305	−94.485	2.93E + 04
Cooling dialyzed solution	I	5.247	−0.047	−9.808	4.14E + 03
Cooling dialyzed solution	II	39.667	−1.164	−352.681	1.08E + 05
Cooling dialyzed solution	III	18.79	−0.525	−163.607	5.05E + 04

The calculated boundary temperatures showed that identical results with great precision were obtained both by the linear function Eq. (1) and Andrade equation Eq. (2), though their theoretical background were quite different. The data of Table 2 also showed that the transition region only covered 1.8–2.4 degrees. It was considered statistically that the contraction of the chains should be at the different speed, when the temperature of the system came into the transition region. The two calculated boundary temperatures were believed consistent with the start and the end of the process of the chain contraction, respectively. It could be considered that the different rates of the contraction of the chains in the three different regions were related to the transition kinetics [Cheng and Yung, unpublished data], and the transition mechanism of coil to globule transition is believed to accord with two stages reversible transition, the rate constants have different values to make the rate of chain contraction different.

It is worthy to emphasize another interesting feature of

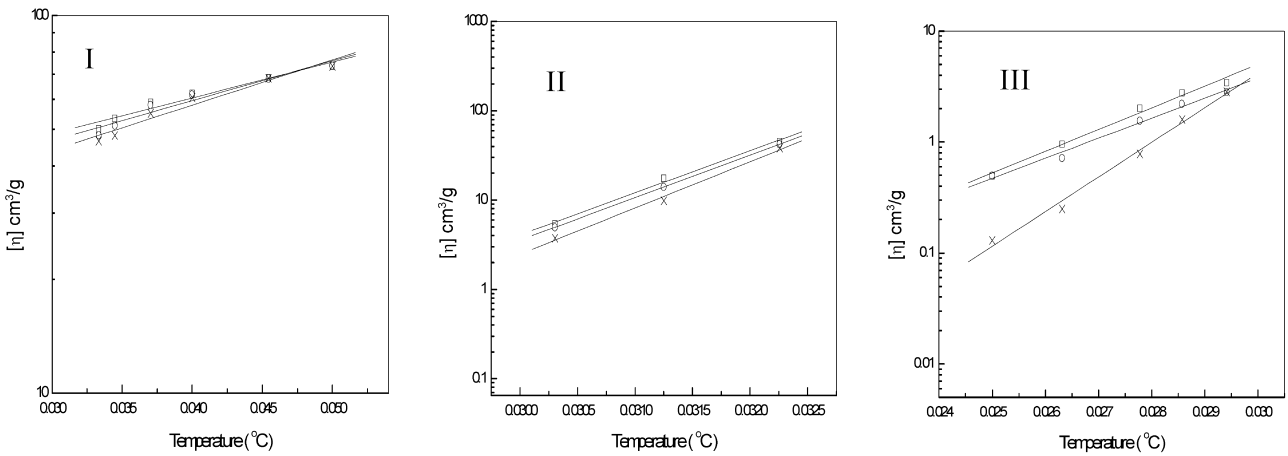

Fig. 3. The $[\eta]$ for each temperature region satisfies the andrade function, $\mathrm{Ln}[\eta] = C + Q/T$ (T in °C). The □, ○, × are the same as in Fig. 1.

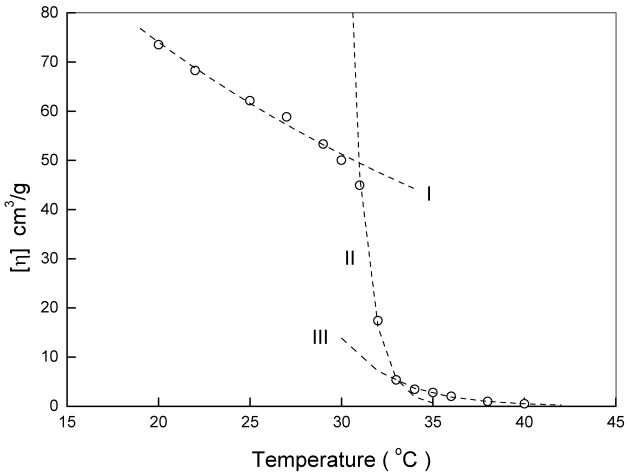

Fig. 4. The variation of $[\eta]$ of the normal PNIPAM solution with the temperature from 20 to 40 °C. The dotted lines are calculated by the coefficients of $\mathrm{Ln}[\eta] = A + BT$.

