= CHEMISTRY ===

Catalytic Properties of Diblock Copolymers of N-Vinylcaprolactam and N-Vinylimidazole

A. I. Barabanova, I. V. Blagodatskikh, O. V. Vyshivannaya, T. P. Klimova, N. V. Grinberg, T. V. Burova, A. V. Muranov, V. I. Lozinskii, V. Ya. Grinberg, A. S. Peregudov, and Academician A. R. Khokhlov

Received June 23, 2015

Abstract—Thermoresponsive diblock copolymers of *N*-vinylcaprolactam (VCL) with *N*-vinylimidazole (NVI) have been synthesized for the first time through two-stage controlled reversible addition—fragmentation chain transfer (RAFT) polymerization. The resulting diblock copolymers exhibit the same catalytic activity toward *p*-nitrophenyl propionate (NPP) hydrolysis as "protein-like" copolymers of VCL and NVI. The catalytic activity of the diblock copolymers is likely caused by their structure favorable for the manifestation of catalytic properties, namely, by micelle-like chain conformations with a relatively dense core formed by the more hydrophobic PVCL block and a periphery formed by the hydrophilic poly-*N*-vinylimidazole (PNVI).

DOI: 10.1134/S0012500815110014

Our recent theoretical and experimental studies have focused on the computer design [1-3], experimental synthesis, and study of catalytic properties of synthetic protein-like polymers (PPs) [4–6]. In particular, statistical heteroblock VCL-NBI copolymers with the protein-like arrangement of hydrophilic (NVI) and hydrophobic (VCL) units in the polymer chain have been synthesized via radical copolymerization [4-6]. In dilute aqueous solutions at temperatures above the lower critical solution temperature (LCST), PPs undergo the coil-globule transition without phase separation. The thermal response of the copolymers is ensured by the PVCL blocks for which the LCST depends on the chain length, being 32-45°C [7]. The PP globules containing the hydrophobic core and the stabilizing hydrophilic shell are actually nanoreactors with a high concentration of catalytically active NVI groups at the surface, exhibiting the properties of highly selective catalysts of different chemical reactions [5].

Thermoresponsive diblock copolymers of NVI and *N*-isopropylacrylamide (NIPA) also exhibit catalytic activity toward the hydrolysis of *p*-nitrophenyl acetate (NPA) [8]. In an aqueous medium with increasing temperature, the diblock copolymers form micelles, with hydrophobic poly-*N*-isopropylacrylamide blocks located inside and hydrophilic catalytically active NVI

units arranged on the outer side as far as is possible. It is evident that this arrangement should lead to an increase in the local concentration of diphilic NPA molecules near the NVI units and, as a result, to an increase in hydrolysis rate.

This work deals with the synthesis of diblock VCL– NVI copolymers with different lengths of separate blocks and with the study of the effect of the microstructure of these copolymers on their catalytic activity in NPP hydrolysis reactions, as well as with comparison of the catalytic activity of statistical PPs and diblock VCL–NVI copolymers.

In this work, diblock copolymers of VCL with NVI were synthesized for the first time through RAFT polymerization [9]. At the first stage, the PVCL block was obtained through the RAFT polymerization of VCL in bulk at 60°C for 20 h in the presence of azobis-isobutyronitrile (AIBN) ([AIBN] = 1.0×10^{-2} mol/L) as the initiator and (1-(*O*-ethylxanthyl)ethyl)benzene (EXEB) ([EXEB] = 5.6×10^{-2} mol/L) as the low-molecular-weight chain-transfer agent. EXEB was synthesized as described elsewhere [10, 11].

The number-average (M_n) and weight-average (M_w) molecular weights and dispersity (M_w/M_n) of the resulting PVCL with the terminal 1-(*O*-ethylxan-thyl)ethyl group (PVCL-RAFT agent) were determined by gel permeation chromatography (GPC) (table). The M_n for PVCL was also determined by ¹H NMR (table). These results are quite consistent with the available data on the synthesis of PVCL through RAFT polymerization [14].

