Solvent Replacement to Thermo-Responsive Nanoparticles from Long-Subchain Hyperbranched PSt Grafted with PNIPAM for Encapsulation

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ABSTRACT: Long-subchain hyperbranched polystyrene (lsc-hp PSt) with uniform subchain length was obtained through copper-catalyzed azide-alkyne cycloaddition click chemistry from seesaw macromonomer of PSt having one alkynyl group anchored at the chain centre and two azido group attached to both chain ends [alkynyl-(PSt-N_3)$_2$]. After precipitation fraction, different portions of lsc-hp PSt having narrow overall molecular weight distribution were obtained for further grafting with alkynyl-capped poly(*N*-isopropylacrylamide) (alkynyl-PNIPAM), which was obtained via single-electron transfer living radical polymerization of NIPAM with propargyl 2-bromoisobutyrate as the initiator and grafted onto the peripheral azido groups of lsc-hp PSt via click chemistry. Thus, amphiphilic lsc-hp PSt grafted with PNIPAM chains (lsc-hp PSt-*g*-PNIPAM) was obtained and would have star-like conformation in tetrahydrofuran (THF). By replacing THF with water, lsc-hp PSt-*g*-PNIPAM was dissolved at molecular level in aqueous solution due to the hydrophilicity of PNIPAM and exhibited thermal induced shrinkage of PNIPAM arms. The water-insoluble lsc-hp PSt would collapse densely and could be served as a reservoir to absorb hydrophobic chemicals in aqueous solution. The influence of overall molecular weight of lsc-hp PSt on the absorption of pyrene was studied. © 2013 Wiley Periodicals, Inc. J. Polym. Sci., Part A: Polym. Chem. **2013**, *51*, 2142–2149

KEYWORDS: amphiphilic copolymers; hyperbranched; hyperbranched polymers; nanocarrier; nanoparticles; star polymers; star-like polymer; stimuli-sensitive polymers; thermal response; vesicles

INTRODUCTION Amphiphilic star-like copolymer, composed of a solvent-dislike branched polymer core and solvent-like linear polymer arms, has received much research attention due to its unique spatial shape, lower viscosity, single-molecular micellization in selective solvent and possible applications in encapsulation of active substances.[1–4]

Hyperbranched and dendritic polymers are mostly used as the core of star-like copolymers.[1,2] They have special physical and chemical properties because of their highly branched architecture and the high numbers of functional end groups,[1] and can be applied as coatings and resin additives,[5] viscosity modifiers,[6] and nano-sized carriers.[7] To improve the performances of hyperbranched/dendritic polymers, grafting linear polymeric chains onto the end groups has been investigated.[1–4,7–12] The obtained star-like copolymers have the combined architectures of both star polymers and hyperbranched/dendritic polymers. As well, if a star-like copolymer is made of hydrophobic hyperbranched/dendritic core and hydrophilic grafting chains, it will have core-shell morphology[1,2,7,8] and some special behaviors can be observed, like single-molecular micellization and supermolecular self-assembly.[8,11–13]

With the improvement of living radical polymerization technique, a variety of macromolecules with hyperbranched/dendritic structure could be synthesize by different facile approaches.[14–19] Single-electron transfer living radical polymerization (SET-LRP) is highly efficient to synthesize hyperbranched/dendritic polymers with well-defined structure and high molecular weight,[14,20–24] by the combination with TERminator Multifunctional INItiator (TERMINI) or thiobromo click methods.[14–19] However, hyperbranched/dendritic polymers used in the related literatures are mainly those prepared from small molecules and the core size is limited.

Long-subchain hyperbranched (lsc-hb) polymers[25–27] have been frequently used as star-like copolymers.[28–32] In 2002, Dworak et al. synthesized star-like copolymers with a hyperbranched poly[*p*- (chloromethyl)styrene] core and poly(ethylene oxide) (PEO) arms by the core-first approach. The hyperbranched core was synthesized by *p*- (chloromethyl)styrene via atom transfer radical polymerization (ATRP), and the PEO arms was grafted onto the core via Williamson reaction.[28] After that, Kali et al. synthesized star-like copolymers with a hyperbranched polystyrene (PSt) core and polyisobutylene (PIB) arms by arm-first approach.[29] Recently, Zhang

et al. have synthesized different star-like copolymers through self-condensing vinyl polymerization based on reversible addition fragmentation transfer (RAFT) polymerization and the second RAFT polymerization of other monomers.[32] However, the subchain length of hyperbranched cores above are not uniform, leading to the difficulty in the investigation of structure-property correlation. Hence, star-like copolymers with the defined structures of both hyperbrached core polymer and linear grafting polymer should be synthesized.

Thermo-responsive polymers are widely researched and can be used in many fields like drug uploading,[33–41] resulting from their responsiveness in a control and reversible way to the temperature.[33–45] Poly(*N*-isopropylacrylamide) (PNIPAM) is among the most concerning ones.[43–47] Lower critical solution temperature (LCST) of PNIPAM is attributed to the alteration of hydrogen bonding between its amide groups and water.[48–50] Molecular weight of PNIPAM,[51] concentration of PNIPAM aqueous solution,[51] and introduction of other components[52] have the influence on PNIPAM LCST. Up to now, lots copolymers having PNIPAM segments have been synthesized to study the architecture-dependent thermo-responsive properties.[33–38,40,42–43,45,51–60] As for those containing PSt and PNIPAM, block copolymers,[43,53–54,57] graft copolymers,[58,59] and PSt colloid particles grafted with PNIPAM[45,56,60] were studied. Since PNIPAM segments above are blocked on its chain end(s), the thermo-responsive behavior is different from that of PNIPAM homopolymer.

In this work, star-like copolymers with lsc-hb PSt as the core and PNIPAM as the grafting chains were prepared and their thermo-responsive behavior was studied in aqueous solution. As well, the influence of overall molecular weight of lsc-hb PSt on the absorption of pyrene was studied.