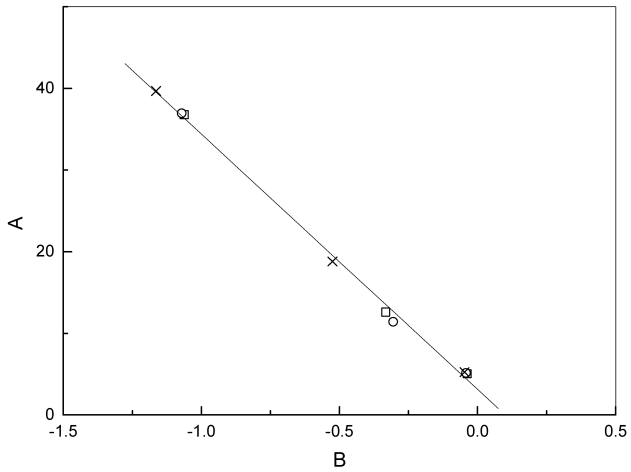

Fig. 5. The linear co-relationships between A and B. The □, ○, × are the same as in Fig. 1.

these coefficients. Though they were quite diverse for different regions, unique linear co-relationships exist between A and B and also between C and Q irrespective to regions or treatment process as shown by Figs. 5 and 6. The dotted lines drawn in Figs. 5 and 6 represent the linear regression lines as

$$A = 3.16 - 31.2B \tag{3}$$

and

$$C = 3.19 - 3.29 \times 10^{-3} Q \tag{4}$$

It was believed that there existed a unique transition mechanism for the three regions. But the inherent reason for this unpredicted phenomenon remained unsolved.

The decrease of intrinsic viscosity with increasing temperature informs us that the conformation of the individual polymer chain did changes during the whole coil to globule and then globule to coil transition cycle. Examining the obtained data, one could see that both the rate of intrinsic viscosity variation with temperature (B) or the activation energy (Q) are quite different for the three stages with the order of II > III > I and for region I the rate or activation energy are practically identical. Taking the data of region I as reference, the relative rates of the three regions are shown in Fig. 7. The variations of the relative activation energy are just like that of the rate as Fig. 7. In region II, the relative rate of $\mathrm{d}\ln[\eta]/\mathrm{d}T$ for heating and cooling the normal solution is greater than that of the dialyzed solution while in region III the relative rate for the dialyzed solution is greater. Since the dialyzed solution only involves the single chain globule to coil transition and for heating and then cooling the normal solution besides this transition the inter-molecular aggregation are also involved, the diverse order of the relative rates in region II and III could be realized.

The most significant difference in measured intrinsic viscosity of the aqueous PNIPAM solution subjected for varying treatment process appears in the globule region III as shown in Figs. 2 and 3. For illustrating it more clearly, the ratio of intrinsic viscosity measured at the same temperature was plotted as a function of temperature in Fig. 8. This ratio is a measure of the relative occupied volume of the macromolecules in solution with a chosen process (cooling

Table 2
The boundary temperature between region I–II and II–III calculated from coefficients listed in Table 1

Process	From coefficients	Boundary temperature (°C)	
		I–II	II–III
Heating normal solution	A, B	30.944	33.116
Heating normal solution	C, Q	30.942	33.104
Cooling normal solution	A, B	30.874	33.318
Cooling normal solution	C, Q	30.873	33.311
Cooling dialyzed solution	A, B	30.804	32.683
Cooling dialyzed solution	C, Q	30.804	32.640