Nesmeyanov Institute of Organoelement Compounds, Russian Academy of Sciences, ul. Vavilova 28, Moscow, 119991 Russia

e-mail: barabanova@polly.phys.msu.ru

| Sample | 1 H NMR $^{(1)}$ | | GPC ⁽³⁾ | | $T^{(4)} \circ C$ | HS-DSC ⁽⁵⁾ | |
|--------|---------------------------|------------------|---------------------|-----------------------|-------------------|------------------------------|-------------------------------|
| | $M_{\rm n}^{(2)}$, g/mol | VCL : NVI, mol % | $M_{\rm n}$, g/mol | $M_{\rm w}/M_{\rm n}$ | $T_{\rm ls}$, C | $T_{\rm t}, ^{\circ}{\rm C}$ | $\Delta_{\rm t} h, {\rm J/g}$ |
| PVCL | 4100 | 100:0 | 2180 | 1.37 | 46 ± 0.5 | 42.0 | 32.3 |
| CP30 | _ | 70:30 | 2500 | 1.42 | 46 ± 0.5 | — | — |
| CP50 | _ | 50:50 | 3400 | 1.41 | 46 ± 0.5 | 42.6 | 33.8 |
| PNVI | — | 0:100 | 8370 | 1.50 | — | — | — |

Synthesis conditions and characteristics of diblock VCL–NVI copolymers

 $^{(1)}$ ¹H NMR spectra of the copolymers were recorded on a Bruker spectrometer (600 MHz). D₂O was used as a solvent.

⁽²⁾ M_n was determined from the integrated intensity ratio of the signal of the –CH groups of the main PVCL chain at 4.0–4.5 ppm to the signal of the –CH methine group of the VCL unit bonded to the terminal 1-(O-ethylxanthyl)ethyl group at 5.35 ppm. ⁽³⁾ Expression of the vector of the vector of the vector of the terminal 1-(O-ethylxanthyl)ethyl group at 5.35 ppm.

⁽³⁾ Experimental conditions: an Agilent 1200 Series system with a refractive index detector, PLmixC column, elution with 1-methylpyrrolidone, 50°C, flow rate 0.5 mL/min. Calibration was performed using polystyrene standards. ⁽⁴⁾ $T_{\rm Is}$ is the temperature at which the light scattering intensity sharply increases. The experiments were carried out on a PhotoCor Complex

⁽⁴⁾ $T_{\rm Is}$ is the temperature at which the light scattering intensity sharply increases. The experiments were carried out on a PhotoCor Complex spectrometer ($\lambda = 633$ nm). The heating rate was 0.3 K/min. Measurements were taken at 1 K intervals (equilibration time, 5 min; measurement time, 5 min). ⁽⁵⁾ $T_{\rm t}$ is the transition temperature (a maximum of the temperature dependence of the excess heat capacity); $\Delta_t h$ is the enthalpy of transition

⁽³⁾ T_t is the transition temperature (a maximum of the temperature dependence of the excess heat capacity); $\Delta_t h$ is the enthalpy of transition (related to the weight of VCL units in the sample); solvent, water; polymer concentration, 6 mg/mL. Measurements were performed with a DASM-4 (Biopribor, Pushchino) differential adiabatic scanning calorimeter in the temperature range 10–110°C at an excess pressure of 0.25 MPa and a heating rate of 1 K/min. Data were collected using the COMPORT software (Institute of Organoelement Compounds, RAS).

At the second stage, diblock copolymers were synthesized via RAFT polymerization of NVI in dimethylformamide in the presence of AIBN and the PVCL– RAFT agent. The polymerization was carried out under the following conditions: [NVI] = 1.8 mol/L, [AIBN] = $2.3 \times 10^{-3} \text{ mol/L}$, [PVCL] = 1.8×10^{-2} (base mol)/L, 60 and 80° C, and 24 h. The composition of copolymers was determined using ¹H NMR (table). The synthesized polymers were diblock copolymers with the same molecular weight of the PVCL block containing 30 (CP30) and 50 mol % (CP50) of NVI units in the polymer chain.

The synthesized diblock NVI–VCL copolymers are characterized by unimodal molecular weight distribution curves (Fig. 1, curves 2 and 3). The shift of the molecular weight distribution curves of CP30 and



Fig. 1. Molecular weight distribution curves of (1) PVCL, (2) CP30, and (3) CP50.

