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Electronic Supporting Information

Synthesis and Property of Clickable A(B-*b*-C)$_{20}$ Miktoarm Star-shaped Block Copolymers with a Terminal Alkyne Group

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1. Experimental section

1.1 Materials. β-cyclodextrin (β-CD, 98%), 2-bromoisobutyryl bromide (98%), N, N, N', N'', N''-pentamethyldiethylene triamine (PMDETA, 99%), Tetrabutylammonium fluoride (TBAF, 97%, Aldrich), and propargyl bromide solution (80 wt.% in toluene) were purchased from Sigma-Aldrich, and used as received. Sodium azide (NaN_3, 98%, Sinopharm Chemical Reagent Co. (SCR)) , p-tolylsulfonyl chloride (TsCl, 99%, SCR), hydrochloric acid (HCl, 37 wt.% in water, SCR), sodium hydride (NaH, 60% in mineral oil, SCR) 1,2-divinylbenzene (DVB, 98%, SCR) and potassium iodide (KI, 98%, SCR) were used without further purification. Copper(I) bromide (Cu(I)Br, 95%, SCR) was stirred overnight in acetic acid, filtered, and washed with ethanol and ethyl ether successively, and dried in vacuum. Tetrahydrofuran (THF, 99%, SCR) was refluxed and distilled from sodium naphthalenide solution. tert-butyl acrylate (tBA, 98%, SCR) and N,N-dimethylformamide (DMF, 99%, SCR) were distilled over CaH_2 under reduced pressure prior to use. Styrene (St, 99%, SCR) was washed with 10% NaOH aqueous solution and water successively, dried over anhydrous $MgSO_4$ and CaH_2 sequentially, and distilled under reduced pressure. Poly(ethylene oxide) methyl ether (mPEO, M_n =5,000) was used as received. 2, 2'-Azobis(isobutyronitrile) (AIBN) was purified by recrystallization with methanol. Monodisperse silica nanoparticles (SN) with diameter of 250 nm (measured by TEM) were synthesized according to the Stöber method.[1] 4-Hydroxyl-2, 2, 6, 6-tetramethylpiperidine-1-oxyl (4-hydroxy-TEMPO) was synthesized and purified by recrystallization with hexane.[2] 1-(Azidomethyl)-4-vinylbenzene, 3-(trimethylsilyl)-propargyl 2-bromoisobutyrate, and 3-azidopropyltriethoxysilane were synthesized according to the literatures.[3-5] All other reagents were purified by common purification procedures.

1.2 Measurements. Gel permeation chromatographic (GPC) analyses were performed at Waters calibrated by narrow polystyrene standards with a DAWN HELEOS (Wyatt multiangle laser light scattering detector, He−Ne 658.0 nm) and THF as the eluent at a flow rate of 1.0 mL/min at 35 °C. ^{1}H NMR spectra were recorded on a DMX 500 MHz spectrometer in $CDCl_3$ and DMSO-d_6 with tetramethylsilane (TMS) as the internal reference for chemical shifts. Transmission electron microscopy (TEM) images were taken with a Philips CM200FEG field emission microscope, and the samples were dispersed in ethanol and then dried on a holey carbon film Cu grid. Scanning electron microscopy (SEM) was conducted on a Philips XL 30 field emission microscope at an accelerating voltage of 10 kV. All dynamic light scattering (DLS) experiments were carried out at 25 °C on a Malvern particle size analyzer (Model Zetasizer NANO ZS90), and the nanoparticles (~0.01 mg) dispersed in DMF (1 mL) were measured at a scattering angle of 90°.

1.3 Synthesis of mono-6-(*p*-tolylsulfonyl)-β-cyclodextrin (β-CD-Ts)

A NaOH solution (3.6 g, 0.09 mol of NaOH in 120 mL water) was added by β-CD (6.0 g, 5.3mmol) at 0-5 ºC, and then by *p*-tolylsulfonyl chloride (TsCl, 1.2 g, 6.3 mmol) during vigorous stirring.[6] After 5 h, the precipitate was removed by filtration. 10% HCl was added into the filtrate, and the pH was adjusted to pH=7. The mixture was kept in the refrigerator overnight to afford a white solid product, which was recrystallized in hot water to afford 2.3 g of product (yield, 38.3%).

1.4 Synthesis of mono-6-(azide)-β-cyclodextrin (β-CD-N_3)

Powdered β-CD-Ts (0.500 g, 0.388 mmol) was suspended in dry DMF (1.5 mL) and heated to 60 ºC to form homogeneous mixture. After KI (0.032 g, 0.194 mmol) and NaN_3 (0.252 g, 3.8 mmol) were added, this mixture was stirred at 60-65 ºC for 24 h, and then cooled to room temperature and centrifugated to remove salts. Acetone (100 mL) was added to produce a white precipitate. After suction filtration and drying overnight, 0.398 g of pure white solid was obtained (yield, 88%).

