¹H NMR study of thermo-induced collapse of polyelectrolyte microgels

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Abstract. Smart polymer gels of microscale size are attracting a lot of attention since their properties, such as fast response to various external stimuli, make them suitable candidates for many potential applications including drug delivery, nanoreactors, or separation techniques. In this research, thermosensitive microgels of poly(*N*-isopropylacrylamide), poly(*N*-vinylcaprolactam), poly(*N*-isopropylacrylamide-*co*-sodium vinylsulfonate) and poly(*N*-vinylcaprolactam-*co*-1-vinylimidazole) were prepared via aqueous free-radical precipitation polymerization. The thermo-induced collapse of the microgels and sub-chain mobility were thoroughly investigated by means of proton nuclear magnetic resonance (¹H NMR) spectroscopy, as well as scanning electron microscopy and dynamic light scattering. It was found that in copolymer microgels a part of the thermosensitive monomer units does not collapse upon heating, and the critical temperature is not affected strongly by the addition of ionogenic groups. That could be explained by non-uniform monomer unit distribution, leading to the appearance of thermosensitive core-charged corona structure of the microgel particle. Core-corona architecture of microgels results in film formation with the ordering of the self-assembly structure.

Keywords: nanomaterials, polymer gels, polyelectrolytes, self-assembly, ¹H NMR

1. Introduction

In recent years, polymer microgels, especially thermo- and pH-sensitive ones, have attracted much attention in the scientific world [1–6]. First of all, this interest is due to the unique properties of these systems with respect to the following points: 1) microgels are able to form stable non-aggregating dispersions of microparticles, each of which, in fact, is a crosslinked single macromolecule, 2) these particles are sufficiently well characterized microscopic objects whose sizes and properties can be controlled by changing the conditions of the external environment.

These properties open up broad prospects for the creation of functional objects and materials, such as superabsorbents, stabilizing surface-active additives, carriers of drugs, photonic crystals, optical sensors [7–12]. The techniques used to synthesize microgels are in most cases relatively simple and can be scaled fairly easily to experimental production, and the resulting objects have narrow size distribution.

Thermo-sensitive microgels are usually developed on the base of polymers exhibiting lower critical solution temperature (LCST) – one of the most studied is poly(*N*-isopropylacrylamide) (PNIPA)

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[13], another example is poly(*N*-vinylcaprolactam) (PVCa) [14].

When comparing the solution properties of PNIPA and PVCa, it is known that aqueous solutions of PNIPA have an LCST of approximately 31 °C, which does not depend on the molar mass of the polymer [15], while the LCST of aqueous solutions of PVCa is above 30 °C and significantly increases with decreasing of PVCa molar mass [16]. According to the phenomenological analysis of their critical miscibility with water, PVCa is a type I polymer [17, 18] and PNIPA is an example of type II polymers [19, 20].

Thermo-sensitivity opens up a unique possibility to synthesize microgels by emulsifier-free heterogeneous precipitation polymerization in water [21–23]. As the polymerization process in this case is carried out at a temperature higher than LCST, the chains will collapse and form precursor particles when they reach a certain critical length. Once the microgels come to a critical size, they are stabilized by the electrostatic stabilization mechanism, which prevents further growth of the particles [8]. The balance between the osmotic pressure and the elasticity of the polymer chains determines the microgel particles size.

The ability to control the environment sensitivity and the distribution of the functional groups by the changes in network structure is a key task for many applications. At the moment, a number of ways to control the internal structure of microgels have been demonstrated [24–29]. One of the easiest ways to govern the temperature and/or pH sensitivity of the microgels is the copolymerization of thermosensitive component with different ionic monomers. In the case of thermo-sensitive macrogels synthesized by radical polymerization under normal conditions, the introduction of charged groups usually shifts its transition (collapse) temperatures to higher values [30]. Copolymerization with carboxylic acids gives the property of pH-sensitivity. Yet, for microgels obtained by precipitation polymerization such behavior is not obvious. Differences in hydrophobicity, copolymerization kinetics, and reactivity could lead to inhomogeneous radial ionic group distributions within the gel particles. A kinetic model for copolymerization of four types of carboxylic acid monomers with *N*-isopropylacrylamide (NIPA) was developed [31]. It was shown that copolymerization at high temperature leads to a multimodal distribution of the –COOH groups and this distribution was experimentally proven by transmission electron microscopy

(TEM) images. However, TEM experiments do not give precise quantitative data about the ionic groups distribution.