EXPERIMENTAL

Materials

N-isopropylacrylamide (NIPAM, 97%, Kohjin Co., Japan) was recrystallized from benzene/hexane (2:1 v/v) prior to use. CuBr (Sinopharm Chemical Reagents Co.) was purified as follows. After crude CuBr was reduced by 0.01 M Na_2SO_3 aqueous solution, the solid was filtered and washed with 1 wt % HBr aqueous solution. Finally, pure CuBr was obtained by washing with acetic acid and alcohol trice. Seesaw macromonomer of PSt having one alkynyl group anchored at the chain centre and two azido group attached to both chain ends [alkynyl-(PSt-N_3)$_2$] with M_n = 8800 and long-subchain hyperbranched PSt (lsc-hp PSt) were synthesized according to our previous literatures.[27] THF was refluxed over CaH_2 for 6 h, dried with sodium/benzophenone, and distilled under reduce pressure before use. *Tris*(2-(dimethylamino) ethyl)amine (Me_6TREN) was synthesized according to the literature.[61] Triethylamine was stirred with KOH for 12 h at room temperature, refluxed with toluene-4-sulfonyl-chloride and distillated before use. Propargyl alcohol (Sinopharm Chemical Reagents Co.), 2-bromoisobutyryl bromide (Sigma-Aldrich), *N*,*N*,*N*′,*N*″,*N*″-pentamethyldiethylenetriamine (Sigma-Aldrich), pyrene (Sigma-Aldrich) and other chemical agents (Aladdin) were used as received.

Synthesis of Propargyl 2-Bromoisobutyrate (PBIB)

After propargyl alcohol (2.8 g, 0.05 mol), triethylamine (5.0 g) and CH_2Cl_2 (30 mL) were added into a 250 mL flask, the mixture was kept in ice bath. After that, 2-bromoisobutyryl bromide (11.6 g, 0.05 mol) dissolved in CH_2Cl_2 (20 mL) was charged dropwise. The reaction stood in ice bath for 1 h, and at 25 °C for additional 7 h. Then, the mixture was washed by distillated water (20 mL) trice and the organic layer was dried by anhydrous $MgSO_4$. After the removal of solvent by rotary evaporation, propargyl 2-bromoisobutyrate (PBIB) was obtained by vacuum distillation (yield: 65 %).

^{1}H-NMR (300 MHz, $CDCl_3$), δ (TMS, ppm): 1.95 (s, CH_3, 6H), 2.54 (t, CH, 1H), 4.46 (d, CH_2, 2H).

Synthesis of Alkynyl-PNIPAM

Alkynyl-capped poly(*N*-isopropylacrylamide) (alkynyl-PNIPAM) was prepared through single-electron transfer living radical polymerization (SET-LRP) of NIPAM with propargyl 2-bromoisobutyrate as the initiator. Into a 20 mL dry glass tube with a magnetic stirring bar, PBIB (206 mg, 1 mmol), CuCl (100 mg, 1 mmol), Me_6TREN (950 mg, 0.6 mmol), isopropanol (10 mL), and NIPAM (10.0 g) were added. After mixing thoroughly, the glass tube was degassed by three freeze-vacuum-thaw cycles, and then sealed under vacuum. After polymerization was carried out at 25 °C for 3.5 h, the reaction mixture was taken out of the tube and diluted with THF. The resulting dispersion was passed through a short column of neutral alumina to remove metal salt and crude product was purified by twice THF/ether precipitation. After being dried under vacuum at room temperature overnight, alkynyl-PNIPAM was obtained (yield: 54%). Proton nuclear magnetic resonance (^{1}H NMR) spectroscopy and gel permeation chromatograph (GPC) confirmed the successful synthesis ($M_{n,NMR}$ = 5600, $M_{n,GPC}$ = 5200, M_w/M_n = 1.07).

Preparation of Narrowly Distributed lsc-hp PSt with Peripheral Azido Groups

The fraction of lsc-hp PSt was performed in a thermostatic water bath (±0.2 °C). After lsc-hp PSt (5.0 g) was completely dissolved in toluene (300 mL), methanol was added dropwise until the solution became a little white. Then, the solution temperature was raised to 50 °C so that it turn clear again. The temperature was slightly lowered to allow a small fraction of lsc-hp PSt to precipitate and kept at this temperature for 12 h. The precipitate was collected, filtered and dried under vacuum overnight. The procedure above was repeated to obtain the desired fractions with different overall molecular weight and narrow molecular weight distribution.

Synthesis of lsc-hp PSt Grafted with PNIPAM by Click Chemistry

Into a 10 mL dry glass tube with a magnetic stirring bar, narrowly distributed lsc-hp PSt (100 mg), CuBr (33 mg, 0.02 mmol), PMDETA (34 mg, 0.02 mmol), THF (2 mL), and alkynyl-PNIPAM (100 mg) were added. After thorough mixing, the glass tube was degassed by three freeze-vacuum-thaw cycles, and then sealed under vacuum. The sealed tube was immersed into a water bath at 40 °C. After polymerization stood for 24 h, the tube was rapidly cooled to 0 °C. The

polymer solution was dialyzed at room temperature against distillated water for 2 days using dialysis tube with cutoff molecular weight of 8000 to 14,000 g/mol. After vacuum lyophilization and further dryness under vacuum at room temperature overnight, lsc-hp PSt grafted with PNIPAM (lsc-hp PSt-*g*-PNIPAM) was achieved (yield: 90%).

Preparation of lsc-hp PSt-*g*-PNIPAM Micelle Dispersion

Under the room temperature, the deionized water (19.0 mL) was added into the solution of lsc-hp PSt-*g*-PNIPAM (5.0 mg) in THF (1.0 mL) under vigorous stirring by a syringe pump at 0.1 mL/min. The mixture was stirred for another 6 h and dialyzed at room temperature against distillated water for 24 h using dialysis tube with cutoff molecular weight of 8000 to 14,000 g/mol to remove THF. The final concentration of lsc-hp PSt-*g*-PNIPAM micelle dispersion was adjusted to 0.25 mg/mL.

Characterization

^{1}H NMR spectra were recorded on a Bruker DRX-300 NMR (300 MHz) instrument in $CDCl_3$ at room temperature with tetramethylsilane as internal standard. Molecular weight and molecular weight distribution were determined at 30 °C on a Waters 150C GPC equipped with Styragel columns (10^3, 10^4, and 10^5 Å) and a Waters 2414 refractive index detector. THF was used as eluent at a flow rate of 1 mL/min. Narrowly distributed PSt standards were used in the calibration of molecular weight.