1.5 Synthesis of 2, 2, 6, 6-tetramethyl-4-(prop-2-ynyloxy) piperidine-1-yloxyl (TEMPO-≡)

TEMPO-≡ was synthesized as follows: [7] NaH (850 mg, 21.3 mmol) was dispersed in dry DMF (100 mL) at 0 °C, and added dropwise by 4-hydroxy-TEMPO (3.0 g, 17.4 mmol). The reaction mixture was then stirred at room temperature for 30 min, with the visible evolution of hydrogen gas. Propargyl bromide (80 wt. % in toluene, 2.0 mL, 18 mmol) was added dropwise at 0 °C. The resulting mixture was stirred at room temperature for another 3 h after water (100 mL) was added, followed by extraction with acetic ether (2 × 50 mL). The organic phase was successionly washed with water (2 × 50 mL), dried over anhydrous $MgSO_4$, filtered and evaporated under reduced pressure then purified by column chromatography (silica gel, 10% acetic ether in hexane) to give the compound as a dark orange solid (2.34 g; yield, 64%).

1.6 One-pot synthesis of (TMS-alkynyl)-PS-alkynyl via ATRP combined with ATNRC.

The mixture of St (10 mL, 82 mmol), 3-(trimethylsilyl)-propargyl 2-bromoisobutyrate (25 μL, 0.14 mmol), toluene (5.0 mL) and PMDETA (0.40 mL, 0.18 mmol) was charged into an 100 mL ampoule and degassed by three freeze-pumpthaw cycles, and then added by CuBr (25.7 mg, 0.18 mmol) under nitrogen as fast as possible, followed by another three freeze-pump-thaw cycles. After sealed under nitrogen, the ampoule was immersed into an oil bath at 90 °C for 4 h, then added by the degassed TEMPO-≡ solution (40 mg, 0.2 mmol with 5 ml toluene) and reacted for another 4 h. The crude product was diluted with THF, and the solution was passed through a column filled with neutral alumina to remove the copper complex. The solution was concentrated under vacuum and precipitated twice in methanol to produce solid product which was collected and dried under vacuum at 40 °C to a constant weight.

1.7 Synthesis of (TMS-alkynyl)-PS-β-CD by click reaction.

(TMS-alkynyl)-PS-alkynyl (2.0 g, 0.1 mmol) and β-CD-N_3 (78 mg, 0.11 mmol) were dissolved in DMF (5 mL) in a dry ampule, and added by CuBr (15.4 mg, 0.11 mmol) and PMDETA (0.24 mL, 0.11 mmol). This mixture was degassed by three freeze-pump-thaw cycles in liquid N_2, and first immersed in an oil bath at 90°C for 24 h, and then taken out and placed in liquid N_2 to terminate the polymerization. The mixture was diluted with THF and passed through the alumina column to remove the copper salt. The product was precipitated in cold methanol and dried in vacuum oven at 40 °C for 4 h.

1.8 Synthesis of 20Br-β-CD-((TMS-alkynyl)-PS).

(TMS-alkynyl)-PS-β-CD (1.1g, 0.05 mmol) was dissolved in pyridine and cooled to °C. 2-Bromoisobutyryl bromide (0.1 mL, 0.77 mmol) was then added dropwise to this solution under magnetic stirring. The reaction temperature was maintained at 0 °C for 2 h and then slowly increased to ambient temperature, wherein the reaction was allowed to continue for 22 h. The as-obtained brown solution was concentrated in a vacuum oven for 12 h. The resulting product was diluted with dichloromethane, and then washed with saturated $NaHCO_3$ aqueous solution and water. The organic layer obtained was concentrated in a vacuum oven, and then crystallized in cold methanol to produce a white precipitate.

1.9 Synthesis of star-shaped PS(PtBA)$_{20}$ polymer by ATRP using 20Br-β-CD-((TMS-alkynyl)-PS) as the macroinitiator.

Polymerization of *tert*-butyl acrylate (*t*BA) was performed using 20Br-β-CD-((TMS-alkynyl)-PS) as a macroinitiator which has 20 ATRP initiation sites. An ampoule charged with CuBr (57.1 mg, 0.40 mmol), PMDETA (0.89 mL, 0.40 mmol), 20Br-β-CD-((TMS-alkynyl)-PS) (0.5 g, 0.02 mmol), *t*BA (10 mL, 69 mmol), and methyl ethyl ketone (10 mL) was vacuumed by three freeze-thaw-cycles in liquid N_2, then sealed and placed in an oil bath at 60 °C for 2.5 h. The ampoule was then taken out from the oil bath and dipped in liquid N_2 to terminate the polymerization. The solution was then diluted with acetone and passed through a neutral alumina column to remove the catalyst, and precipitated in the mixed solvent of methanol/water. After filtration, the final product was purified by dissolution−precipitation twice with acetone and methanol/water and dried at 40°C in vacuum.

