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

Supporting Information

CO_2- and Temperature-Switchable “Schizophrenic” Block Copolymer: from Vesicles to Micelles

Anchao Feng, Chengbo Zhan, Qiang Yan, Bowen Liu, Jinying Yuan*
Key Lab of Organic Optoelectronic & Molecular Engineering of Ministry of Education,
Department of Chemistry, Tsinghua University, Beijing, 100084, China
Corresponding Author Email: yuanjy@mail.tsinghua.edu.cn

1. Materials

N-isopropylacrylamide (NIPAM, Acros, 98.5%) was recrystallized twice from toluene and hexane (1:3). N,N-diethylaminoethyl methacrylate (DEAEMA, Acros, 98%) was passed through basic alumina column and distilled in vacuo from CaH_2 and then stored at -20 °C before use. Dodecylthiol (Acros, 99%), carbon disulfide (Acros, 99%) and 2, 2-Azobis (isobutyronitrile) (AIBN, Alfa Aesar, 98%) were used as received. 2-dodecylsulfanylthiocarbonylsulfanyl-2-methyl propionic acid (DMP) was synthesized according to reference.[1] Methylene dichloride, methanol, ethanol, acetone, acetonitrile, tetrahydrofuran, N, N-dimethylformamide (DMF), and 1,4-dioxane were received from Beijing Chemical Reagent Co. Ltd (China) and purified before use. Distilled water was utilized throughout the studies.

2. Instruments and Measurements

Nuclear Magnetic Resonance Spectroscopy (NMR). ^1H NMR spectra for the polymer structural analysis were obtained from a JEOL JNM-ECA300 (300MHz) and a JEOL JNM-ECA600 (600MHz) spectrometer.

Fourier Transform Infrared Spectroscopy (FT-IR). The absorption spectra of all products were recorded on an AVATAR 360 ESP FT-IR spectrometer and the results were collected at 30 scans with a spectral resolution of 1 cm^{-1}.

Gel Permeation Chromatography (GPC). GPC analyses of polymers were performed using N, N-dimethyl formamide (DMF) as the eluent. The GPC system was a Shimadzu LC-20AD pump system, a MZ-Gel SDplus 10.0 μm guard column (50 × 8.0 mm, 10^2 Å) followed by a MZ -Gel SDplus 5.0 μm bead-size column (50 – 10^6 Å, linear) and a Shimadzu RID-10A refractive index detector. The system was calibrated with narrow molecular weight distribution polystyrene standards ranging from 200 to 10^6 $g \cdot mol^{-1}$.

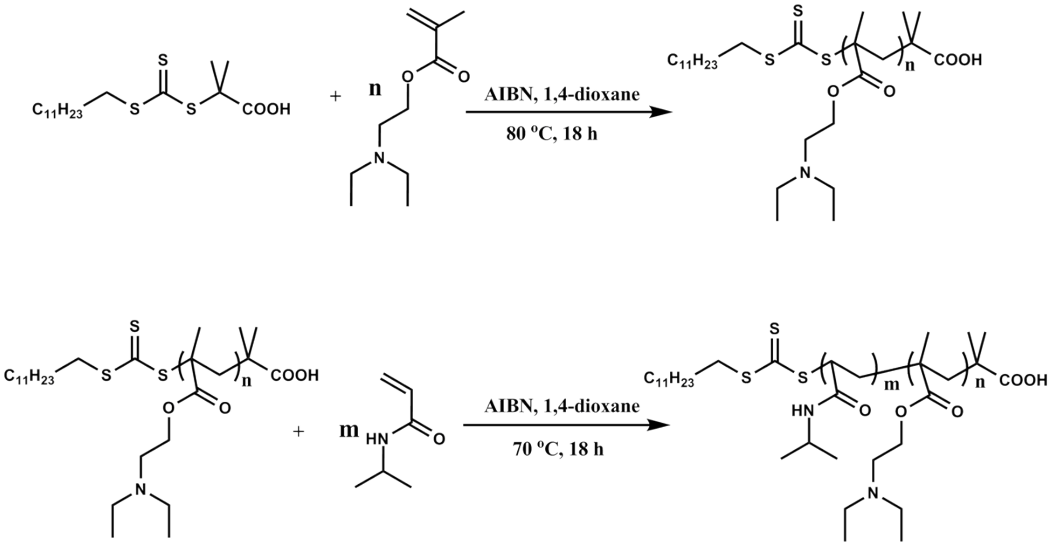
Transmission electron microscopy (TEM). The visualized images of the assemblies were obtained from a JEM-2010 Microscope with an accelerating voltage of 120 kV and H-7650B microscope with an accelerating voltage of 80 kV. The samples were prepared by drop-coating the aqueous solution on a carbon-coated copper grid and staining with 0.1% phosphotungstic acid hydrate.