Laser Light Scattering (LLS) Study

A commercial spectrometer (ALV/DLS/SLS-5022F) equipped with multi-τ digital time correlation (ALV5000) and a cylindrical 22 mW UNIPHASE He-Ne laser (λ_0= 632 nm) as the light source was used. The incident beam was vertically polarized with respect to the scattering plane. In static LLS (SLS), the angular dependence of the absolute excess time-average scattering intensity can lead to the weight-average molecular weight ($M_{w,SLS}$) and the gyration radius (R_g). The specific refractive index increment (dn/dC) of different polymers was determined by a self-made differential refractometer.[62] In dynamic LLS (DLS), Laplace inversion of each measured intensity-intensity time correlation function $G^{(2)}(q,t)$ in the self-beating mode can lead to a line-width distribution $G(\Gamma)$, where q is the scattering vector. For dilute solutions, Γ is related to the translational diffusion coefficient D by $(\Gamma/q^2)_{q\to0,C\to0} \to D$, so that $G(\Gamma)$ can be converted into a hydrodynamic radius distribution $f(R_h)$ via the Stokes-Einstein equation, $R_h = (k_BT/6\pi\eta_0)/D$, where k_B, T, and η_0 are Boltzmann constant, absolute temperature and solvent viscosity, respectively. The time correlation functions were analyzed by CONTIN analysis.

For the structural characterization of different polymers, the measurements were performed at 25 °C with THF as the solvent. For the study of thermal response, lsc-hp PSt-*g*-PNIPAM aqueous dispersions were tested in the temperature range of 25 to 40 °C. All the LLS measurements were carried out after the temperature reached its equilibrium.

Absorption of Pyrene by lsc-hp PSt-*g*-PNIPAM

Pyrene (20 mg) in acetone (1.0 mL) was added into a 50 mL flask and stood for the complete evaporation of acetone. After that, lsc-hp PSt-*g*-PNIPAM (5.0 mg) micelle dispersion (20.0 mL) was added. The dispersion was kept at room temperature under stirring. After certain durations (2 h, 4 h, 6 h, 8 h, 24 h, and 72 h), the up-layer clear solution (2.0 mL) was took out to determine the amount of pyrene absorbed by lsc-hp PSt-*g*-PNIPAM micelles on a Unico UV/vis 2802PCS spectrophotometer. After each measurement, the taken-out micelle dispersion was put back.

RESULT AND DISCUSSION

Star-like amphphilic copolymers with lsc-hp PSt core and PNIPAM grafting arms were prepared as illustrated in Scheme 1. Due to PNIPAM grafting chains, lsc-hp PSt-*g*-PNIPAM can be molecularly dissolved in water, that is, form single-molecular micelles in aqueous solution. As well, it can exhibit thermal response.

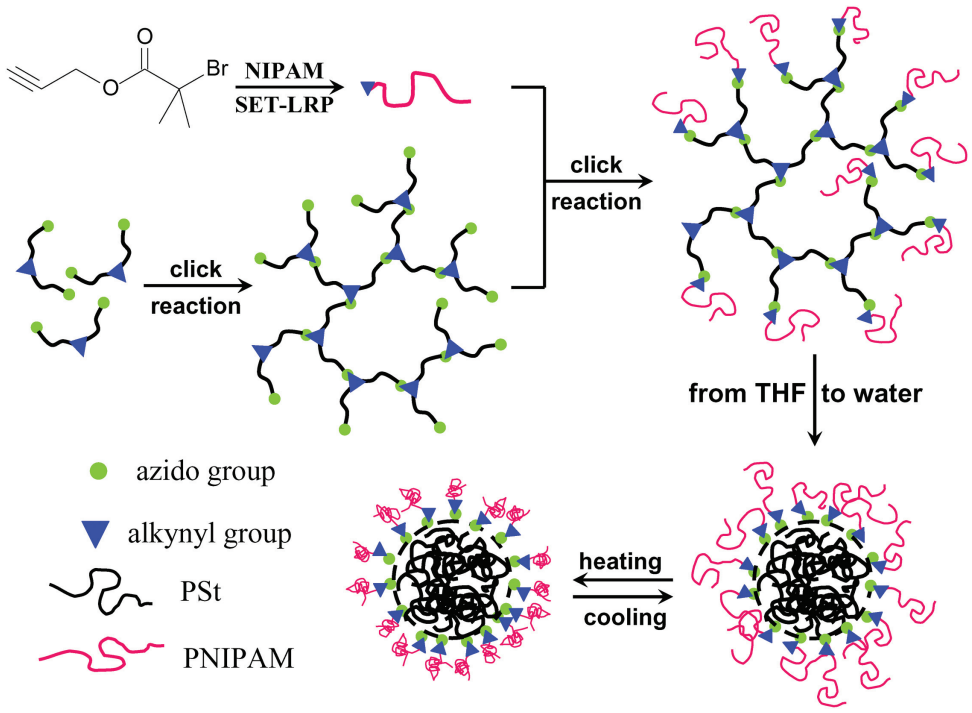
Preparation of Narrowly Distributed lsc-hp PSt with Uniform Subchains

Through click chemistry of seesaw macromonomers, alkynyl-$(PSt\text{-}N_3)_2$, lsc-hp PSt with uniform subchain length was obtained. However, molecular weight distribution of the products is extremely broad, as shown in Figure 1. After the precipitation fraction, the narrowly distributed fractions with different overall molecular weight but uniform subchain length were obtained. GPC diagrams of the first five fractions (Fig. 1) are symmetrically mono-modal and polydispersity index (PDI = M_w/M_n) ranges from 1.20 to 1.30 (Table 1), suggesting that narrowly distributed lsc-hp PSt with uniform subchains has been prepared through precipitation fraction. Thus, Fraction 1 (lsc-hp PSt_{400}) and Fraction 4 (lsc-hp PSt_{150}) were used to graft with alkynyl-PNIPAM through alkynyl-azido click reaction.