1.10 Synthesis of PS(PtBA-b-PS)$_{20}$ star-shaped copolymer by ATRP using PS(PtBA)$_{20}$ star-shaped polymer as the macroinitiator.

The reaction mixture of CuBr (5.7 mg, 0. 04 mmol), PMDETA (0.09 mL, 0.04 mmol), AB$_{20}$ star-shaped polymer (0.5 g, 0.005 mmol), and St (10 mL, 82 mmol) in anisole (5.0 mL) was charged into an ampoule and degassed by three freeze-pump-thaw cycle in liquid N_2 and then placed in a thermostated oil bath at 90°C. After 7 h, the mixture was dipped in liquid N_2 to terminate the reaction. The mixture was then diluted with THF and passed through a column of neutral alumina to remove the copper salt. The polymers were precipitated with an excess of methanol, filtered, and dried under vacuum to yield A(B-*b*-C)$_{20}$ star-shaped block copolymer, PS(P*t*BA-*b*-PS)$_{20}$.

1.11 Synthesis of star-shaped PS(P*t*BA)$_{20}$ with azide-functionalized P*t*BA.

The star-shaped polymer, PS(P*t*BA)$_{20}$ (2.0 g, 0.01mmol) was dissolved in DMF (15 mL), and added by sodium azide (Br in P*t*BA: sodium azide = 1:10 by mole ratio). The mixture was stirred at room temperature for 24 h, and then added by dichloromethane (25.0 mL). The mixture was then washed with distilled water for three times. The organic layer was dried with anhydrous $MgSO_4$, and the solvent was evaporated under vacuum. The final product, star-shaped PS(P*t*BA)$_{20}$ with azide-functionalized P*t*BA was collected and dried at 40°C in vacuum oven.

1.12 Synthesis of alkyne-terminated mPEO (mPEO−propargyl).

Alkyne-terminated mPEO (i.e., mPEO-propargyl) was obtained by nucleophilic substitution of the hydroxyl group of mPEO into the alkyne group. Briefly, mPEO-OH (5.0 g, 1.0 mmol) and THF (60 mL) were added in a 250 mL dried ampule. The system was then purged with argon. NaH (60% in mineral oil, 243 mg, 7.1 mmol) was introduced until the solution turned reddish-brown. After the ampoule was placed in ice bath, propargyl bromide (80 wt. % in toluene, 0.6 mL, 18 mmol) was added dropwise during 2 h, and the reaction continued at room temperature for another 24 h. The mPEO-alkyne was obtained by separation of the formed salts and precipitation in diethyl ether twice, and dried under vacuum.

1.13 Synthesis of PS(PtBA -b-PEO)$_{20}$ star-shaped copolymer by click reaction.

Star-shaped PS(P*t*BA)$_{20}$ with azide-functionalized P*t*BA and mPEO-alkyne were dissolved in DMF (10 mL) in a dry ampule, and then added by CuBr and PMDETA. The reaction mixture (mPEO-alkyne: star-like P*t*BA−N_3: copper bromide: PMDETA = 1.5: 1: 10: 10 by mole ratio) was degassed by three freeze-pump-thaw cycles in liquid N_2. The ampoule was first immersed in an oil bath at 90 °C for 24 h, and then taken out and placed in liquid N_2 to terminate the polymerization. The mixture was diluted with THF and passed through the alumina column to remove the copper salt. The product was precipitated in cold methanol and dried in vacuum oven at 40°C for 4 h, yielding PS(PEO-*b*-PEO)$_{20}$ star-shaped block copolymer.

1.14 Deprotection of alkynyl group of A(B-*b*-C)$_{20}$ star-shaped copolymer at the end of PS arm.

To a 100 mL round-bottomed flask, A(B-*b*-C)$_{20}$ star-shaped copolymer and THF (15 mL), and then TBAF (30 equal to *t*BA unit) in 5 mL THF solution were added. The reaction mixture was allowed to stir overnight at room temperature. After most of the solvent was removed at reduced pressure, the remaining portion was precipitated/dissolved twice. The obtained product was dried under vacuum.

1.15 Synthesis of raspberry-like particles (SN-*g*-A(B-*b*-C)$_{20}$) by click reaction of A(B-*b*-C)$_{20}$ star-shaped block copolymer onto silica.

Silica particles were first functionalized by azide groups through the self-assembly of 3-azidopropyltriethoxysilane from the surfaces of SN with the same procedures as reported previously,[4] to obtain azide-modified silica nanoparticles (SN-N_3).