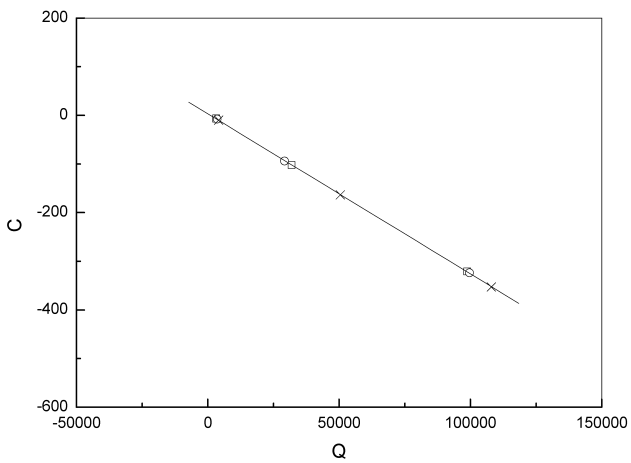

Fig. 6. The linear co-relationships between C and Q. The □, ○, × are the same as in Fig. 1.

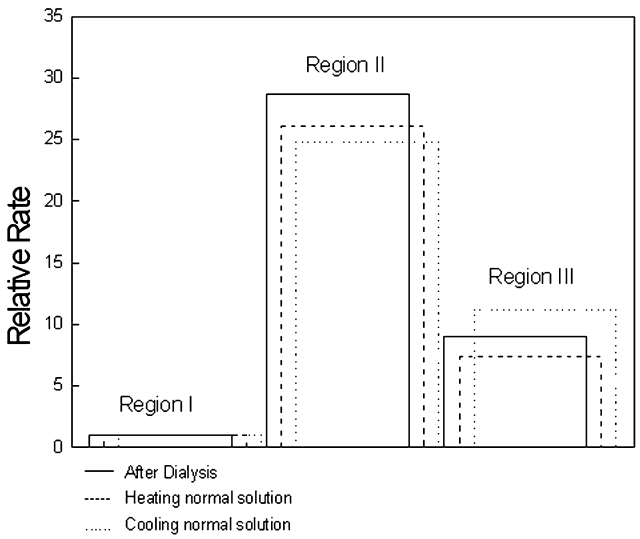

Fig. 7. The relative rate of variation of intrinsic viscosity with temperature for the three regions, the rate of variation of intrinsic viscosity of the region I as the reference value.

the normal solution and dialyzed solution) as the reference state. Fig. 8 also demonstrates the existence of the three distinct regions. In the coil region I, the ratio practically equals to 1 and in the transition region II the ratio first increases and then decreases to 1 leaving a small maximum peak at the center of this temperature region. While in the globule region III, the ratio increases with increasing temperature as cooling process of the dialyzed solution to be the reference state. The appearance of this small peak may be regarded as the result of the simultaneously occurred inter-chain aggregation and intra-chain physical cross-linking having different rates and temperature coefficients. The heating–cooling cycling process of the normal solution corresponds to a coil–globule transition followed by a reversing globule–coil transition. Taking the latter as the reference state, the viscosity ratio shows similar trends as shown in Fig. 8. These ratios are greater than one both in region II and III. It quantitatively illustrates the hysteresis phenomena in the heating–cooling cycle as reported repeatedly from dynamic laser light scattering experiment at extremely dilute concentration by Wu [14].