Dynamic Light Scattering (DLS). The average radius and size distribution of the aggregates was analyzed by a Malvern 3000HS Zetasizer using a monochromatic coherent He–Ne laser (633 nm) as the light source and a detector that detected the scattered light at an angle of 90º.

Fluorescence Spectroscopy (FS). Fluorescence was measured with a Hitachi F-7000 spectrofluorometer.

Injection of CO_2. In all experiments, the flow rate of CO_2 injected into a given solution of 15 mL was about 1 mL/ s.

3. Synthetic Procedures



Scheme S1. Synthetic route for the diblock copolymer poly[N, N-diethylaminoethyl methacrylate)-block- (N-isopropylacrylamide)] PDEAEMA-*b*-PNIPAM) via sequential RAFT protocol.

Synthesis of poly (N, N-diethylaminoethyl methacrylate) RAFT macromolecular initiator

The typical reaction was as follows: a solution of DMP (91.16 mg, 0.25 mmol), AIBN (4.1 mg, 0.025mmol) and DEAEMA (3.70 g, 20 mmol) in 3 mL of 1,4-dioxane was added to a 25 mL round bottom flask. The flask was carefully degassed by three freeze-pump-thaw cycles and then sealed under vacuum. After thermo-stating at 70 °C for 18 h, the reaction tube was quenched into liquid nitrogen, opened, and diluted with 1,4-dioxane. The product was purified by dialysis against water (pH 4.5) for 3 days followed by lyophilization, yielding 2.55 g product (conversion: 69 %). In ^{1}H NMR spectrum, the signal at 3.35 ppm originated from the 2 protons of the methylene adjacent to the -S-C(S)-S- segment was used to determine the M_n values of PDEAEMA block. $M_{n,\ \mathrm{NMR}}$ = 11500 g/mol, $M_{n,\ \mathrm{GPC}}$ = 12800 g/mol, M_w/M_n = 1.14. ^{1}H NMR ($CDCl_3$, 300 MHz) (Fig. S1): δ_H (ppm) = 3.97 (s, -$COO\mathbf{CH_2}CH_2$-), 2.64 (s, -$COOCH_2\mathbf{CH_2}$-), 2.55 (s, -$N\mathbf{CH_2}CH_3$), 2.02 – 1.58 (m, -$\mathbf{CH_2}C(CH_3)_2COOH$).

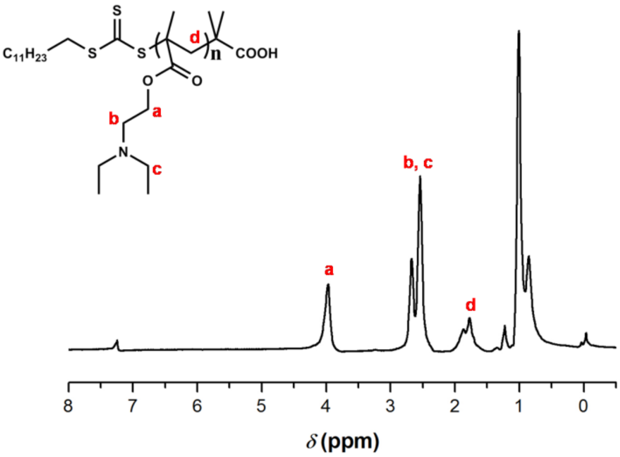


Fig. S1 ^{1}H NMR spectrum of poly (N, N-diethylaminoethyl methacrylate) RAFT macromolecular initiator.