SN-N_3 was dispersed in DMF and added by A(B-*b*-C)$_{20}$ star-shaped block copolymer, CuBr and PMDETA. This reaction mixture was degassed by three freeze-pump-thaw cycles in liquid N_2, and then allowed to proceed at 90 °C for 24.0 h, the SN-*g*-A(B-*b*-C)$_{20}$ was centrifuged, washed with THF and ethanol thoroughly, and then dispersed in DMF.

1.16 Synthesis of raspberry-like nanocrystals on the surfaces of SN-*g*-A(B-*b*-C)$_{20}$.

Briefly, SN-*g*-A(B-*b*-C)$_{20}$ (0.2 g) nanospheres were dispersed in 30 mL CH_2Cl_2, and added by 10 mL TFA. The reaction mixture was stirred at room temperature for 24 h. After the hydrolysis, the resulting SN-*g*-PS(PAA-*b*-PS)$_{20}$ or SN-*g*-PS(PAA-*b*-PEO)$_{20}$ was centrifuged, washed with THF and ethanol thoroughly.

SN-*g*-PS(PAA-*b*-PS)$_{20}$ or SN-*g*-PS(PAA-*b*-PEO)$_{20}$ nanospheres were dispersed in 10 mL mixtures: (i) For SN-*g*-PS(PAA-*b*-PS)$_{20}$, the mixture of DMF and benzyl alcohol (BA) ($V_{DMF} : V_{BA} = 9:1$) was used; (ii) For SN-*g*-PS(PAA-*b*-PEO)$_{20}$, the mixture of DMF and diphenyl ether ($V_{DMF} : V_{dipheny\ ether} = 9:1$) was employed.

(1). Ag nanoparticles. $AgNO_3$ (58.9 mg) was used as the precursor, and ethanol was used as the reducer. The reaction temperature was controlled at 100 °C for 10 h to obtain Ag nanocrystals.

(2). Fe_3O_4 nanoparticles. $FeCl_2 \cdot 4H_2O$ (69 mg), $FeCl_3 \cdot 6H_2O$ (94 mg), and ammonium hydroxide (2 mL) were used and the reaction was carried out at 50 °C for 30 min to produce Fe_3O_4 nanocrystals.

1.17 Synthesis of monolayer A(B-*b*-C)$_{20}$ star-shaped block copolymer grafted onto glass slices by click reaction.

The glass slice was first immersed in Piranha solution ($V_{H2SO4} : V_{H2O2} = 7:3$) for 24 h, and washed with water and ethanol thoroughly, and then functionalized by azide groups through the self-assembly of 3-zzidopropyltriethoxysilane from the surface and the same click reaction as 1.15, to obtain monolayer A(B-*b*-C)$_{20}$ star-shaped block copolymer grafted onto the glass slice.

1.18 Synthesis of A(B-*b*-C)$_{20}$ stabilized PS colloid by Pickering emulsion polymerization.

Typically, St (1.6 g), 1-(azidomethyl)-4-vinylbenzene (0.4 g) 1,2-divinylbenzene (0.04 g), hexadecane (0.2 g), AIBN (0.06 g), and PS(P*t*BA -*b*-PEO)$_{20}$ (0.25 g) were mixed in 100 mL three necked bottle, and then added by 150 mL of deionized water. This mixture was immersed in an ice bath and treated by sonication. When 2 cm polished copper wire was added in the system, the bottle was immersed in an oil bath at 80 °C for 6 h under N_2 atmosphere to finish polymerization.

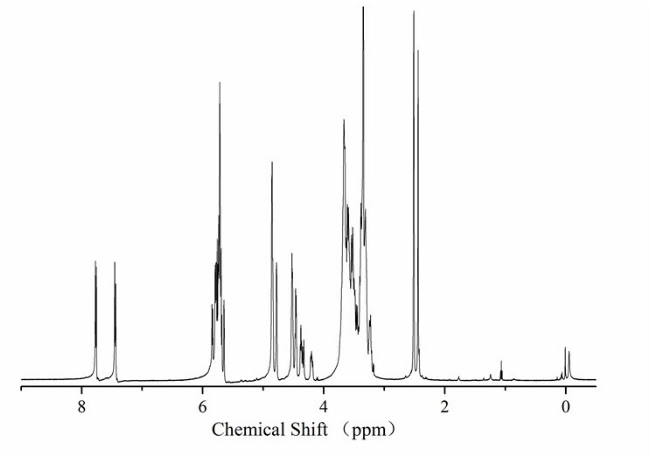

Figure S1. ^1H NMR spectrum of β-CD-Ts in DMSO-d_6.