Nowadays, proton nuclear magnetic resonance (¹H NMR) spectroscopy method is widely used for investigation of the changes in the chain structure and dynamics during temperature-induced phase separation in polymer solutions and hydrogels [32–34]. The coil-globule transition (collapse in the case of polymer gels) leads to a pronounced decrease of the integral intensity of the polymer groups in the NMR spectra, indicating the formation of more compact structures. It allows estimation of the phase transition temperature T_p (determined as an onset temperature of the collapse) and the fraction of mobile component in polymer network.

In the present work we applied ¹H NMR spectroscopy as an experimental technique to study the collapse of polymer microgels induced by temperature. We estimated the effect of introduction of charged groups on the mobility of polymer chains in thermosensitive microgels of PVCa and PNIPA undergoing collapse and compared the polymer behavior depending on its type (I or II). It was found that the charged groups preferably form the outer layer of the microgel particle, when the core consists mainly of thermosensitive polymer and determines the collapse conditions of the whole microgel. Our results and analysis might help to clarify the distribution of the charged groups in the interior of the microgel particles and to understand how subchain conformations change with temperature.

2. Experimental part

2.1. Materials

N-vinylcaprolactam (VCa, Sigma-Aldrich, USA) was purified by distillation under vacuum. Monomers *N*-isopropylacrylamide (NIPA, Wako, Japan), sodium vinylsulfonate (VSA, TCI, Japan), 1-Vinylimidazole (VIm, TCI, Japan), cross-linker *N,N'*-methylenebisacrylamide (BIS, Fluka, Switzerland), initiators 2,2'-azobis(2-methylpropionamide) dihydrochloride (AMPA, Wako, Japan), potassium persulfate (PS, Wako, Japan), and D₂O (99,9%, Sigma-Aldrich, USA) were all used as received. Water was purified using a Milli-Q system (Millipore, USA).

2.2. Microgel synthesis

Thermosensitive microgels were synthesized by free-radical thermo-initiated precipitation polymerization

in water in the presence of BIS crosslinker (see Table 1 for details). Polymerizations were conducted in two-necked round bottom flask equipped with a magnetic stirrer; the temperature control was carried out using a thermocouple. One neck of the flask with a reflux condenser was connected to the source of nitrogen. The second neck of the flask was used for introduction of the reaction components, and was sealed with a glass stopper. Monomers and cross-linker were dissolved in water and stirred (800 rpm) at 70 °C for 60 minutes under a nitrogen flow to allow full dilution and oxygen removal. Then the aqueous initiator solution was added under continuous stirring: AMPA was used as the initiator for VCa-based microgels, and PS was used for NIPA-based microgels. All polymerization reactions were carried out for 24 hours under continuous nitrogen flow at 70 °C and 800 rpm mixing. Stable microgel dispersions were obtained, allowed to cool, and were purified by dialysis (20 000 Da molecular weight cut-off, for 7 days). Further, the microgel solutions were kept at 5 °C. The relative amount of charged units in the reaction mixtures was: VIm to VCa – 5 mol%, VSA to NIPA – 5 and 10 mol%, corresponding microgel samples will be referred to in the text as P(VCa-VIm), P(NIPA-VSA₅), and P(NIPA-VSA₁₀). The conversion for all the samples was determined gravimetrically by lyophilization drying, and was estimated to be nearly 100% (see Table 1). The content of ionisable groups in synthesized microgels was estimated by elemental analysis. The obtained data allow to conclude that it is very close to the initial reagents content (about 4.8% of VSA for P(NIPA-VSA₅), 9.5% of VSA for P(NIPA-VSA₁₀) and 4.7 of VIm for P(VCa-VIm)).