Synthesis of diblock polymer of poly[(N, N-diethylaminoethyl methacrylate)-block- (N-isopropylacrylamide)]

The above PDEAEMA-CTA macro-initiator was chain extended with NIPAM to yield diblock copolymers following a similar procedure. For example, NIPAM (0.45 g, 4 mmol), PDMAEMA-CTA (0.3 g, 0.05 mmol), and AIBN (3.28 mg, 0.02 mmol) were dissolved in 4 mL of 1, 4-dioxane and added to a 25 mL round-bottom flask. After thermo-stating at 70 °C for 18 h, the reaction tube was quenched into liquid nitrogen and exposed to air. Powdery solid was obtained after precipitated into 200 mL of cold hexane for three times. The product was collected and dried in vacuum oven at 25 °C for 24 h, yielding 0.51 g product (conversion: 48 % of NIPAM). Block copolymer compositions were determined by calculating the integral ratio of the characteristic signals between PDEAEMA and PNIPAM block in ^{1}H NMR spectrum. $M_{n,NMR}$ = 15900 g/mol, $M_{n,GPC}$ = 18100 g/mol, M_w/M_n = 1.25. ^{1}H NMR ($CDCl_3$, 300 MHz) (Fig. S2): δ_H (ppm) = 3.97 (s, -COOC$\mathbf{H_2}$CH_2- and –NHC$\mathbf{H}$(CH_3)$_2$), 2.64 (s, -COOCH_2C$\mathbf{H_2}$-), 2.55 (s, -NC$\mathbf{H_2}$CH_3), 1.97 – 1.61 (m, -C$\mathbf{H_2}$C(CH_3)$_2$COOH), 1.60 – 1.48 (m, -COCHC$\mathbf{H_2}$-).

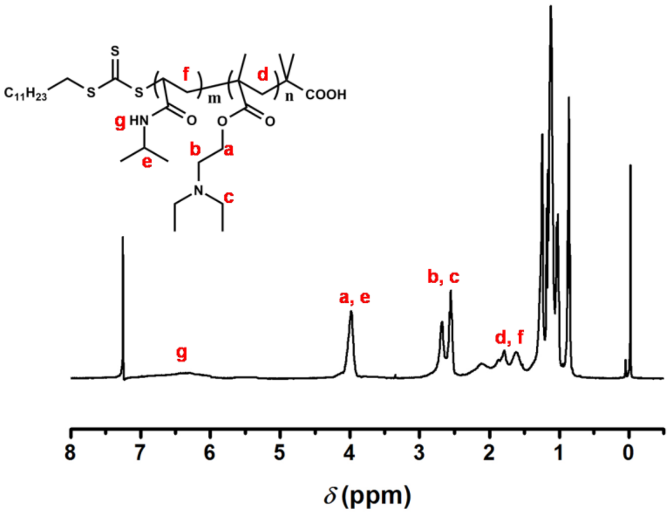


Fig. S2 ^{1}H NMR spectrum of diblock polymer of poly [(N, N-diethylaminoethyl methacrylate)-block- (N-isopropylacrylamide)].