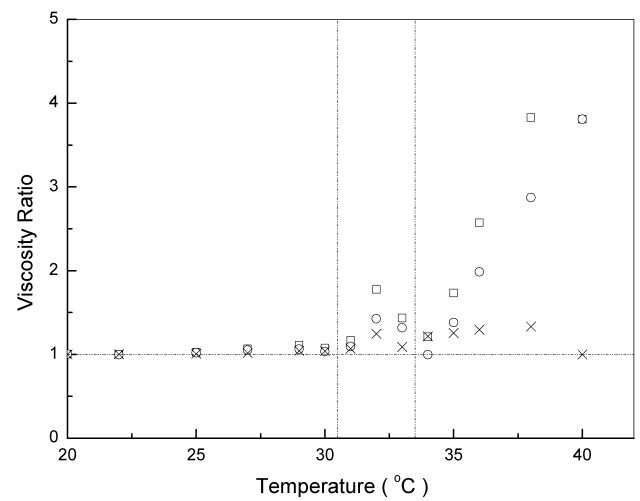

Fig. 8. The $[\eta]$ ratio measured at the same temperature of aqueous PNIPAM solution for varies thermo-history with the temperature. □: Heating (normal)/cooling (dialyzed); ○: cooling (normal)/cooling (dialyzed); ×: heating (normal)/cooling (normal).

Heating the normal aqueous PNIPAM solution from 20 °C gradually to higher temperature, it becomes slightly turbid at 35 °C and the turbidity increases with increasing temperature. However, there is no trouble to measure the viscosity of the turbid emulsolid solution for the temperature as high as to 40 °C. This fact evidently reveals that aggregation of macromolecules and phase separation of solution occurred. But on the other side, heating the aqueous PNIPAM solution containing SDS, it remains transparent at 40 °C indicating the absence of aggregation and phase separation. The solution still remains transparent after removing SDS from solution by electro-dialysis treatment at 40 °C for a long time. We may regard that aggregation is absent in this solution and the macromolecules are in isolated single chain state.

During the prolonged dialysis of the SDS containing PNIPAM solution at a higher temperature as 40 °C, the continually proceeded intrachain physical crosslinking should leads the collapsed coil to squeeze more solvated and trapped solvent molecules out off the globule and resulting a more compact conformation and a small intrinsic viscosity.

Assuming the achieved lowest intrinsic viscosity of the dialyzed solution at 40 °C, corresponds to the intrinsic viscosity of the compact globule, we may define a swelling factor β

$$\beta = [\eta]/[\eta]_{\text{compact globule}} \tag{5}$$

as the ratio of the volume of macromolecules in solution compared to the volume of the compact globule with ordered structure. The intrinsic viscosity data listed in Table

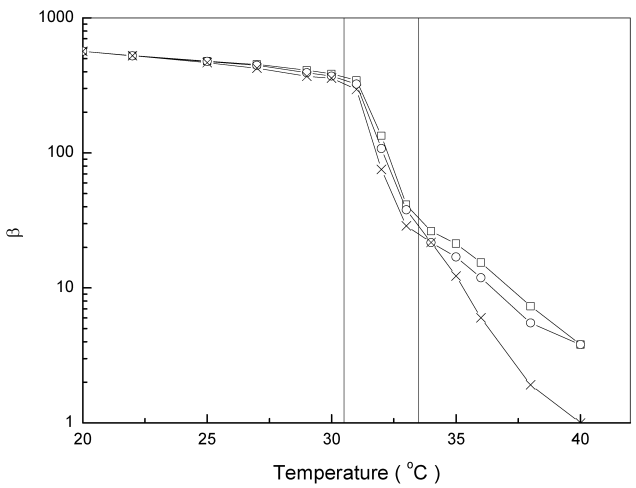

Fig. 9. The variation of the logarithm of the swelling factor of the PNIPAM solution, log β with the temperature. The □, ○, × are the same as in Fig. 1.

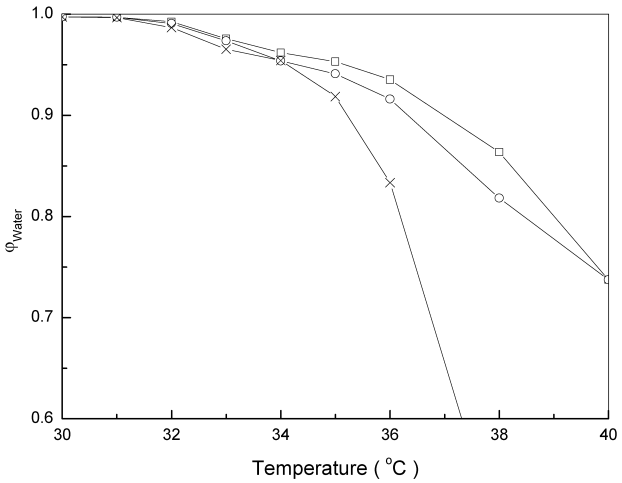

Fig. 10. The volume fraction of trapped water of the PNIPAM solution with the temperature. The □, ○, × are the same as in Fig. 1.