2.3. Scanning electron microscopy

Images of single microgel particles were obtained using Hitachi S-4800 field emission scanning electron

microscope (SEM) with transmitted electrons detector (STEM) at variable acceleration voltage of 5–30 kV (Hitachi, Japan). Diluted microgel dispersions were placed onto carbon grids (Gilder Grid, USA). The grids were kept for at least 24 hours in a vacuum oven at room temperature and were taken out immediately before the investigation.

2.4. Particle size measurement

Measurements of particle size changes due to the volume phase transition were conducted by dynamic light scattering (DLS). A Delsa Nano C (Beckman Coulter, USA) particle size analyzer was used for the measurements, and the CONTIN statistical method was used for calculations. The temperature was controlled up to ± 0.2 °C. The microgel dispersions were diluted in water before the measurements to avoid interactions.

2.5. Nuclear magnetic resonance experiments

¹H NMR spectra were obtained at different temperatures using an AL300BX spectrometer (JEOL, Japan) operating at 300.4 MHz. Samples for ¹H NMR were prepared as follows: 4 mL of the microgel dispersion were centrifuged for 10 minutes at 14 000 rpm, then the supernatant was removed and the precipitate was lyophilized for 24 hours. Dried microgels were dispersed in D₂O (concentration of microgels – 5%) and placed in NMR tubes.

3. Results and discussion

Microgels on the base of two types of thermo-sensitive polymers – *N*-isopropylacrylamide and *N*-vinylcaprolactam – were synthesized using free-radical thermo-initiated precipitation polymerization (reaction scheme is presented on the Figure 1, see Experimental part for details). Two different series of samples were obtained: (i) microgels based on homopolymers of

Table 1. Ingredients used for the synthesis of microgels.

Sample code		PVCL	P(VCa-VIm)	PNIPA	P(NIPA-VSA ₅)	P(NIPA-VSA ₁₀)
Solvent [g]	H ₂ O	100	100	100	100	100
Thermosensitive monomer [g]	NIPA	0	0	1	1	1
	VCa	1	1	0	0	0
Ionic monomer [g]	VSA	0	0	0	0.05	0.1
	VIm	0	0.04	0	0	0
Initiator [g]	PS	0	0	0.07	0.07	0.08
	AMPA	0.06	0.06	0	0	0
Crosslinker [g]	BIS	0.011	0.012	0.013	0.014	0.015
Conversion [%]		98.3	97.5	98.7	98.1	97.6

Figure 1. Reaction scheme of the precipitation polymerization of microgels.

PNIPA and PVCa; (ii) microgels based on NIPA and VCa copolymers containing a certain fraction of the charged groups, PNIPA-*co*-sodium vinylsulfonate (VSA is a strong acidic component: 5 and 10 wt%) and VCa-*co*-*N*-vinylimidazole (VIm is a weak basic component: 5 wt%). All further experiments with PVCa-*co*-VIm microgels were carried out with control of the pH to be 6.0, to be sure that all VIm groups are ionized (pKa value of VIm is around 6.0). DLS analysis of diluted microgel dispersions showed that all synthesized microgels have quite narrow size distribution, are monomodal and exhibit thermosensitive properties, collapsing upon heating. The hydrodynamic diameter of PNIPA-containing microgels at temperature below the LCST is ~ 650 – 750 nm, and increases slightly with the introduction of ionic comonomers. The average diameter of PVCa microgels is

about 500 nanometers, and increases up to 800 nm with the introduction of 5% VIm. Heating of the microgel solutions leads to the collapse of microgels particles: average diameter decreases approximately three times for both PNIPA and PVCa (Figure 2). The systems can undergo several cycles of heating-cooling without precipitation.

For PNIPA-*co*-VSA microgel samples, it should be noted that the introduction of ionic units does not drastically influence the transition temperature for microgels – it could be estimated as $33 \pm (1-2)^{\circ}\text{C}$ even for 10 wt% of VSA units, which is close to PNIPA LCST. However, in case of usual macrogels of the same composition, the introduction of 5 wt% VSA charged groups leads to the increase of the collapse temperature up to 40°C , while the introduction of 10 wt% of VSA groups shifts the collapse

Figure 2. The temperature dependence of hydrodynamic diameter of the microgels in water solution as obtained by DLS: a) NIPA-based, b) VCa-based at pH = 6.