Synthesis of lsc-hp PSt Grafted with PNIPAM by Click Chemistry

Alkynyl-PNIPAM arms were separately synthesized through SET-LRP of NIPAM with PBIB as the initiator in the presence of CuCl/Me6-TREN.[63] Figure 2(A) shows the IR spectrum of the PNIPAM arms and their characteristic absorbance of $\upsilon_{C=O}$ at 1653 cm^{-1} is obviously present. Figure 2(B) shows ^{1}H-NMR spectrum of alkynyl-PNIPAM. The signals at 4.01 (f), 2.05 (e), 1.60 (d), and 1.18 (c) ppm can be clearly observed and are characteristic of PNIPAM block. The signal of alkynyl proton (a) is overlapped with those from PNIPAM but the signal (b) of methylene protons from PBIB appears at 4.67 ppm. From the integrate heights of b and c, number-average molecular weight of alkynyl-PNIPAM by NMR ($M_{n,NMR}$) is calculated to be 5600. GPC diagram of alkynyl-PNIPAM suggests narrow distribution (PDI = 1.07) and $M_{n,GPC}$ of 5200.

Grafting alkynyl-PNIPAM onto peripheral azido groups of lsc-hp PSt results in amphiphilic star-like copolymers with long-subchain hyperbranched PSt as core and PNIPAM chains as arms. All the overall molecular weight, subchain length of lsc-hp PSt and PNIPAM arm length are well defined.



SCHEME 1 Synthesis strategy of star-like amphphilic copolymers with lsc-hp PSt core and PNIPAM grafting chains.

Figure 3(A) shows FTIR spectra of lsc-hp PSt-*g*-PNIPAM and its precursors. Before grafting, the spectrum of lsc-hp PSt shows the absorbance signals at 2094 and 756 cm^{-1}, which represent $\upsilon_{N=N=N}$ of the peripheral azido groups of lsc-hp PSt and $\gamma_{=CH}$ of the phenyl of lsc-hp PSt, respectively. After grafting onto the PNIPAM arms, the signal at 2094 cm^{-1} disappeared, indicating that azido groups have completely reacted. Besides, FTIR spectrum of lsc-hp PSt-*g*-PNIPAM shows the absorbance at 1653 cm^{-1}, attributed to $\upsilon_{C=O}$ of PNIPAM, while PSt absorbance bands at 3151, 1494 and 756 cm^{-1} are still present, indicating that PNIPAM arms have successfully grafted onto the lsc-hp.

^{1}H-NMR results also confirm the successful grafting of alkynyl-PNIPAM arms onto lsc-hp PSt, as shown in Figure 2(B). NMR spectrum of lsc-hp PSt-*g*-PNIPAM exhibits the main signals from both St and NIPAM units, such as methine proton of NIPAM at 4.01 ppm and aromatic protons of St around 6.61 ppm. As well, the signal of methylene protons next to alkynyl group disappears in lsc-hp PSt-*g*-PNIPAM spectrum, indicating the removal of probably unreacted alkynyl-PNIPAM during the purification.

Based on the integrate heights of the signals at 4.01 and 6.61 ppm, the copolymer composition of lsc-hp PSt-*g*-PNIPAM can be calculated. Furthermore, the number of PNIPAM grafting chains on each lsc-hp PSt molecule (N_p) could be estimated from $M_{n,GPC}$ of fractioned lsc-hp PSt and $M_{n,NMR}$ of PNIPAM. The values are 64 and 24 for lsc-hp PSt_{400}-*g*-PNIPAM and lsc-hp PSt_{150}-*g*-PNIPAM, respectively.

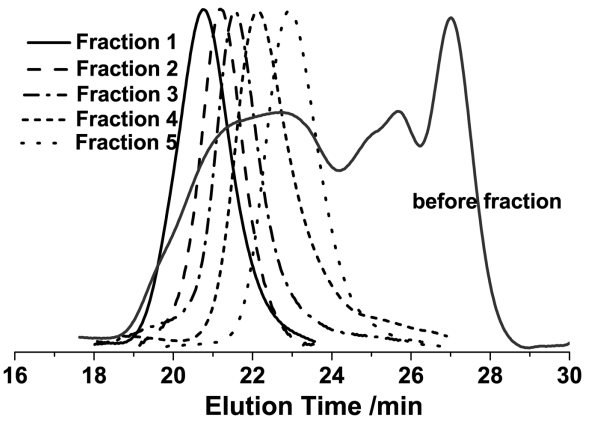


FIGURE 1 GPC diagrams of lsc-hp PSt with uniform subchains before and after fraction (Fraction 1–5).

TABLE 1 GPC Characterization of t lsc-hp PSt Before and After Fraction (Fraction 1–5)

sample	$M_{n,GPC}$[a]	M_w/M_n[a]	DP_w[b]	$M_{w,SLS}$[c]
lsc-hp PSt_{400}	400 k	1.30	83	1 M
lsc-hp PSt_{310}	310 k	1.25	65	–
lsc-hp PSt_{180}	180 k	1.30	38	–
lsc-hp PSt_{150}	150 k	1.20	31	390 k
lsc-hp PSt_{90}	90 k	1.25	19	–

[a] $M_{n,GPC}$ and M_w/M_n were obtained from GPC with refractive index detector.
[b] DP_w is the number of alkyny-$(PSt\text{-}N_3)_2$ seesaw macromonomer in the fractions and was obtained by $M_{w,GPC}/M_{w,macromonomer}$.
[c] $M_{w,SLS}$ was determined by static light scattering.

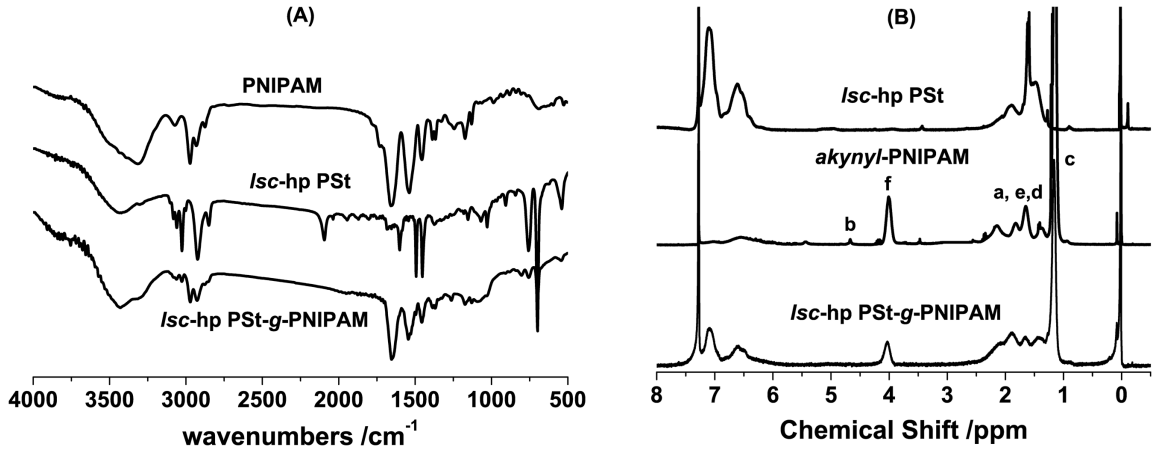


FIGURE 2 FT-IR (A) and ^{1}H-NMR (B, in $CDCl_3$) spectra of different polymers.

