Thermoresponsive AuNPs Stabilized by Pillararene-Containing Polymers

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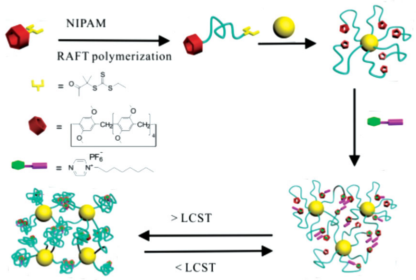
Pillararene-containing thermoresponsive polymers are synthesized via reversible addition–fragmentation chain transfer polymerization using pillararene derivatives as the effective chain transfer agents for the first time. These polymers can self-assemble into micelles and form vesicles after guest molecules are added. Furthermore, such functional polymers can be further applied to prepare hybrid gold nanoparticles, which integrate the thermoresponsivity of polymers and molecular recognition of pillararenes.



1. Introduction

Host–guest chemistry continues to be the central of supramolecular chemistry.[1] Recently, introducing host molecules into polymers has attracted much attention.[2] Host molecules, such as crown ether,[2a,b] cyclodextrins (CDs),[2c] and cucurbiturils[2d] have been introduced into polymers. For example, Jiang and Wang first reported the construction of polymeric micelles by using host–guest inclusion complexation between hydrophilic β-CD-containing poly(glycidyl methacrylate) (PGMA-CD) and hydrophobic adamantane-containing poly(*tert*-butyl acrylate) (PtBA-ADA).[3] Sawamoto developed cation template mediated cyclopolymerization of poly(ethylene glycol) dimethacrylates, yielding polymeric pseudo-crown ethers with large in-chain cavities for unique cation recognition.[4] As pioneers in this field, Harada and his co-workers even obtained macroscopic supramolecular hydrogel using polyacrylamide functionalized with host (cyclodextrin) or guest (adamantane, ferrocene, or azobenzene) moieties.[5] These hydrogels exhibited self-healing properties and the strength of such supramolecular materials could be restored completely through host–guest interactions. Therefore, introducing host molecules into polymers could bridge supramolecular chemistry and macromolecular self-assembly, and consequently provide new methods to prepare functional materials.

Pillararenes, a new generation of supramolecular hosts since first reported by Ogoshi in 2008,[6] have attracted much attention.[7] They are composed of 1,4-alkylbenzene linked by methylene bridges at the *para* positions. Due to their novel symmetric pillar-shaped architectures, unique host–guest properties and particularly facile functionalization,[8] pillararenes play important roles in constructing interesting supramolecular systems, such as supramolecular polymers, transmembrane channels, drug

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Macromol. Rapid Commun. **2015**, DOI: 10.1002/marc.201500167

delivery systems.[9] Great efforts have been made in the synthesis of pillararenes with different repeating units and their derivatives,[8] their host–guest interaction,[10] and their self-assembly behavior,[11] but introducing pillararenes into polymers is quite limited.[10,12]

On the other hand, gold nanoparticles (AuNPs) have attracted growing interest and been widely used for the recognitions, sensors, biomedicine, and catalysis due to their high chemical stability, facile synthesis, and easy surface functionalization.[13] The surface modification of gold nanoparticles may affect the performance, and host–guest interaction provides an effective method to get synergistic effects when combining gold nanoparticles with macrocycles.[14]

In the present work we, for the first time, report the synthesis of pillararene-containing thermoresponsive polymers poly(*N*-isopropylacrylamide) (PNIPAM) via reversible addition-fragmentation chain transfer (RAFT) polymerization, in which pillararene on the end of polymer chain could bind with pyrazinium salt and self-assembly into vesicles. Such pillararene-containing polymers were further applied to prepare PNIPAM stabilized AuNPs, which not only shows the thermoresponsiveness of PNIPAM, but also exhibits the molecular recognition of pillararenes (Scheme 1).