temperature even up to 49 °C [35]. Such behavior of independence of the transition temperature for PNIPA-*co*-VSA microgels on the content of ionic groups could be due to the core-shell structure of the microgels. In the structure, the core consists mainly of thermosensitive units, while ionic groups are mostly located at the exterior of the particle. Based on the modeling of the thermo-induced precipitation copolymerization process [31, 36], differences in hydrophobicity, copolymerization kinetics, and monomers reactivity could lead to inhomogeneous distributions of radial ionic groups within the polymer globule or gel particles. In this case, the collapse of the whole particle should be governed by the collapse of the microgel core consisting only of the thermosensitive homopolymer. Similar behavior is observed for PVCa-*co*-VIm microgels. The introduction of 5% of VIm groups only leads to the shift of transition temperature by 3 °C. The transition temperature interval is much wider in case of PVCa-based microgels, which is characteristic for polymers of type I, and that makes it more difficult to determine the exact transition temperature. For macrogels of PVCa, the introduction of charged units results in quite significant changes in collapse temperature [37].

For better understanding of this phenomenon, ¹H NMR spectroscopy method was applied to study the dynamics of the collapse, which may provide an in-depth analysis of the microgel polymeric subchain conformation at different temperatures.

All samples were gradually heated to the temperatures above LCST, and likewise cooled down to the initial temperature. NMR spectra were measured upon reaching equilibrium at each temperature.

For the numerical analysis of the process of conformational transition, the fraction of collapsed polymer units as a function of temperature was introduced $f(T)$, as shown by Equation (1):

$$f(T) = 1 - \frac{I(T)}{I_0(T_0)} \quad (1)$$

where $I_0(T_0)$ and $I(T)$ are integral intensities of the selected polymer resonances at an initial temperature T_0 (usually several degrees below the estimated phase separation temperature) and at a temperature $T > T_0$, respectively. In the calculations we took into account that, in accordance with the Boltzmann equation, the integrated intensity decreases with the increase of the absolute temperature as $1/T$ [38, 39]. The calculation of integral intensities was carried out using peaks corresponding to the temperature-sensitive polymers.

Fraction $f(T)$ characterizes the amount of polymer subchains that have lost their mobility due to the transition to the collapsed state, (i.e. $f = 1$ when all chains are in collapsed state).

Figure 3a shows temperature dependence of the fraction $f(T)$ for PNIPA and PNIPA-*co*-VSA5 microgels. Figure 3b corresponds to PVCa and P(VCa-VIm) microgels. Fraction $f(T)$ of all samples increases drastically with heating, which indicates the collapse of the hydrogel subchains. $f(T)$ is equal to 1 at 50 °C for the samples based on thermosensitive homopolymers PNIPA and PVCa. This means that all subchains have restricted mobility due to the more compact arrangement in collapsed state. However, the $f(T)$ fraction of all copolymer samples containing ionogenic groups does not reach the value of 1 both

Figure 3. Temperature dependence of phase-separated fraction $f(T)$ for microgels based on: (a) PNIPA, (b) P(VCa).

for PNIPA and PVCA based microgels (0.9 for the P(VCa-VIm) and 0.91 for P(NIPA-VSA₅)), even when they are heated to temperatures well above the LCST of homopolymers or collapse transition temperatures for whole microgel particles. These results indicate that some part of microgels subchains does not lose its mobility under poor solvent conditions (Figure 4). This allows concluding that these subchains are enriched by exceeding amount of charged monomer units in comparison with others. This observation is in accordance with the assumption of inhomogeneous radial ionic groups distributions within gel particles, especially for P(NIPA-co-VSA).

It is interesting to note that the comparison of $f(T)$ fraction for PNIPA- and PVCA-based microgels shows that the $f(T)$ curve is much steeper for PNIPA samples. Consequently, the subchains mobility in PNIPA microgels drastically changes in a very short temperature interval - about 1–2 °C, whereas the subchains mobility in PVCA microgels varies in a wider temperature interval, ~10 °C. Introduction of VIm units expands this interval even more. This observation is in accordance with data demonstrated by Meeusen *et al.* [17] since PVCA aqueous solutions show a type I LCST behavior PVCA hydrogels shows a continuous temperature induced swelling to shrinking transition in contrast to PNIPA – II type LCST behavior polymer [40].