CP50 toward higher molecular weights as compared with PVCL and close-to-unity M_w/M_n values (table) points to the controlled ("living") character of the polymerization reaction.

The catalytic activity of CP30 and CP50 was studied for the NPP hydrolysis reaction as an example in the temperature range 25-55°C at pH 7.0 and was compared with the catalytic activity of PNVI. The hydrolysis kinetics was studied by measuring the optical density of a colored product, *p*-nitrophenol (408 nm), at different temperatures as a function of time. Figure 2 shows the temperature dependence of the hydrolysis rate (V) of NPP in the presence of PNVI, CP30, and CP50 in the Arrhenius coordinates. As temperature increases from 25 to 60°C, the reaction rate in the presence of PNVI additions linearly increases (Fig. 2, curve 1). Another situation is observed for the substrate hydrolysis in the presence of copolymers (Fig. 2, curves 2 and 3). The dependence of $\ln V$ on 1/T is nonlinear: in the temperature range from 40 to 55° C, the reaction rate increases faster than in the temperature range from 25 to 40°C. Figure 2 also demonstrates that, even at low temperatures (25–40°C), the diblock copolymers exhibit somewhat higher catalytic activity than PNVI and that the larger the number of NVI units in the copolymer, the higher the catalytic activity. A similar behavior has been observed for the NPA hydrolysis in the presence of diblock copolymers of NIPA with NVI [8].

We compared the catalytic activity of CP50 with the available results of studying the catalytic activity of PPs composed of VCL and NVI [5]. In [5], it has been shown that the NPP hydrolysis rate in the presence of VCL–NVI PPs (the PP concentration was

254



Fig. 2. NPP hydrolysis rate (V) ([NPP] = 0.4 μ mol/mL) vs. 1/*T* at pH 7.0 in a 0.05 M K₂H₂PO₄/Na₂HPO₄ solution in the presence of (*1*) PNVI, (*2*) CP30, and (*3*) CP50. The concentration of NVI units in PNVI and copolymers is 2.4 μ mol/mL.

 $0.5 \,\mu$ mol/mL as calculated for the NVI content) increases fivefold with increasing temperature from 25 to 50°C at pH 7.3. Roughly under the same conditions (pH 7.0), the hydrolysis rate in the presence of CP50 increases 5.2 times with increasing temperature from 25 to 50°C. Thus, the diblock copolymers exhibit the same catalytic activity as PPs.

To find a correlation between the catalytic properties of CP30 and CP50 and their ability to change the conformation with increasing temperature, dilute aqueous solutions of copolymers were studied at different temperatures by static and dynamic light scattering methods (SLS–DLS).

The cloud point T_{ls} (table) corresponding to the phase separation of PVCL, CP30, and CP50 solutions was determined by the light scattering method as the temperature at which a sharp increase in the light scattering intensity is observed (Fig. 3).

Figure 4 shows the distribution of the scattered light intensity over the hydrodynamic radius of particles (R_h) in dilute solutions of CP50 at different temperatures. The diblock copolymer at 25°C (Fig. 4, curve *I*) is a molecular solution with $R_h = 2.7 \pm 0.2$ nm. As the temperature approaches T_{ls} in the range 40–45°C, supermolecular micelles of 70–80 nm in size are formed (Fig. 4, curve 2). Thus, the deterioration of solvent quality for the PVCL block with an increase in temperature leads to structural rearrangements in a CP50 solution to form micelles consisting of the more hydrophobic core and the hydrophilic shell of NVI units of the diblock copolymer. At 47°C, a sharp increase in light scattering intensity is observed,



Fig. 3. Intensity of scattered light at an angle of 90° in solutions of (1) PVCL, (2) CP30, and (3) CP50 as a function of temperature.

reflecting the formation of submicron particles (460 nm) of a new phase. The observed phase transition is completely reversible with decreasing temperature. An analogous structural rearrangement is also observed in the CP30 copolymer.

