Electronic Supplementary Material (ESI) for ChemComm. This journal is © The Royal Society of Chemistry 2014

Supporting Information

Nanoparticle-to-vesicle and nanoparticle-to-toroid transitions of pH-sensitive ABC triblock copolymer by in-to-out switch

Xin Xiao, Shangjin He, Meihan Dan, Fei Huo, and Wangqing Zhang

Key Laboratory of Functional Polymer Materials of the Ministry of Education, Synergetic Innovation Center of Chemical Science and Engineering (Tianjin), Institute of Polymer Chemistry, Nankai University, Tianjin 300071, China.

1 Experimental

1.1 Materials

N,*N*-dimethylacrylamide (DMA, 99.5%, Alfa) and styrene (St, >98%, Tianjin Chemical Company) were distilled under reduced pressure prior to use. *N*-(4-vinylbenzyl)-*N*,*N*-dibutylamine (VBA, Scheme S1) was synthesized by the nucleophilic substitution reaction of chloromethylstyrne (CMS) with the secondary amine of *N*-dibutylamine (DBA) as described previously (J. Xu, G. Chen, R. Yan, D. Wang, M. Zhang, W. Zhang, P. Sun, *Macromolecules*, **2011**, *44*, 3730-3738). The RAFT agent of S-1-dodecyl-S'-(α , α '-dimethyl- α ''-acetic acid) trithiocarbonate (DDMAT, Scheme S1) was synthesized as discussed elsewhere (J. T. Lai, D. Filla, R. Shea, *Macromolecules*, **2002**, *35*, 6754-6756). The initiator of 2,2'-azobis (2-methylpropionitrile) (AIBN, >99%, Tianjin Chemical Company) was purified by crystallization from ethanol. The initiator of 4'-azobis (4-cyanovaleric acid) (V-501, >98%, Aldrich) and other reagents were analytic grade and were used as received.



Scheme S1. The chemical structure of VBA and DDMAT.

1.2 Synthesis of the PDMA₃₈-TTC macro-RAFT agent

$$M_{\rm n,th} = \frac{[\text{monomer}]_0 \times M_{\rm monomer}}{[\text{RAFT}]_0} \times conversion + M_{\rm RAFT}$$
(S1)



Scheme S2. Synthesis of the PDMA-TTC macro-RAFT agent, the PDMA-*b*-PS-TTC seed-nanoparticles, and the PDMA-*b*-PS-*b*-PVBA triblock copolymer corona-shell-core nanoparticles.

The PDMA₃₈-TTC macro-RAFT agent was synthesized via RAFT polymerization of DMA in 1,4-dioxane using DDMAT as RAFT agent and V-501 as initiator as shown in Scheme S2. Into a 100 mL Schlenk flask with a magnetic bar, DMA (6.00 g, 0.061 mol), DDMAT (0.526 g, 1.44 mmol), V-501 (40.4 mg, 0.144 mmol), and 1,4-dioxane (24.0 g) were added. The solution was initially degassed with nitrogen at 0 °C for 30 min, and then the flask was immersed into a preheated oil bath at 70 °C for 75 min. The polymerization was quenched by rapid cooling upon immersion of the flask into iced water. To collect the polymer, the flask content was precipitated into cold diethyl ether, collected by three precipitation/filtration cycles, and then dried at room temperature under vacuum to afford a pale yellow power of PDMA₃₈-TTC. Characterizations of PDMA₃₈-TTC: the theoretical molecular weight $M_{n,th} = 4.0$ kg/mol calculated by eq S1, the molecular weight determined by ¹H NMR analysis $M_{n,NMR} = 4.0$

Entry	Polymer	[M] ₀ /RAFT/I	Reaction time	Conv (%)	M _{n,th} (kg/mol)
1	PDMA ₃₈ -TTC	420/10/1	75 min	90	4.0
2	PDMA ₃₈ - <i>b</i> -PS ₁₆₇ -TTC	577/3/1	18 h	87	21.3
3	PDMA ₃₈ - <i>b</i> -PS ₁₆₇ - <i>b</i> -PVBA ₁₉	60/3/1	20 h	93	26.2
4	PDMA ₃₈ -b-PS ₁₆₇ -b-PVBA ₃₇	123/3/1	20 h	91	30.6
5	PDMA ₃₈ -b-PS ₁₆₇ -b-PVBA ₇₆	246/3/1	20 h	93	40.2
6	PDMA ₃₈ - <i>b</i> -PS ₁₆₇ - <i>b</i> -PVBA ₁₁₄	366/3/1	20 h	92	49.1

Table S1. Polymerization conditions for the synthesis of the polymers.