Let's compare the phase separation temperatures T_p of the microgels. P(NIPA-VSA₅) microgels (Figure 3) subchains show coil-globule transition around 32.7 °C, which is only 0.4 °C higher in comparison

with LCST for homopolymer PNIPA (32.3 °C). It could be possible only when the core of the gel particle consisted of NIPA homopolymer and with addition of approximately less than 1% of ionogenic groups, leaving most of charged units to the corona. For PVCA-based microgels, the effect is similar, but not so clear due to much wider transition region.

Likewise, $f(T)$ fraction curves were measured while heating and cooling down. It was found that they match with a high degree of accuracy and do not form any hysteresis loop. Two cycles of heating-cooling were conducted for PNIPA-based microgels, and the curves for the 1st and 2nd cycle do not differ (Figure 3a, triangle and square symbols), indicating full reversibility of thermo-induced conformational transition of subchains. In our previous works [41, 42], it was found that the collapse of thermosensitive polyelectrolyte macrogels is not reversible: the samples do not restore their volume after collapse due to the formation of ion pairs in collapsed gel. In this case, the collapse of the microgels is most probably determined by the behavior of the NIPA-enriched core and, accordingly, the mechanism is close to collapse of homo PNIPA, which transition is reversible.

4. Conclusions

In summary, we may conclude that copolymerization of thermosensitive and ionogenic comonomers in the course of precipitation polymerization results in formation of a microgel particle with a thermosensitive core and a charged corona for both investigated pairs of monomers.

Such core-corona disposition makes charged groups more accessible for modification or interaction in external environment, and is useful for a variety of applications. As an example, we investigated the influence of ionogenic groups on the self-assembly of the particles on the surface. We distributed the microgels as a layer on the carbon substrate and observed it by scanning electron transmission microscopy (Figure 5). It was found that the presence or absence of charged units may affect the arrangement of the microparticles on the substrate. Neutral PVCA and weakly charged P(VCa-VIm) microparticles are located on the substrate randomly, the distances between the particles are inconsistent, while charged P(NIPA-VSA₅) are arranged on a substrate with higher order. With the increase of ionic sulfonate groups amount in P(NIPA-VSA₁₀), the ordering structure is reminiscent of a honeycomb hexagonal structure. Such

Figure 4. Scheme of the dependence of $f(T)$ fraction on the microgel structure.

Figure 5. The self-assembly of the microgel particles on surface as observed by STEM. a) PVCa Neutral, b) P(VCa-VIm) 5 wt% of weakly charged units, c) P(NIPAAm-VSA_{5%}) 5 wt% of charged units, d) P(NIPAAm-VSA_{10%}) 10 wt% charged units.

ordering of the microspheres is due to the repulsion from the similarly charged surfaces of the microgels. Self-arrangement can be exploited in different applications, such as microstructured films and optical devices, for example, as films with antibiofouling properties[43].