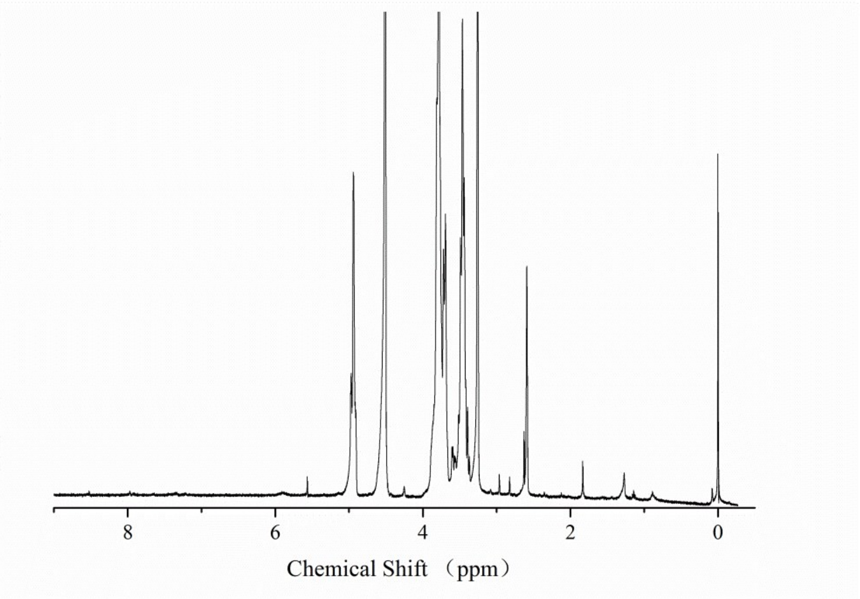

Figure S2. ^1H NMR spectrum of β-CD-N_3 in DMSO-d_6.

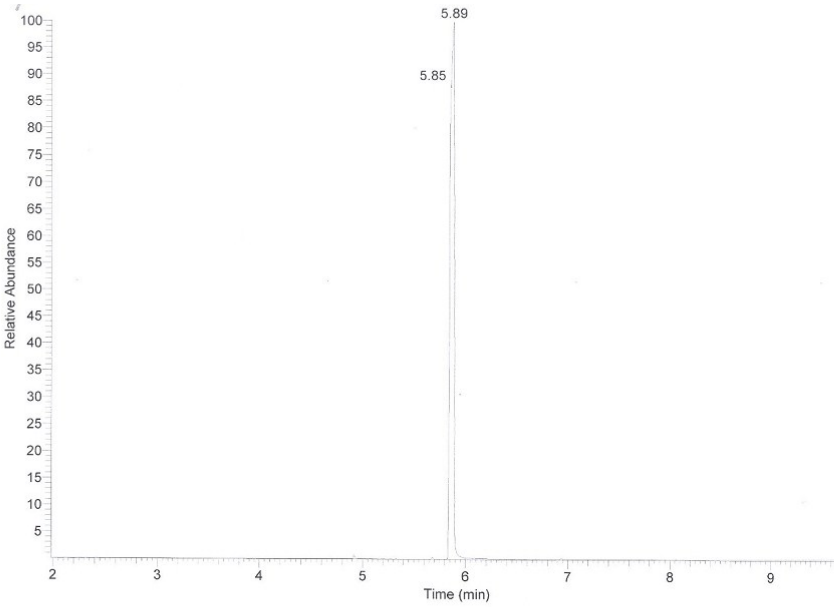

Figure S3. GC-MS spectrum of TEMPO-≡.

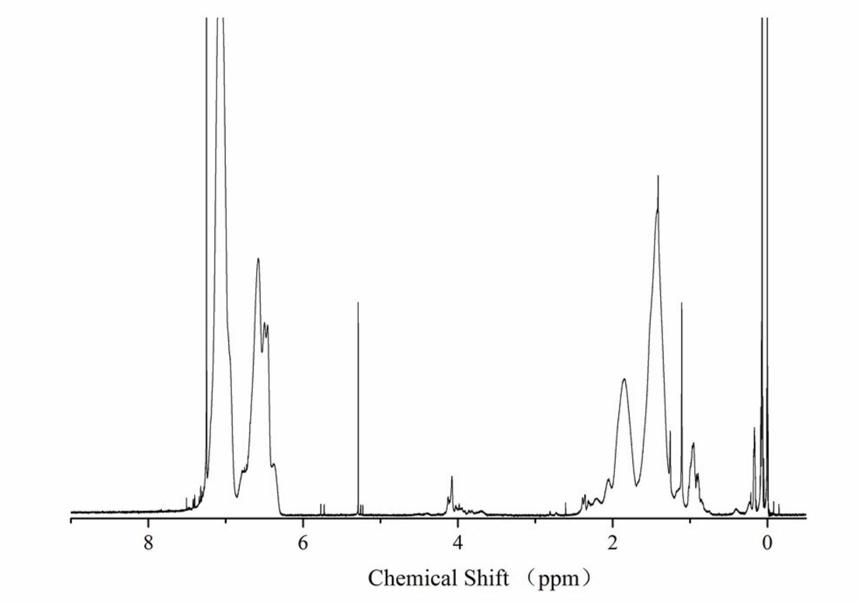

Figure S4. ^{1}H NMR spectrum of (TMS-alkynyl)-PS-alkynyl in $CDCl_3$.