$$N_p = \frac{2A_{4.01} \times 113}{A_{6.61} \times 104} \times \frac{(M_{n,GPC})_{hp-PSt}}{(M_{n,NMR})_{PNIPAM}} \quad (1)$$

where $A_{6.61}$ and $A_{4.01}$ are the integrate heights of the corresponding signals, $(M_{n,GPC})_{hp\text{-}PSt}$ and $(M_{n,NMR})_{PNIPAM}$ are the related number-averaged molecular weights, respectively.

To further confirm the formation of star-like architecture for lsc-hp PSt-*g*-PNIPAM, static LLS (SLS) and dynamic LLS (DLS) studies were carried out in THF. In SLS, the measurement was done at each angle for three times with duration of 30 s. The error was set under 5%. Weight-average molecular weight by SLS ($M_{w,SLS}$) and gyration radius (R_g) were obtained according to eq. 2.

$$\frac{KC}{Rvv(q)} \approx \frac{1}{M_w}\left(1 + \frac{1}{3}R_g q^2\right) + 2A_2C \quad (2)$$

where $R_{VV}(q)$, A_2, and q are Rayleigh ratio, the second virial coefficient, and scattering factor, respectively. The constant, K, equals to $4\pi^2 (dn/dC)^2/(N_A\lambda_0^4)$ with C, N_A, and λ_0 being polymer concentration, Avogadro's number and wavelength of laser light, respectively. Berry plot was used in calculation.

As summarized in Table 2, $M_{w,SLS}$, R_g or hydrodynamic radius (R_h) for lsc-hp PSt-*g*-PNIPAM is larger correspondingly than that for lsc-hp PSt, indicating PNIPAM arms have been grafted onto the core. As it is well-known, the value of R_g/R_h reflects the polymer conformation and architecture.[64,65] For hyperbranched polymer, R_g/R_h is between 1.10 and 1.40,[66] but it ranges from 1.5 to 1.8 for star polymers.[67] The data in Table 2 demonstrated clear difference in R_g/R_h between lsc-hp PSt and lsc-hp PSt-*g*-PNIPAM, suggesting the variation of hyperbranched architecture to star-like architecture.

Thermal Responsive Behavior of lsc-hp PSt-*g*-PNIPAM Observed by LLS

With solvent replacement from THF to water at room temperature, aqueous solutions of lsc-hp PSt-*g*-PNIPAM were obtained. In the solvent replacement procedure, no sediment was produced and the final mixtures kept clear, indicating that lsc-hp PSt-*g*-PNIPAM would be molecularly dissolved in water, that is, single-molecular micelles would be formed.

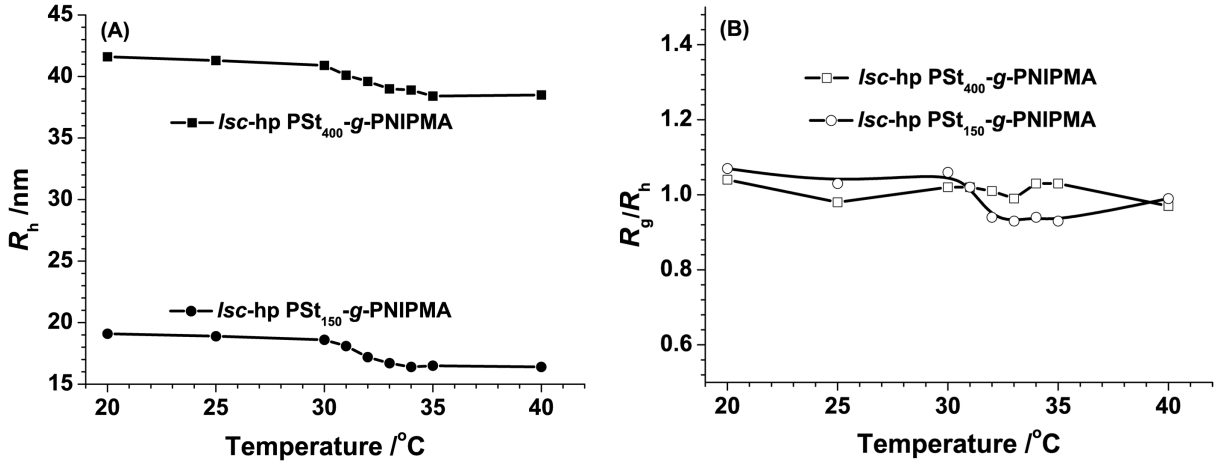


FIGURE 3 Temperature dependence of R_h (A) and R_g/R_h (B) for lsc-hp PSt-*g*-PNIPAM after solvent replacement from THF to water ($C_{polymer}$ = 0.1 mg/mL for DLS; $C_{polymer}$ = 0.01, 0.04, 0.07, and 0.1 mg/mL for SLS).

TABLE 2 Structure Parameters of lsc-hp PSt and lsc-hp PSt-*g*-PNIPAM in THF

Polymer	d*n*/d*C* (mL/g)[a]	$M_{w,SLS}$[b]	R_g (nm)[b]	R_h (nm)[c]	R_g/R_h[b]
lsc-hp PSt_{400}	0.108	1.0 M	34	28	1.21
lsc-hp PSt_{400}-*g*-PNIPAM	0.104	2.1 M	153	102	1.53
lsc-hp PSt_{150}	0.108	390 k	18	14	1.28
lsc-hp PSt_{150}-*g*-PNIPAM	0.104	800 k	100	60	1.63

[a] The d*n*/d*C* value of PSt was determined at 25 °C ($\lambda = 633$ nm). The d*n*/dC value of lsc-hp PSt-*g*-PNIPAM was estimated by: $dn/dC_{\text{lsc-hp PSt-}g\text{-PNIPAM}} = w_1 \times dn/dC_{\text{lsc-hp PSt}} + w_2 \times dn/dC_{\text{PNIPAM}}$, which w_1 and w_2 are weight percentage of lsc-hp PSt and PNIPAM, respectively.
[b] Angle of SLS measurement ranged from 15° to 150° under $C_{\text{polymer}} =$ 0.01, 0.04, 0.07, and 0.1 mg/mL.
[c] DLS measurement was done at 30° under $C_{\text{polymer}} = 0.1$ mg/mL.