1.3 Synthesis of the PDMA₃₈-b-PS₁₆₇-TTC seed-nanoparticles

The seed-nanoparticles of the PDMA₃₈-*b*-PS₁₆₇-TTC diblock copolymers were prepared by the PDMA₃₈-TTC macro-RAFT agent mediated dispersion polymerization of styrene as shown in Scheme S2 as discussed elsewhere (Y. Su, X. Xiao, S. Li, M. Dan, X. Wang, W. Zhang, *Polym. Chem.*, **2014**, *5*, 578-587). Into a 250 mL Schlenk flask, the synthesized PDMA₃₈-TTC (1.50 g, 0.375 mmol), St (7.50 g, 72.1 mmol) and the ethanol/water mixture (51.0 g, 8/2 by weight) containing the initiator of AIBN (20.5 mg, 0.125 mmol) were added. The flask content was degassed with nitrogen at 0 °C for 30 min. The polymerization was started by immersing the flask into a preheated oil bath at 70 °C for 18 h. The polymerization was quenched by immersing the flask into iced water. The monomer conversion was detected by UV-vis analysis as discussed elsewhere (X. Xiao, S. He, M. Dan, Y. Su, F. Huo, W. Zhang, *J. Polym. Sci. Part A: Polym. Chem.*, **2013**, *51*, 3177-3190). The resultant dispersion was dialyzed against the ethanol/water mixture (8/2 by weight) for three days to afford the stock dispersion of the PDMA₃₈-*b*-PS₁₆₇-TTC nanoparticles with the diblock copolymer concentration at 14.0 wt%. To collect the polymer for the GPC analysis and ¹H NMR analysis, a given volume of the colloidal dispersion (4 mL) was separated by centrifugation (12500 rpm, 15 min), washed twice with ethanol, and finally dried

at room temperature under vacuum to afford the diblock copolymer in pale yellow. Characterizations of PDMA₃₈-*b*-PS₁₆₇-TTC: $M_{n,th} = 21.6$ kg/mol, $M_{n,NMR} = 21.5$ kg/mol, $M_{n,GPC} = 18.6$ kg/mol, PDI = 1.12. In the subsequent discussion, the synthesized diblock copolymer is labeled as PDMA₃₈-*b*-PS₁₆₇-TTC, in which the polymerization degree (DP) of the PDMA and PS blocks is calculated by the monomer conversion.

1.4 The preparation of PDMA-*b*-PS-*b*-PVBA triblock copolymer nanoparticles through seeded dispersion RAFT polymerization

The PDMA-b-PS-b-PVBA triblock copolymer nanoparticles were synthesized by the seeded dispersion RAFT polymerization of VBA in the ethanol/water mixture (8/2 by weight) under $[VBA]_0$: [seed-nanoparticles of PDMA₃₈-*b*-PS₁₆₇-TTC]_0: [AIBN]_0 = 366~60:3:1 and with a constant solid concentration at 15 wt% as shown in Scheme S2. In a typical seeded dispersion polymerization to prepare the PDMA₃₈-*b*-PS₁₆₇-*b*-PVBA₇₆ triblock copolymer nanoparticles, the colloidal dispersion of the PDMA₃₈-b-PS₁₆₇-TTC seed-nanoparticles (4.57 g, containing 0.63 g or 0.029 mmol of PDMA₃₈-b-PS₁₆₇-TTC), VBA (0.573 g, 2.34 mmol), AIBN (1.57 mg, 0.0095 mmol), and the ethanol/water mixture (2.87 g, 8/2 by weight) were added into a 25 mL Schlenk flask with a magnetic bar. The flask content was degassed with nitrogen at 0 °C for 30 min. The polymerization was started by immersing the flask into a preheated oil bath at 70 °C, and was quenched after 20 h. The resultant colloidal dispersion of the synthesized PDMA-b-PS-b-PVBA triblock copolymer nanoparticles was dialyzed against the ethanol/water mixture (8/2 by weight) for three days to remove the residual monomer to afford the 15 wt% stock colloidal dispersion. To collect the triblock copolymer for the gel permeation chromatography (GPC) analysis, ¹H NMR analysis and differential scanning calorimeter (DSC) analysis, the synthesized PDMA-b-PS-b-PVBA triblock copolymer nanoparticles were separated by centrifugation of the colloidal dispersion (12500 rpm, 30 min), washed twice with ethanol, and finally dried at room temperature under vacuum to afford the triblock copolymer in pale yellow.

1.5 pH-Induced morphology transition of the PDMA-b-PS-b-PVBA triblock copolymer

nanoparticles

Into the 3.0 wt% dispersion of the PDMA-*b*-PS-*b*-PVBA nanoparticles in the ethanol/water mixture with the weight ratio of ethanol/water at 2/8, 4/6, 6/4, and 8/2 (5.0 mL, containing about 0.109 ~ 0.346 mmol of the VBA unit), a given volume of HCl aqueous solution (0.5 ~ 1.25 mL, pH = 0.5, containing about 0.159 ~ 0.396 mmol of HCl) was added (Note: the pH \approx 2 of the colloidal dispersion in the ethanol/water mixture was approximately measured by was a PHSJ-4A portable pH Meter). After acidification at room temperature (~ 25 ⁰C) for three days, the colloidal dispersion was dialyzed against water for three days.