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References

- [1] Plamper F. A., Richtering W.: Functional microgels and microgel systems. *Accounts of Chemical Research*, **50**, 131–140 (2017).
<https://doi.org/10.1021/acs.accounts.6b00544>
- [2] Hamzah Y. B., Hashim S., Rahman W. A. W. A.: Synthesis of polymeric nano/microgels: A review. *Journal of Polymer Research*, **24**, 134/1–134/19 (2017).
<https://doi.org/10.1007/s10965-017-1281-9>
- [3] Farooqi Z. H., Khan S. R., Begum R.: Temperature-responsive hybrid microgels for catalytic applications: A review. *Materials Science and Technology*, **33**, 129–137 (2017).
<https://doi.org/10.1080/02670836.2016.1170396>
- [4] Wedel B., Hertle Y., Wrede O., Bookhold J., Hellweg T.: Smart homopolymer microgels: Influence of the monomer structure on the particle properties. *Polymers*, **8**, 162/1–162/21 (2016).
<https://doi.org/10.3390/polym8040162>
- [5] Ballauff M., Lu Y.: ‘Smart’ nanoparticles: Preparation, characterization and applications. *Polymer*, **48**, 1815–1823 (2007).
<https://doi.org/10.1016/j.polymer.2007.02.004>
- [6] Kozhunova E., Ji Q., Hill J. P., Ariga K.: Hollow capsules fabricated by template polymerization of *N*-vinylcaprolactam. *Journal of Nanoscience and Nanotechnology*, **15**, 2389–2393 (2015).
<https://doi.org/10.1166/jnn.2015.9701>
- [7] Oh J. K., Drumright R., Siegwart D. J., Matyjaszewski K.: The development of microgels/nanogels for drug delivery applications. *Progress in Polymer Science*, **33**, 448–477 (2008).
<https://doi.org/10.1016/J.PROGPOLYMSCI.2008.01.002>
- [8] Pich A., Richtering W.: Polymer nanogels and microgels. *Polymer Science: A Comprehensive Reference*, **6**, 309–350 (2012).
<https://doi.org/10.1016/B978-0-444-53349-4.00167-9>
- [9] Richtering W., Potemkin I. I., Rudov A. A., Sellge G., Trautwein C.: Could multiresponsive hollow shell-shell nanocontainers offer an improved strategy for drug delivery? *Nanomedicine*, **11**, 2879–2883 (2016).
<https://doi.org/10.2217/nnm-2016-0327>