Comparing the data listed in Table 2 and those shown in Figure 3, R_h of star-like copolymers with two overall molecular weights of lsc-hp PSt sharply decreases from 102 and 60 nm in THF to 40 and 19 nm in water for lsc-hp PSt_{400}-*g*-PNIPAM and lsc-hp PSt_{150}-*g*-PNIPAM, respectively. This result suggests that the core of *ls*-hp PSt collapses seriously and might cause the crowded package of PNIPAM arms around the core. Indeed, R_g/R_h value of lsc-hp PSt-*g*-PNIPAM drops to about 1.0 after the solvent replacement, supporting the suggestion of dense conformation of lsc-hp PSt-*g*-PNIPAM.[68,69] In other words, loose star-like conformation of lsc-hp PSt-*g*-PNIPAM in THF would be converted into dense spherical conformation with dense core and crowded arms in water.

The thermal responsive behavior of lsc-hp PSt-*g*-PNIPAM was studied by SLS and DLS. Due to conformation transition of PNIPAM arms upon heating, obvious decrease in R_h appears at 29.6 and 30.2 °C for lsc-hp PSt_{400}-*g*-PNIPAM and lsc-hp PSt_{150}-*g*-PNIPAM, respectively. Lower critical solution temperature (LCST) of PNIPAM homopolymer in aqueous solution is 32 °C, being higher than the value of lsc-hp PSt-*g*-PNIPAM because PNIPAM arms are attached onto hydrophobic PSt core.[70] Moreover, LCST of lsc-hp PSt_{400}-*g*-PNIPAM is a little higher than that of lsc-hp PSt_{150}-*g*-PNIPAM, probably attributed to higher density of PNIPAM arms around PSt core.[71]

Absorption of Pyrene by lsc-hp PSt-*g*-PNIPAM in Aqueous Solution

Because of hydrophobic PSt core, lsc-hp PSt-*g*-PNIPAM could act a reservoir to encapsulate hydrophobic chemicals in aqueous solution. Thus, pyrene was used as a model and lsc-hp PSt-*g*-PNIPAM (5.0 mg) micelle dispersion (20.0 mL) was used to absorb pyrene.

Figure 4(A) shows the comparison of Uv-vis spectra of lsc-hp PSt-*g*-PNIPAM aqueous solution before and after the absorption of pyrene. Besides the absorbance band of phenyl group at 202 nm, those of pyrene appears at 240, 273, and 335 nm, indicating that water insoluble pyrene has transfer into the core of lsc-hp PSt-*g*-PNIPAM. Figure 4(B) demonstrates the variation of absorbed pyrene amount with time. For both lsc-hp PSt_{400}-*g*-PNIPAM and lsc-hp PSt_{150}-*g*-PNIPAM, the absorption of pyrene reaches nearly the equilibrium at 10 h. The absorption amount of pyrene for lsc-hp PSt_{150}-*g*-PNIPAM is a little faster and higher, because its overall surface area and weight percent of PSt are larger, which can be estimated from NMR analysis. The saturated encapsulation amounts of pyrene are 12.5 and 8.5, respectively for lsc-hp PSt_{150}-*g*-PNIPAM and lsc-hp PSt_{400}-*g*-PNIPAM, being 2.5 and 1.6 times of polymer weights.

CONCLUSIONS

Through azide-alkyne cycloaddition click chemistry from see-saw macromonomer of alkynyl-$(PSt\text{-}N_3)_2$ and precipitation fraction, lsc-hp PSt with uniform subchain length and overall molecular weight was obtained. SET-LCR of NIPAM in isopropanol mediated with PBIB/CuCl/Me_6-TREN produced alkynyl-PNIPAM, which was grafted onto the peripheral azido groups of lsc-hp PSt via click chemistry. Thus, amphiphilic lsc-hp PSt grafted with PNIPAM chains was successfully prepared and confirmed by different techniques. With the

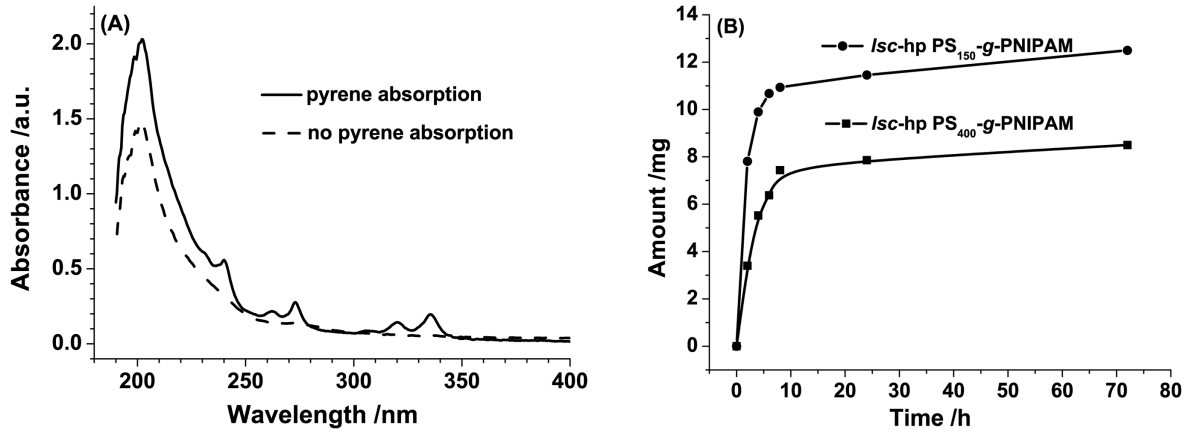


FIGURE 4 Comparison of UV spectra of lsc-hp PSt-*g*-PNIPAM aqueous solution before and after pyrene absorption (A), and dependence of pyrene absorption of lsc-hp PSt-*g*-PNIPAM on time.

solvent replacement, aqueous solutions of lsc-hp PSt-*g*-PNIPAM were obtained accompanying with the sharp decrease in molecular size and the conformation change. Heating the aqueous solution of lsc-hp PSt-*g*-PNIPAM led to the collapse of PNIPAM arms, resulting in the decrease of macromolecule size. LCST of lsc-hp PSt_{400}-*g*-PNIPAM with higher overall molecular weight of PSt core was observed to be lower, due to less grafting density of PNIAM arms and the hydrophilicty of PSt core. This amphiphilc star-like copolymer can be served as a reservoir to encapsulate hydrophobic chemicals such as pyrene.