Studying CP50 and PVCL by high-sensitivity differential scanning calorimetry (HS-DSC) has shown that both polymers undergo a phase transition involving separation of the solution into two phases. The enthalpies of phase transitions calculated for the weight of VCL units in these samples are the same (table). It is known that the major contribution to the enthalpy of the transition of PVCL is made by dehy-



Fig. 4. Scattered light intensity distribution over the particle size in aqueous solutions of CP50 at (1) 25, (2) 43, and (3) 47° C at a concentration of 2 mg/mL.

dration of its chains accompanying the formation of the concentrated phase. The above results indicate that the hydrate structure of PVCL persists in CP50; i.e., the hydrophilic block of the copolymer behaves autonomously and does not disturb the cooperativity of dehydration of PVCL blocks of the copolymer on heating. This result confirms the block structure of the synthesized copolymer.

Thus, the HS-DSC data are consistent with SLS– DLS evidence.

Comparison of temperature dependences of hydrolysis reaction rate and the results of studying the structure of solutions of diblock copolymers allows us to assume that their catalytic activity toward hydrolysis at temperatures close to the $T_{\rm is}$ of the copolymer is caused by its structure favorable for the manifestation of catalytic properties, namely, by micelle-like conformations of chains with a relatively dense core formed by the more hydrophobic PVCL block and a periphery consisting of the hydrophilic PNVI block. It has been shown that conformational changes in the PVCL block at temperatures preceding $T_{\rm is}$ and formation of core—shell micelles favor the enhancement of the catalytic activity, and it can be regulated by changing temperature.

ACKNOWLEDGMENTS

This work was supported by the Russian Science Foundation (project no. 14-13-00544).

REFERENCES

- 1. Khokhlov, A.R. and Khalatur, P.G., *Physica A*, 1998, vol. 249, pp. 253–261.
- 2. Khokhlov, A.R. and Khalatur, P.G., *Phys. Rev. Lett.*, 1999, vol. 82, pp. 3456–3460.
- 3. Khokhlov, A.R. and Khalatur, P.G., *Adv. Polym. Sci.*, 2006, vol. 195, pp. 1–100.
- Lozinskii, V.I., Simenel, I.A., Kurskaya, E.A., Kulakova, V.K., Grinberg, V.Ya., Dubovik, A.S., Galaev, I.Yu., Mattiasson, B., and Khokhlov, A.R., *Dokl. Chem.*, 2000, vol. 375, nos. 4–6, pp. 273–276.
- Lozinskii, V.I., Simenel, I.A., and Khokhlov, A.R., *Dokl. Chem.*, 2006, vol. 410, nos. 4–6, pp. 170–173.
- Lozinsky, V.I., Simenel, I.A., Kulakova, V.K., et al., *Macromolecules*, 2003, vol. 36, pp. 7308–7323.
- Kirsh, Yu.E., *Polivinilpirrolidon i drugie polivinilamidy* (Polyvinylpyrrolidone and Other Polyvinylamides), Moscow: Nauka, 1998.
- Ge, Z.S., Xie, D., Chen, D.Y., Jiang, X.Z., Zhang, Y.F., Liu, H.W., and Liu, S.Y., *Macromolecules*, 2007, vol. 40, pp. 3538–3546.
- Rizzardo, E., Chiefari, J., Mayadunne, R.T.A., Moad, G., and Thang, S.H., ACS Symp. Ser., 2000, vol. 768, pp. 278–296.
- 10. Wan, D.C., Satoh, K., Kamigaito, M., and Okamoto, Y., *Macromolecules*, 2005, vol. 38, pp. 10397–10405.
- 11. Charmot, D., Copart, P., Michelet, D., Zard, S., and Biadatti, T., US Patent 6153705, 2000.
- 12. Balke, S.T., Hamielec, A.E., LeClair, B.P., and Pearce, S.L., *Ind. Eng. Chem.*, *Prod. Res. Dev.*, 1969. vol. 8, pp. 54–57.
- 13. Wan, D., Zhou, Q., Pu, H., and Yang, G., *J. Polym. Sci. Part A: Polym. Chem.*, 2008, vol. 46, pp. 3756–3765.

Translated by G. Kirakosyan