- [10] Lohaus T., de Wit P., Kather M., Menne D., Benes N. E., Pich A., Wessling M.: Tunable permeability and selectivity: Heatable inorganic porous hollow fiber membrane with a thermo-responsive microgel coating. *Journal of Membrane Science*, **539**, 451–457 (2017).
<https://doi.org/10.1016/j.memsci.2017.05.052>
- [11] Mohanty P. S., Nöjd S., van Gruijthuijsen K., Crassous J. J., Obiols-Rabasa M., Schweins R., Stradner A., Schurtenberger P.: Interpenetration of polymeric microgels at ultrahigh densities. *Scientific Reports*, **7**, 1487/1–1487/12 (2017).
<https://doi.org/10.1038/s41598-017-01471-3>
- [12] Pacholski C.: Two-dimensional arrays of poly(*N*-isopropylacrylamide) microspheres: Formation, characterization and application. *Zeitschrift für Physikalische Chemie*, **229**, 283–300 (2015).
<https://doi.org/10.1515/zpch-2014-0605>
- [13] Beltran S., Baker J. P., Hooper H. H., Blanch H. W., Prausnitz J. M.: Swelling equilibria for weakly ionizable, temperature-sensitive hydrogels. *Macromolecules*, **24**, 549–551 (1991).
<https://doi.org/10.1021/ma00002a032>
- [14] Kirsh Y. E., Yanul N. A., Popkov Y. M.: Temperature behavior of thermo-responsive poly-*N*-vinylcaprolactam and poly-*N*-isopropylmethacrylamide in aqueous solutions involving organic solutes. *European Polymer Journal*, **38**, 403–406 (2002).
[https://doi.org/10.1016/S0014-3057\(00\)00219-6](https://doi.org/10.1016/S0014-3057(00)00219-6)
- [15] Schild H. G.: Poly(*N*-isopropylacrylamide): Experiment, theory and application. *Progress in Polymer Science*, **17**, 163–249 (1992).
[https://doi.org/10.1016/0079-6700\(92\)90023-R](https://doi.org/10.1016/0079-6700(92)90023-R)
- [16] Kirsh Y. E.: Water-soluble poly-*N*-vinylamides: Synthesis and physicochemical properties. Wiley, New York (1998).
- [17] Meeussen F., Nies E., Berghmans H., Verbrugghe S., Goethals E., du Prez F.: Phase behaviour of poly(*N*-vinyl caprolactam) in water. *Polymer*, **41**, 8597–8602 (2000).
[https://doi.org/10.1016/S0032-3861\(00\)00255-X](https://doi.org/10.1016/S0032-3861(00)00255-X)
- [18] van Durme K., Verbrugghe S., du Prez F. E., van Mele B.: Influence of poly(ethylene oxide) grafts on kinetics of LCST behavior in aqueous poly(*N*-vinylcaprolactam) Solutions and networks studied by modulated temperature DSC. *Macromolecules*, **37**, 1054–1061 (2004).
<https://doi.org/10.1021/ma035319t>
- [19] Afroze F., Nies E., Berghmans H.: Phase transitions in the system poly(*N*-isopropylacrylamide)/water and swelling behaviour of the corresponding networks. *Journal of Molecular Structure*, **554**, 55–68 (2000).
[https://doi.org/10.1016/S0022-2860\(00\)00559-7](https://doi.org/10.1016/S0022-2860(00)00559-7)
- [20] van Durme K., van Assche G., van Mele B.: Kinetics of demixing and remixing in poly(*N*-isopropylacrylamide)/water studied by modulated temperature DSC. *Macromolecules*, **37**, 9596–9605 (2004).
<https://doi.org/10.1021/ma048472b>
- [21] Hazot P., Chapel J. P., Pichot C., Elaissari A., Delair T.: Preparation of poly(*N*-ethyl methacrylamide) particles via an emulsion/precipitation process: The role of the crosslinker. *Journal of Polymer Science Part A: Polymer Chemistry*, **40**, 1808–1817 (2002).
<https://doi.org/10.1002/pola.10259>
- [22] Hoare T., Pelton R.: Functional group distributions in carboxylic acid containing poly(*N*-isopropylacrylamide) microgels. *Langmuir*, **20**, 2123–2133 (2004).
<https://doi.org/10.1021/la0351562>
- [23] Berndt I., Pedersen J. S., Lindner P., Richtering W.: Influence of shell thickness and cross-link density on the structure of temperature-sensitive poly-*N*-isopropylacrylamide–poly-*N*-isopropylmethacrylamide core–shell microgels investigated by small-angle neutron scattering. *Langmuir*, **22**, 459–468 (2006).
<https://doi.org/10.1021/la052463u>
- [24] Boyko V., Pich A., Lu Y., Richter S., Arndt K-F., Adler H-J. P.: Thermo-sensitive poly(*N*-vinylcaprolactam-co-acetoacetoxyethyl methacrylate) microgels: 1 – Synthesis and characterization. *Polymer*, **44**, 7821–7827 (2003).
<https://doi.org/10.1016/j.polymer.2003.09.037>
- [25] Berndt I., Richtering W., Kiel D.: Doubly temperature sensitive core–shell microgels. *Macromolecules*, **36**, 8780–8785 (2003).
<https://doi.org/10.1021/ma034771+>
- [26] Maccarrone S., Ghavami A., Holderer O., Scherzinger C., Lindner P., Richtering W., Winkler R. G.: Dynamic structure factor of core–shell microgels: A neutron scattering and mesoscale hydrodynamic simulation study. *Macromolecules*, **49**, 3608–3618 (2016).
<https://doi.org/10.1021/acs.macromol.6b00232>
- [27] Schmid A. J., Dubbert J., Rudov A. A., Pedersen J. S., Lindner P., Karg M., Potemkin I. I., Richtering W.: Multi-shell hollow nanogels with responsive shell permeability. *Scientific Reports*, **6**, 22736/1–22736/13 (2016).
<https://doi.org/10.1038/srep22736>
- [28] Rizzi L. G., Levin Y.: Influence of network topology on the swelling of polyelectrolyte nanogels. *The Journal of Chemical Physics*, **144**, 114903/1–114903/5 (2016).
<https://doi.org/10.1063/1.4943981>
- [29] Schroeder R., Rudov A. A., Lyon L. A., Richtering W., Pich A., Potemkin I. I.: Electrostatic interactions and osmotic pressure of counterions control the pH-dependent swelling and collapse of polyampholyte microgels with random distribution of ionizable groups. *Macromolecules*, **48**, 5914–5927 (2015).
<https://doi.org/10.1021/acs.macromol.5b01305>
- [30] Kawasaki H., Sasaki S., Maeda H.: Effect of pH on the volume phase transition of copolymer gels of *n*-isopropylacrylamide and sodium acrylate. *The Journal of Physical Chemistry B*, **101**, 5089–5093 (1997).
<https://doi.org/10.1021/jp962809x>
- [31] Hoare T., McLean D.: Kinetic prediction of functional group distributions in thermosensitive microgels. *Journal of Physical Chemistry B*, **110**, 20327–20336 (2006).
<https://doi.org/10.1021/jp0643451>