Synthesis of homopolymer poly (N-isopropylacrylamide)

The typical reaction was as follows: a solution of DMP (72.80 mg, 0.2 mmol), AIBN (3.28 mg, 0.02 mmol) and NIPAM (1.13 g, 10 mmol) in 3 mL of 1,4-dioxane was added to a 25 mL round bottom flask. The flask was carefully degassed by three freeze-pump-thaw cycles and then sealed under vacuum. After thermo-stating at 70 °C for 10 h, the resulting solution was immersed to liquid nitrogen in order to stop the radical polymerization. Powdery solid was obtained after precipitated into 200 mL of cold diethyl ether for three times. The product was collected and dried in vacuum oven at 25 °C for 24 h, yielding 0.76 g product (conversion: 67%). Similarly, the signal at 3.4 ppm originated from the 2 protons of the methylene adjacent to the -S-C(S)-S- segment in ^{1}H NMR spectrum was used to determine the M_n values of PNIPAM block. $M_{n,NMR}$ = 5160 g/mol, $M_{n,GPC}$ = 5820 g/mol, M_w/M_n = 1.16. ^{1}H NMR ($CDCl_3$, 300 MHz) (Fig. S3): δ_H (ppm) = 3.96 (s, -NHC$\mathbf{H}$(CH_3)$_2$), 2.08 (s, -COC$\mathbf{H}$CH_2-), 1.74 (s, -COCHC$\mathbf{H_2}$-), 1.06 (s, -NHCH(C$\mathbf{H_3}$)$_2$).

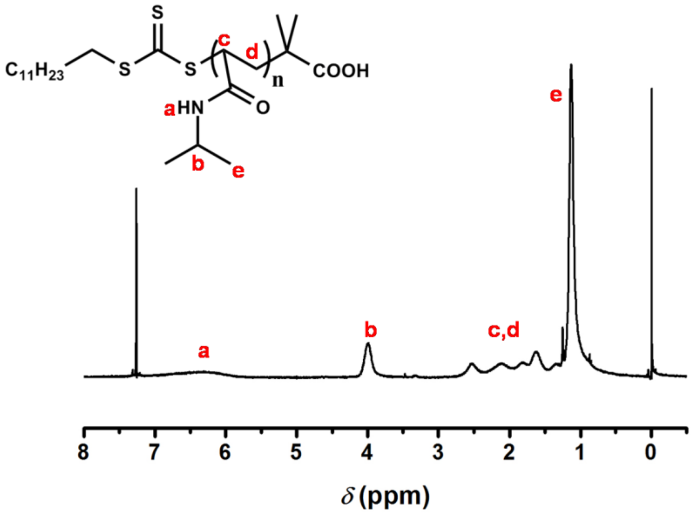


Fig. S3 ^{1}H NMR spectrum of homopolymer poly (N-isopropylacrylamide).

4. The Critical Aggregation Concentration (CAC) of the PDEAEMA-b-PNIPAM in Aqueous Media.

The critical aggregate concentration (CAC) of PDEAEMA-*b*-PNIPAM was measured by the fluorescent probe method, using pyrene as a probe molecule. Aqueous solutions of PDEAEMA-*b*-PNIPAM assemblies at different concentrations were prepared, as well as a 5 mg/mL pyrene solution in acetone. To each of the aqueous solutions of PDEAEMA-*b*-PNIPAM assemblies (2 mL), 20 μL stock solution of pyrene was added. The solutions were sonication for 5 min before fluorescent emission measurements. For each spectrum obtained, the intensity ratio of the first and third peaks, I_1/I_3 was calculated. The CAC was chosen as the concentration at which I_1/I_3 began to drop, indicating that the aggregation of the copolymer occurred. The results show that the CAC was about 0.02 mg/mL (Fig. S4).