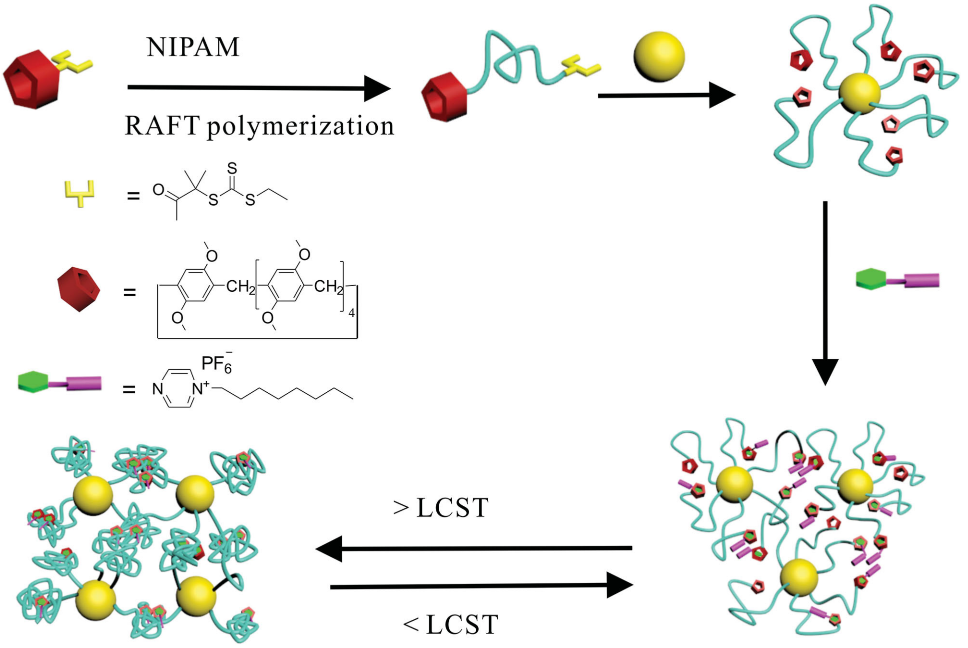
2. Experimental Section

All experiment details were described in the Supporting Information.

3. Results and Discussion

3.1. Synthesis of Polymers

To obtain end functional polymers, controlled radical living polymerizations are widely used, including nitroxide mediated polymerization (NMP),[15] atom transfer radical polymerization (ATRP),[16] and RAFT.[17,18] RAFT polymerization was used in this work because of the facile modification of hydroxyl group on pillararene to form host molecule functionalized chain transfer agent (CTA). Selection of CTA is crucial to obtain end functional polymers with narrow dispersion,[19] and compound containing trithiocarbonate group could serve as excellent CTA when acrylamide was used as the monomer.[20] Based on these literature studies, P5A functionalized compound (P5A-CTA, Scheme S1, Supporting Information, and characterization in Figures S1–S3, Supporting Information) was first designed and synthesized by condensation reaction of monohydroxyl dimethylpillar[5]arene (DMP5A-OH) with 2-(((ethylthio)-carbonothioyl)thio)-2-methyl-propanoic acid (EMP). Then pillararene end capped PNIPAM (P5A-PNIPAM) was synthesized via RAFT polymerization of *N*-isopropylacrylamide by using P5A-CTA as the chain transfer agent. As shown in Figure 1 and Figure S4 (Supporting Information), P5A-PNIPAM ($M_{n,GPC} = 1.36 \times 10^4$ g mol^{-1}) with a designed degree of polymerization (DP) and narrow polydispersity (PDI = 1.09) was synthesized. Moreover, such obtained polymers (P5A-PNIPAM) could serve as macromolecular chain transfer agents and block copolymers (P5A-PNIPAM-*b*-PDMA) were synthesized via RAFT polymerization of



■ *Scheme 1.* Preparation of the thermoresponsive supramolecular hybrid.