1 were converted to β with $[\eta]_{\text{compact globule}} = 0.13$. A plot of $\ln \beta$ versus T is shown in Fig. 9. It demonstrates that the collapsed globule in region III still presents as a swollen state containing a large amount of solvent. The volume fraction of water in the globule could be estimated from the swelling factor β simply as

$$\phi_{\text{water}} = (\beta - 1)/\beta \tag{6}$$

The calculated ϕ_{water} of the globule as a function of temperature was drawn in Fig. 10. It is numerically in accordance with that estimated from the dynamic light scattering studies carried out by Wu [20,23]. The heating process of the dialyzed solution corresponds only to the dissociation process of the intrachain physical cross-linking while the interchain aggregation is absent. Fig. 10 shows that the globules formed in region III still contain a lot of water and the amount of which changes gradually with temperature. It suggests that a complicated hydration–dehydration process must be involved in the whole transition.

4. Conclusion

The temperature dependence of the intrinsic viscosity of aqueous PNIPAM solution shows three distinct regions. By quantitatively analyzing the data, the transition temperature of coil-to-globule and globule-to-coil could be determined precisely. In the globule region, the collapsed chain still consists of a lot of water and changes regularly with temperature. It indicates the hydration–dehydration process should be involved in the whole transition.

Acknowledgements

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References

[1] Post CB, Zimm BH. Biopolymers 1979;18:1487. Post CB, Zimm BH. Biopolymers 1982;21:2123.
[2] Sun ST, Nishio I, Wislow G, Tanaka T. J Chem Phys 1980;73:5971.
[3] Park IH, Wang QW, Chu B. Macromolecules 1987;20:1965.
[4] Kubota K, Fujishige S, Ando I. J Phys Chem 1990;94:5154.
[5] Nakata M. Phys Rev 1995;E51:5770.
[6] Creighton TE. Protein folding. New York: Freeman; 1992.
[7] Chan HS, Dill KA. Phys Today 1993;46(2):24.
[8] Heskins M, Guillet JE. J Macromol Sci—Chem 1968;A2(8):1441.
[9] Li M, Jiang M, Zhang Y, Fang Q. Macromolecules 1997;30:470.
[10] Zhang Y, Li M, Jiang M, Wu C. Macromolecules 1998;31:2527.
[11] Zhou S, Wu C. Chem J Chin Universities 1994;15:1567.
[12] Wu C, Wang X, Gao Y. Acta Polymerica Sinica 1998;3:9.
[13] Yang H, Yan X, Cheng R. J Polym Sci, Polym Phys 2000;38:1188.
[14] Wang X, Qiu X, Wu C. Macromolecules 1998;31:2972.
[15] Wu C, Wang X. Phys Rev Lett 1998;80(18):4092.
[16] Meewes M, Ricka J. Macromolecules 1991;24:5811.
[17] Walter R, Ricka J, Qullet Ch, Nyffenegger R, Binkert Th. Macromolecules 1996;29:4019.
[18] Yang H, Yan X, Cheng R. Macromol Rapid Commun 2002;23:1037.
[19] Zhu H, Wang J. J Nanjing University Chem Technol 1996;18:65.
[20] Zhou S, Fan S, Au-yeung SCF, Wu C. Polymer 1995;36:1341.
[21] Chiantore O, Guaita M, Trossarelli L. Makromol Chem 1979;180:969.
[22] Yan X, Yu X, Cheng R. J Polym Sci, Phys Ed 1998;36:2677.
[23] Wu C. Polymer 1998;39:4609.
[24] Cheng R. Gaofenzi Tongxun 1960;3:163.