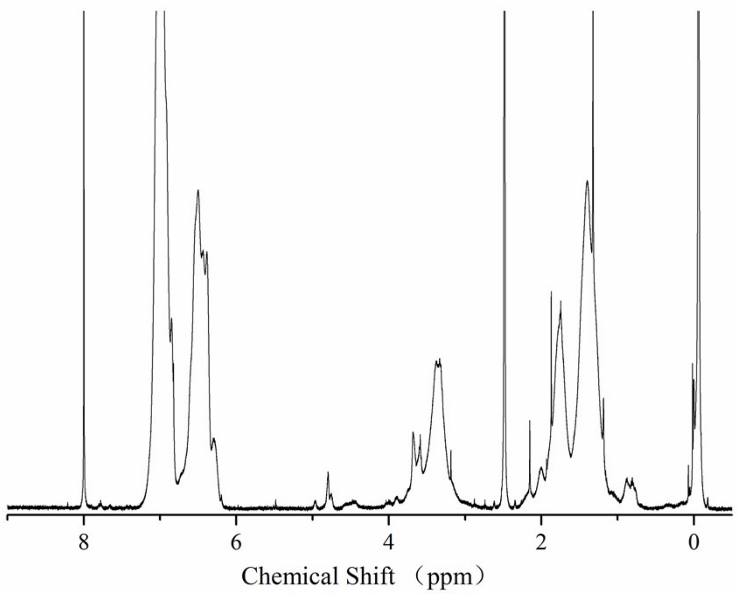

Figure S5. ^{1}H NMR spectrum of (TMS-alkynyl)-PS-β-CD in CDCl$_3$.

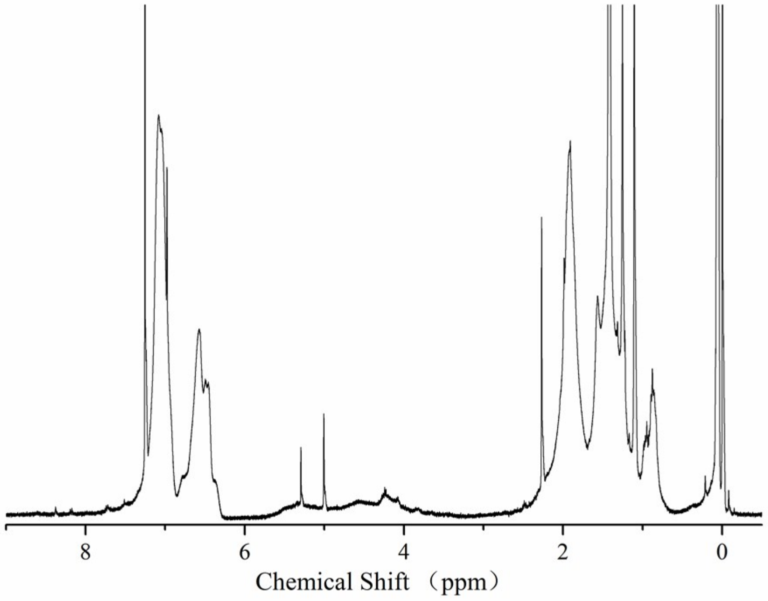

Figure S6. ^{1}H NMR spectrum of 20Br-β-CD-((TMS-alkynyl)-PS) in CDCl$_3$.

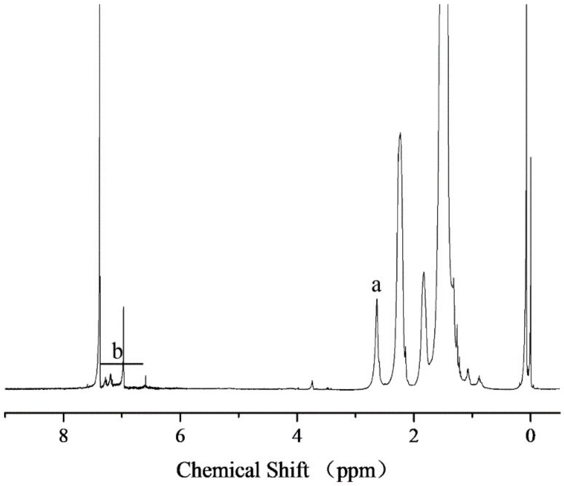

Figure S7. ^1H NMR spectrum of PS(P*t*BA)$_{20}$ in CDCl$_3$. Number-average molecular weight, $M_{n,NMR}$ of PS(P*t*BA)$_{20}$ calculated from ^1H NMR data based on the equation:

$$M_{n,PS(PtBA)_{20}} = \frac{A_a \times 128}{{A_b}/{5} \times 104} \times M_{n,PS} + M_{n,PS} \qquad \textbf{(1)}$$

Where A_a and A_b are the integral area of the characteristic methine group proton on P*t*BA chain and the integral area of phenyl protons on PS chain, respectively, 104 and 128 are the molecular weights of St monomer and and tBA monomer, respectively, and $M_{n,PS}$ is the molecular weight of (TMS-alkynyl)-PS-alkynyl.