1.6 Instruments

The ¹H NMR analyses were performed on a Bruker Avance III 400MHz NMR spectrometer using CDCl₃ or D₂O as solvent. The molecular weight and its distribution or the polydispersity index (PDI) of the synthesized polymers were determined by GPC analysis on a Waters 600E GPC system, where THF was used as eluent and the near-monodisperse polystyrene was used as calibration standard. Transmission electron microscopy (TEM) observation was performed using a Tecnai G² F20 electron microscope at an acceleration of 200 kV. The DSC analysis was performed on a NETZSCH DSC 204 differential scanning calorimeter under dry nitrogen atmosphere at the heating/cooling rate of 10 °C/min. The Zeta-potential measurements were conducted using a Nano-ZS90 (Malvern) Zetasizer instrument. The UV-vis analysis of the monomer conversion was performed on a Varian 100 UV-vis spectrophotometer. A FEI Nanosem 430 scanning electron microscope (SEM) and a Bruker MultiMode atomic force microscope (AFM) in the tapping mode were used to check the toroid morphology of the PDMA-*b*-PS-*b*-PVBA nanoparticles.

2 Characterizations



Figure S1. TEM image of the seed-nanoparticles of the PDMA₃₈-*b*-PS₁₆₇-TTC diblock copolymer.



Figure S2. GPC traces of the synthesized polymers.



Figure S3. ¹H NMR spectra of PDMA₃₈-TTC (A), PDMA₃₈-b-PS₁₆₇-TTC (B) and PDMA₃₈-b-PS₁₆₇-b-PVBA₇₆ (C) in CDCl₃.



Figure S4. (A) DSC thermograms of PDMA₃₈-*b*-PS₁₆₇-*b*-PVBA₇₆ and the reference polymers of PS₁₈₆-TTC, PDMA₃₈-TTC, PVBA₅₄-TTC, and PDMA₃₈-*b*-PS₁₆₇-TTC, and (B) the curves of first-order derivative of PDMA₃₈-*b*-PS₁₆₇-*b*-PVBA₇₆.



Figure S5. TEM (A), SEM (B) and AFM (C) images of the PDMA₃₈-*b*-PS₁₆₇-*b*-PVBA₁₁₄ nano-objects after acidification in the 8/2 ethanol/water mixture.



Figure S6. Zeta potential of the PDMA₃₈-*b*-PS₁₆₇-*b*-PVBA₇₆ nano-objects: (I) before acidification and (II) after acidification in the 8/2 ethanol/water mixture. Insets: the schematic structure of the triblock copolymer nano-objects.



Figure S7. (A) ¹H NMR spectra of the PDMA₃₈-*b*-PS₁₆₇-*b*-PVBA₃₇ nano-objects in D₂O, and (B) the normalized intensity of the signal corresponding to the PVBA₃₇ block under conditions (I) before acidification and (II) after acidification in the 8/2 ethanol/water mixture.



Figure S8. TEM images, schematic structure and zeta potential of the PDMA₃₈-*b*-PS₁₆₇-*b*-PVBA₇₆ triblock copolymer nano-objects before acidification (A) and after acidification in the 0/10 (1, B), 2/8 (2, C), 4/6 (3, D), 6/4 (4, E) and 8/2 (5, F) ethanol/water mixtures.



Figure S9. (A) ¹H NMR spectra of the PDMA₃₈-*b*-PS₁₆₇-*b*-PVBA₇₆ triblock copolymer nano-objects dispersed in D₂O, in which the nano-objects are prepared before (A-I) and after acidification in the 0/10

(A-II), 2/8 (A-III), 4/6 (A-IV) 6/4 (A-V) and 8/2 (A-VI) ethanol/water mixtures, and (B) the summary of the normalized intensity of the signal at $\delta = 0.76$ ppm corresponding to the PVBA₇₆ block.

3 Equation

out - emigrated PVBH chains percent (%) =
$$\frac{I_c}{I_a} \div \frac{6DP_{PVBA}}{6DP_{PDMA}}$$

= $\frac{I_{0.76}}{I_{3.5-2.4}-2/3 \times I_{0.76}} \div \frac{6DP_{PVBA}}{6DP_{PDMA}}$
= $\frac{3I_{0.76}}{3I_{3.5-2.4}-2I_{0.76}} \times \frac{DP_{PDMA}}{DP_{PVBA}}$ (S2)