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REFERENCES AND NOTES

1 B. I. Voit, A. Lederer, *Chem. Rev.* **2009,** *109*, 5924–5973.

2 S. J. Teertstra, M. Gauthier, *Prog. Polym. Sci.* **2009,** *29*, 277–327.

3 B. M. Rosen, J. C. Wilson, D. A. Wilson, M. Peterca, M. R. Imam, V. Percec, *Chem. Rev.* **2009,** *109*, 6275–6540.

4 V. Percec, B. Barboiu, T. K. Brea, M. Van Der Sluis, R. B. Grubbs, J. M. J. Frechet, *J. Polym. Sci.: Part A: Polym. Chem.* **2000,** *38*, 4776–4791.

5 M. Q. Zhao, Y. F. Zhou, M. L. Bruening, D. E. Bergbreiter, R. M. Crooks, *Langmuir* **1997,** *13*, 1388–1391.

6 G. Tonhauser, D. Wilms, Y. Korth, H. Frey, C. Friedrich, *Macromol. Rapid Commun.* **2010,** *31*, 2127–2132.

7 C. Gao, D. Y. Yan, *Prog. Polym. Sci.* **2004,** *29*, 183–275.

8 Y. Y. Mai, Y. F. Zhou, D. Y. Yan, *Macromolecules* **2005,** *38*, 8679–8686.

9 A. Carlmark, C. Hawker, A. Hulta, M. Malkoch, *Chem. Soc. Rev.,* **2009,** *38*, 352–362.

10 Y. Y. Xu, C. Gao, H. Kong, D. Y. Yan, P. Luo, W. W. Li, Y. Y. Mai, *Macromolecules* **2004,** *37*, 6264–6267.

11 H. A. Cheng, X. J. Yuan, X. Y. Sun, K. P. Li, Y. F. Zhou, D. Y. Yan, *Macromolecules* **2010,** *43*, 1143–1147.

12 W. Tao, Y. Liu, B. B. Jiang, S. R. Yu, W. Huang, Y. F. Zhou, D. Y. Yan, *J. Am. Chem.Soc.* **2012,** *134*, 762–764.

13 X. Y. Zhu, L. Chen, D. Y. Yan, Q. Chen, Y. F. Yao, Y. Xiao, J. Hou, J. Y. Li, *Langmuir.* **2004,** *20*, 484–490.

14 M. B. Rosen, V. Percec, *Chem. Rev.* **2009,** *109*, 5069–5119.

15 V. Percec, B. Barboiu, C. Grigoras, T. K. Bera, *J. Am. Chem. Soc.* **2003,** *125*, 6503–6516.

16 V. Percec, C. Grigoras, H. Kim, *J. Polym. Sci. Part A: Polym. Chem.* **2004.** *42*, 505–513.

17 V. Percec, C. Grigoras, T. K. Bera, B. Barboiu, P. Bissel, *J. Polym. Sci. Part A: Polym. Chem.* **2005.** *43*, 4894–4906.

18 M. B. Rosen, G. Lligadas, C. Hahn, V. Percec, *J. Polym. Sci. Part A: Polym. Chem.* **2009.** *47*, 3931–3939.

19 M. B. Rosen, G. Lligadas, C. Hahn, V. Percec, *J. Polym. Sci. Part A: Polym. Chem.* **2009.** *47*, 3940–3948.

20 V. Percec, T. Guliashvili, J. S. Ladislaw, A. Wistrand, A. Stjerndahl, M. J. Sienkowska, M. J. Monteiro, S. Sahoo, *J. Am. Chem. Soc.* **2006,** *128*, 14156–14165.

21 N. H. Nguyen, M. E. Levere, J. Kulis, M. J. Monteiro, V. Percec, *Marcomolecules,* **2012,** *45*, 4606–4622.

22 N. H. Nguyen, M. E. Levere, V. Percec, *J. Polym. Sci. Part A: Polym. Chem.* **2012,** *50*, 860–873.

23 M. E. Levere, N. H. Nguyen, X. F. Leng, V. Percec, *Polym. Chem.* **2013,** *4*, 1635–1647.

24 S. Paillet, A. Roncin, G. Clisson, G. Pembouong, L. Billon, C. Derail, M. Save, *J. Polym. Sci. Part A: Polym. Chem.* **2012,** *14*, 2967–2979.

25 L. W. Li, C. He, W. D. He, C. Wu, *Macromolecules* **2011,** *44*, 8295–8307.

26 C. He, L. W. Li, W. D. He, W. X. Jiang, C. Wu, *Marcomolecules,* **2011,** *44*, 6233–6236.

27 C. He, W. D. He, L. W. Li, W. X. Jiang, J. Tao, J. Yang, L. Chen, X. S. Ge, S. Q. Chen, *J. Polym. Sci. Part A: Polym. Chem.* **2012,** *50*, 3214–3224.

28 K. Dworak, A. Kowalczuk-Bleja, B. Trzebicka, W. Walach, *Polym. Bull.* **2002,** *49*, 9–16.

29 G. Kali, M. Szesztay, A. Bodor, B. Ivan, *Macromol. Chem. Phys.* **2007,** *208*, 1388–1393.

30 C. C. Chu, Y. Wang, C. F. Yeh, L. S. Wang, *Macromolecules* **2008,** *41*, 56329–165640.

31 A. Kowalczuk-Bleja, B. Sierocka, J. Muszynski, B. Trzebicka, A. Dworak, *Polymer* **2005,** *46*, 8555–8564.

32 C. B. Zhang, Y. Zhou, Q. Liu, S. X. Li, S. Perrier, Y. L. Zhao, *Macromolecules* **2011,** *44*, 2034–2049.

33 C. Weber, R. Hoogenboomd, U. S. Schubert, *Prog. Polym. Sci.* **2012,** *37*, 686–714.

34 W. Cui, X. M. Lu, K. Cui, L. Niu, Y. Wei, Q. Lu, *Langmuir* **2012,** *28*, 9413–9420.

35 Y. L. Luo, W. Yu, F. Xu, L. L. Zhang, *J. Polym. Sci. Part A: Polym. Chem.* **2012,** *50*, 2053–2067.

36 S. M. Zhu, J. B. Li, Y. U. Chen, Z. X. Chen, C. X. Chen, Y. Li, Z. W. Cui, D. Zhang, *J. Nanopart. Res.* **2012,** *14*, 1132–1143.