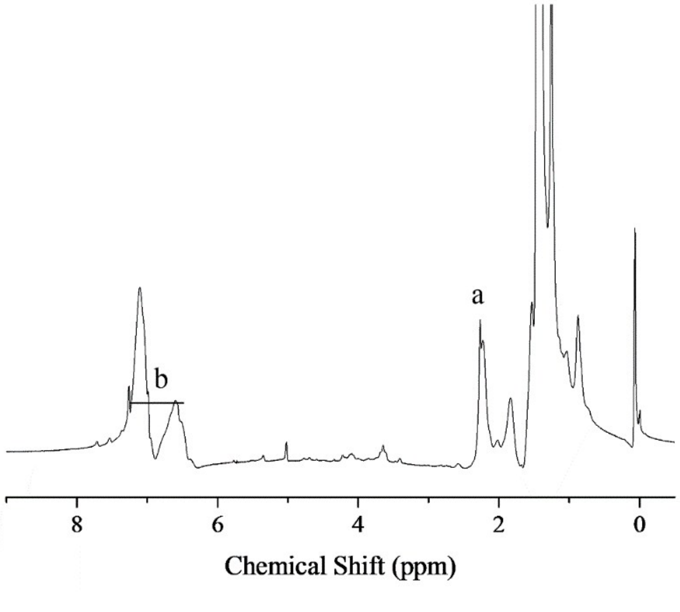

Figure S8. ^1H NMR spectrum of PS(P*t*BA-*b*-PS)$_{20}$ in CDCl$_3$. $M_{n,NMR}$ of PS(P*t*BA-*b*-PS)$_{20}$ calculated from ^1H NMR data based on the equation:

$$M_{n,PS(PtBA-b-PS)_{20}} = \frac{A_b/_5 \times 104}{A_a \times 128} \times \left(M_{n,PS(PtBA)_{20}} - M_{n,PS}\right) + M_{n,PS(PtBA)_{20}} \quad \textbf{(2)}$$

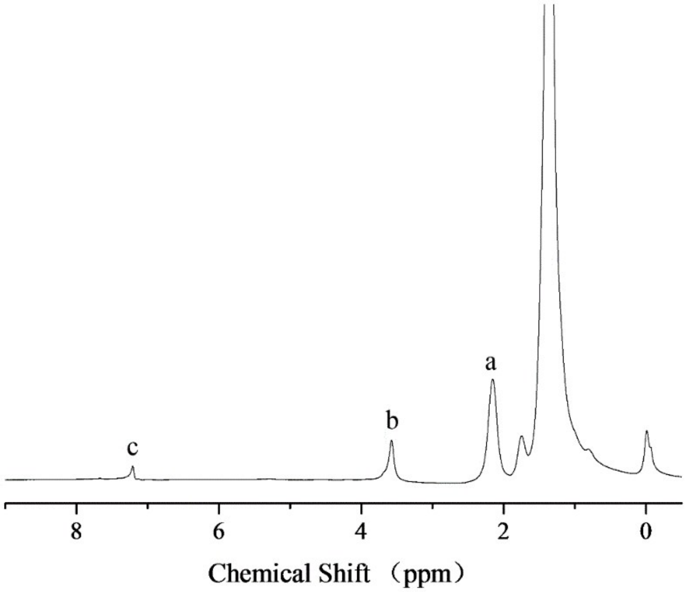

Figure S9. ^{1}H NMR spectrum of PS(P*t*BA-*b*-PEO)$_{20}$ in CDCl$_3$. $M_{n,NMR}$ of PS(P*t*BA-*b*-PEO)$_{20}$ calculated from ^{1}H NMR data based on the equation:

$$M_{n,PS(PtBA-b-PEO)_{20}} = \frac{A_a \times 128}{A_c/_5 \times 104} \times M_{n,PS} + \frac{A_b/_4 \times 44}{A_c/_5 \times 104} \times M_{n,PS} + M_{n,PS} \quad \textbf{(3)}$$