- [32] Hanyková L., Spěvák J., Ilavský M.: ^1H NMR study of thermotropic phase transition of linear and cross-linked poly(vinyl methyl ether) in D_2O . *Polymer*, **42**, 8607–8612 (2001).
[https://doi.org/10.1016/S0032-3861\(01\)00381-0](https://doi.org/10.1016/S0032-3861(01)00381-0)
- [33] Spěvák J., Hanyková L., Starovoytova L.: ^1H NMR relaxation study of thermotropic phase transition in poly(vinyl methyl ether)/ D_2O solutions. *Macromolecules*, **37**, 7710–7718 (2004).
<https://doi.org/10.1021/ma0486647>
- [34] Spěvák J., Hanyková L., Labuta J.: Behavior of water during temperature-induced phase separation in poly(vinyl methyl ether) aqueous solutions. NMR and optical microscopy study. *Macromolecules*, **44**, 2149–2153 (2011).
<https://doi.org/10.1021/ma200010h>
- [35] Kozhunova E. Y., Makhaeva E. E., Grinberg N. V., Burova T. V., Grinberg V. Y., Khokhlov A. R.: Collapse of hydrogels based on copolymers of *N*-isopropylacrylamide and sodium vinylsulfonate. *Moscow University Physics Bulletin*, **67**, 372–376 (2012).
<https://doi.org/10.3103/S0027134912040091>
- [36] Komarov P. V., Khalatur P. G., Khokhlov A. R.: Principles of designing nanostructured polymeric catalysts: Mesoscopic simulation. *Doklady Physical Chemistry*, **464**, 222–225 (2015).
<https://doi.org/10.1134/S0012501615090092>
- [37] Okhapkin I. M., Bronstein L. M., Makhaeva E. E., Matveeva V. G., Sulman E. M., Sulman M. G., Khokhlov A. R.: Thermosensitive imidazole-containing polymers as catalysts in hydrolytic decomposition of *p*-nitrophenyl acetate. *Macromolecules*, **37**, 7879–7883 (2004).
<https://doi.org/10.1021/ma0487453>
- [38] Hanyková L., Labuta J., Spěvák J.: NMR study of temperature-induced phase separation and polymer–solvent interactions in poly(vinyl methyl ether)/ D_2O /ethanol solutions. *Polymer*, **47**, 6107–6116 (2006).
<https://doi.org/10.1016/J.POLYMER.2006.06.061>
- [39] Velychkivska N., Bogomolova A., Filippov S. K., Starovoytova L., Labuta J.: Thermodynamic and kinetic analysis of phase separation of temperature-sensitive poly(vinyl methyl ether) in the presence of hydrophobic *tert*-butyl alcohol. *Colloid and Polymer Science*, **295**, 1419–1428 (2017).
<https://doi.org/10.1007/s00396-017-4100-2>
- [40] Tokuhito T., Amiya T., Mamada A., Tanaka T.: NMR study of poly(*N*-isopropylacrylamide) gels near phase transition. *Macromolecules*, **24**, 2936–2943 (1991).
<https://doi.org/10.1021/ma00010a046>
- [41] Kozhunova E. Y., Makhaeva E. E., Khokhlov A. R.: Effect of ionogenic groups on the collapse of thermosensitive gels. *Polymer Science Series A*, **53**, 1135–1140 (2011).
<https://doi.org/10.1134/S0965545X11120078>
- [42] Kozhunova E. Y., Makhaeva E. E., Khokhlov A. R.: Collapse of thermosensitive polyelectrolyte semi-interpenetrating networks. *Polymer*, **53**, 2379–2384 (2012).
<https://doi.org/10.1016/j.polymer.2012.04.001>
- [43] Frueh J., Gai M., Yang Z., He Q.: Influence of polyelectrolyte multilayer coating on the degree and type of biofouling in freshwater environment. *Journal of Nanoscience and Nanotechnology*, **14**, 4341–4350 (2014).
<https://doi.org/10.1166/jnn.2014.8226>