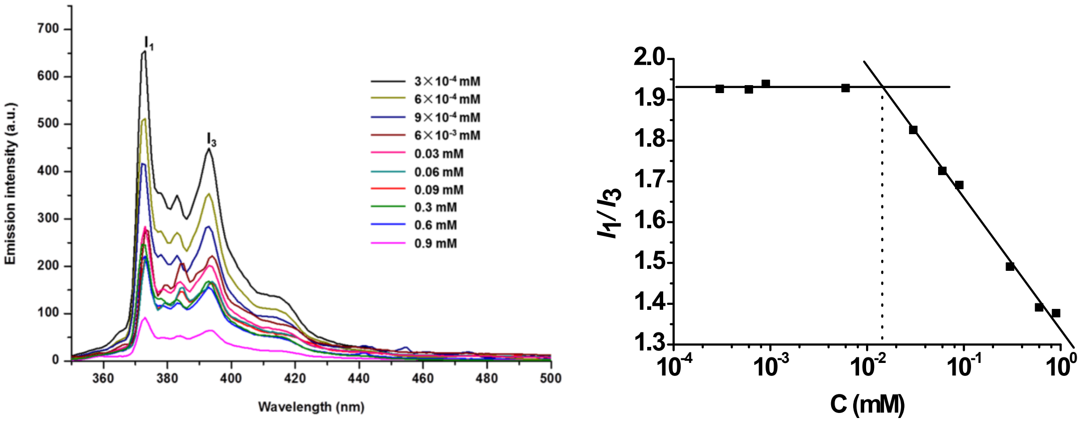


Fig. S4 Determination of CAC for the block copolymer PDEAEMA-*b*-PNIPAM using the fluorescent method with pyrene as a probe.

5. CO_2 and Temperature Controlled Reversible Morphology Transition

In the initial state, the hydrodynamic radius, R_h, of the PDEAEMA-*b*-PNIPAM vesicles is 105.2 nm monitored by dynamic light scattering (DLS). When CO_2 was passed through the copolymer solution at a rate of 1.0 mL/min for 5 min, the average radius of system get down to 10 nm and almost cannot be obtained. To exert a cycle of heating and cooling stimuli to the solution system, we can observe a jumped average radius from 10 nm to 74.2 nm. Then when we exerted N_2 to the solution of room temperature at a rate of 1.0 mL/min for 20 min, the size of the polymersomes restored back to 105 nm. In addition, this process can be reversible and repeatable at least 3 times under an alternating CO_2/N_2 and heating/cooling stimulation, as shown in Fig. S5.

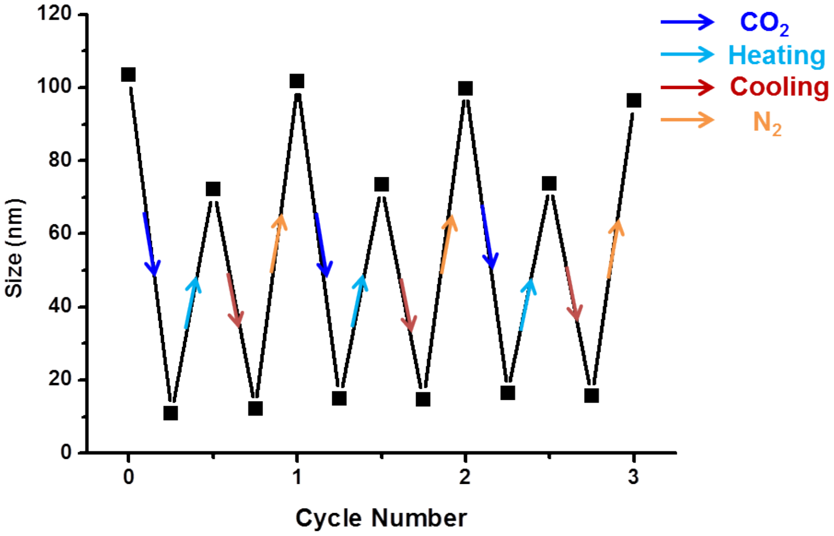


Fig. S5 The size change of the PDEAEMA-*b*-PNIPAM system upon an alternating CO_2/N_2 and heating/cooling stimulation.

Notes and references

1 a) J. Lai, D. Filla and R. Shea, *Macromolecules*, 2002, **35**, 6754. b) A. Feng, Q. Yan, H. Zhang, L. Peng and J. Yuan, Chem. Commun., 2014, **50**, 4740.