37 Y. Z. Pan, H. Q. Bao, N. G. Sahoo, T. F. Wu, L. Li, *Adv. Funct. Mater.* **2011,** *21*, 2754–2763.

38 H. Yang, A. C. C. Esteves, H. J. Zhu, D. J. Wang, J. H. Xin, *Polymer* **2012,** *53*, 3577–3586.

39 H. J. Zhang, Q. Yan, Y. Kang, L. L. Zhou, H. Zhou, J. Y. Yuan, S. J. Wu, *Polymer* **2012,** *53*, 3719–3725.

40 S. R. Deka, A. Quarta, R. D. Corato, A. Riedinger, R. Cingolani, T. Pellegrino, *Nanoscale,* **2011,** *3*, 619–629.

41 Z. Iatridi, G. Mattheolabakis, K. Avgoustakisb C. Tsitsilianis, *Soft Matter,* **2011,** *7*, 11160–11169.

42 C. W. Chiu, J. J. Lin, *Prog. Polym. Sci.* **2012,** *37*, 406–444.

43 J. Adelsberger, A. Kulkarni, A. Jain, W. N. Wang, A. M. Bivigou-Koumba, P. Busch, V. Pipich, O. Holderer, T. Hellweg, A. Laschewsky, P. Muller-Buschbaum, C. M. Papadakis, *Macromolecules* **2010,** *43*, 2490–2501

44 K. Kubota, S. Fujishige, I. Ando, *J. Phys. Chem.* **1990,** *94*, 5154–5158.

45 J. Gao, C. Wu, *Macromolecules* **1997,** *30*, 6873–6876.

46 H. G. Schild, *Prog. Polym. Sci.* **1992,** *17*, 163–249

47 H. Wei, X. S. Chen, X. Z. Zhang, R. X. Zhuo, *Prog. Polym. Sci.* **2009,** *34*, 893–910.

48 K. J. Zhou, Y. J. Lu, J. F. Li, L. Shen, G. Z. Zhang, Z. W. Xie, C. Wu, *Macromolecules* **2008,** *41*, 8927–8931.

49 S. Y. Lin, K. S. Chen, R. C. Liang, *Polymer* **1999,** *40*, 2619–2624.

50 K. Katsumoto, T. Tanaka, H. Sato, Y. Ozaki, *J. Phys. Chem. A* **2002,** *106*, 3429–3435.

51 Y. Xia, N. A. D. Burke, H. D. H. Stolver, *Macromolecules* **2006,** *39*, 2275–2283

52 X. P. Qiu, F. Tanaka, F. M. Winnik, *Macromolecules* **2007,** *40*, 7069–7071

53 Q. Jiang, Z. L. Lei, *Biotechnol Bioprocess Eng* **2011,** *16*, 1187–1195.

54 A. Nyka1nen, M. Nuopponen, A. Laukkanen, S. P. Hirvonen, M. Rytela1, O. Turunen, H. Tenhu, R. Mezzenga, O. Ikkala, J. Ruokolainen, *Macromolecules* **2007,** *40*, 5827–5834.

55 L. Zhang, E. S. Daniels, L. V. Dimonie, A. Klein, *J. Polym. Sci. Part A: Polym. Chem.* **2010,** *48*, 2502–2511.

56 Q. H. Sun, Y. L. Deng, *Langmuir* **2005,** *21*, 5812–5816.

57 W. A. Zhang, X. C. Zhou, H. Li, Y. Fang, G. Z. Zhang, *Macromolecules* **2005,** *38*, 909–914.

58 J. X. Zhang, L. Y. Qiu, K. J. Zhu, Y. Jin, *Macromol. Rapid Commun.* **2004,** *25*, 1563–1567.

59 C. Vasile, G. G. Bumbu, I. Mylonas, G. Bokias, G. Staikos, *Polym. Int.* **2004,** *53*, 1176–1179.

60 P. W. Zhu, D. H. Napper, *J. Colloid Interface Sci.* **1994,** *164*, 489–494.

61 M. Ciampolini, N. Nard, *Inorganic Chemistry.* **1966,** *5*, 41–45.

62 C. Wu, K. Q. Xia, *Rev. Sci. Instrum.* **1994,** *65*, 587–590.

63 S. Fleischmann, B. M. Rosen, V. Percec, *J. Polym. Sci. Part A: Polym. Chem.* **2010,** *48*, 1190–1196.

64 C. Wu, J. Zuo, B. Chu, *Macromolecules* **1989,** *22*, 633–639.

65 M. Antonietti, S. Heinz, M. Schmidt, *Macromolecules* **1990,** *23*, 3796–3805.

66 W. Burchard, M. Schmidt, W. H. Stockmayert, *Macromolecules* **1980,** *13*, 1265–1272.

67 J. M. V. Lena, A. C. Kathleen, P. G. Alice, *Macromolecules* **1991,** *24*, 1670–1677.

68 Z. Zhou, D. G. Peiffer, B. Chu, *Macromolecules* **1994,** *27*, 1428–1433.

69 Y. F. Tu, X. H. Wan, D. Zhang, Q. F. Zhou, C. Wu, *J. Am. Chem. Soc.* **2000,** *122*, 109201–10205.

70 J. Adelsberger, M. K. Andreas, M. B. Achille, P. Busch, O. Holderer, T. Hellweg, A. Laschewsky, M. B. Peter, M. P. Christine, *Colloid Polym Sci* **2011,** *289*, 711–720.

71 X. C. Zhou, X. D. Ye, G. Z. Zhang, *J. Phys. Chem. B* **2007,** *111*, 5111–5115.