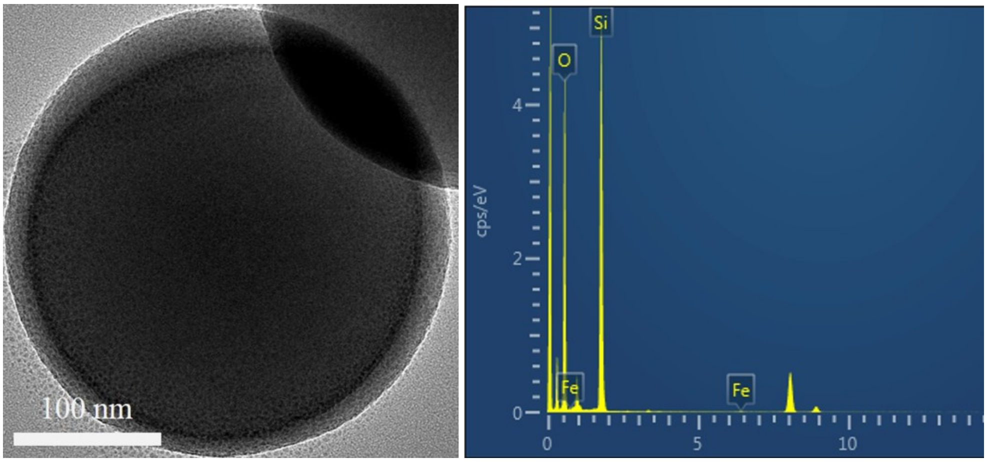

Figure S10. HRTEM image of the SN-*g*-PS(P*t*BA-*b*-PS)$_{20}$ with Fe$_3$O$_4$ nanoparticles.

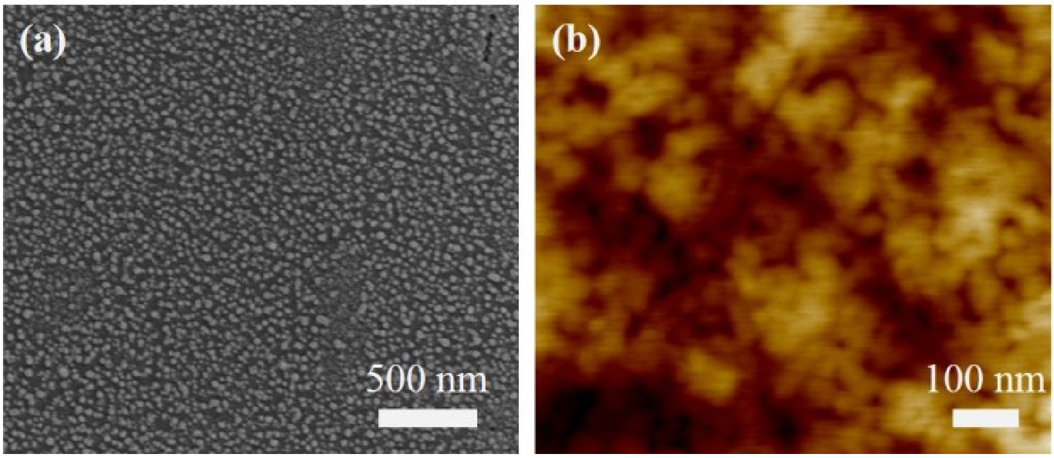

Figure S11. Images of the PS(P*t*BA-*b*-PS)$_{20}$ grafted on the glass slice (a) by SEM, and (b) by AFM.

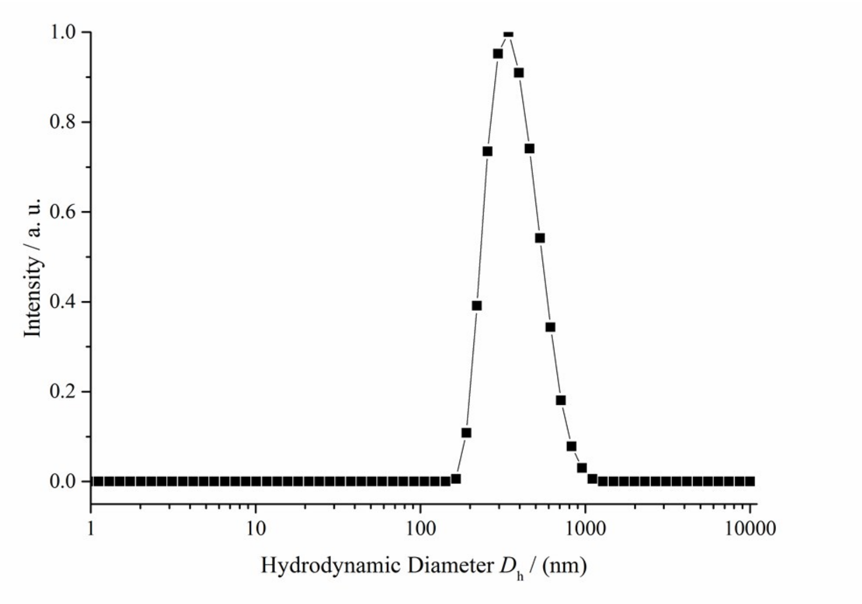

Figure S12. Distribution of hydrodynamic diameter of the raspberry-like latex.

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