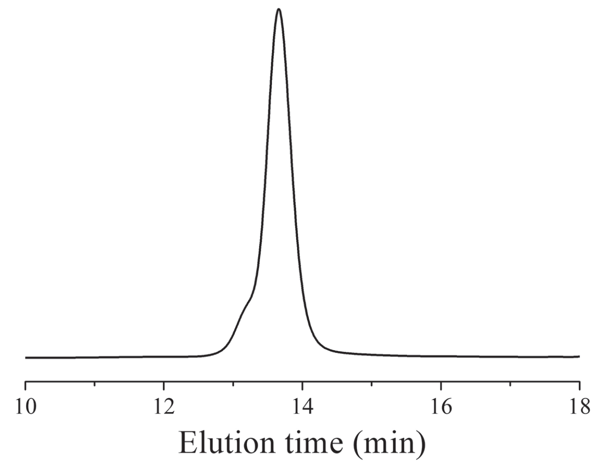


Figure 1. GPC curve of P5A-PNIPAM. Eluent: DMF with LiBr (0.5 mg mL^{-1}).

N,N-dimethylacrylamide (DMA) (Figures S5 and S6, Supporting Information), showing the effectiveness of P5A-CTA as chain transfer agent, although some polymer radicals lost the initiation activity.

3.2. Complexation Interaction between Polymer and Guest

Owing to the end group pillararene, P5A-PNIPAM could form complexes with proper guest, and further construct supra amphiphiles, similar to other supramolecular systems.[21] Herein, *n*-octylpyrazinium hexafluorophosphate (G) was chosen as the guest molecule. The host–guest complexation of P5A-CTA with G and that of P5A-PNIPAM with G were first investigated (Figures S7–S10, Supporting Information). Protons of pyrazinium group and methylene shifted upfield after complexation due to the shielding effect of the electron-rich cavities of pillararenes. The complexation between P5A and G may have effect on the assembly process. As shown in Figure S11 (Supporting Information), P5A-PNIPAM formed micelles with diameter of 15 nm in water. After G was added into P5A-PNIPAM solution, compared to the original clear spheres formed by P5A-PNIPAM, vesicles with diameter of 24 nm were observed, which could be supported by laser light scattering study. DLS and SLS of P5A-PNIPAM with G were performed with variable angles and concentrations (Figures S12 and S13, Supporting Information). The hydrodynamic radius R_h was measured to be 12 nm, independent on the scattering angles and the experimental concentration. The radius of gyration R_g was calculated to be 13 nm, thus R_g/R_h was 1.08, which generally indicates vesicle morphology of the aggregates of assemblies.[22] As compared, DLS of unfunctionalized PNIPAM with G was carried out and the R_h was measured to be 3 nm (Figure S14, Supporting Information), revealing that P5A-PNIPAM formed complexes with G through the host–guest interaction. The reason may be that after G inserted into the cavity of P5A to form complexes, the outside hydrophobic alkyl chains and pillararenes began to aggregate, the irregular arrangement and the rigidity of pillararenes with relative large molecular weight (942 g mol^{-1}) lead to the formation of vesicles. This self-assembly process was rarely reported,[22–24] where the chain end played an important role.

3.3. Preparation of AuNPs and Characterization

The terminal trithiocarbonate groups introduced by RAFT polymerization may enable this functional polymer to stabilize gold nanoparticles through chemisorption.[20,25] Thus polymers covered gold nanoparticles, named P5A-PNIPAM-AuNPs (characterization in Figure 2 and Figure S15, Supporting Information), were obtained by mixing P5A-PNIPAM with citrate-AuNPs, which were prepared according to the literature.[26] The polymer content was 58% calculated by thermogravimetric analysis (TGA, Figure S15, Supporting Information).

This hybrid gold nanoparticles (P5A-PNIPAM-AuNPs) showed good water solubility and kept stable in water for several weeks. Compared to the separate citrate-AuNPs spheres (Figure 2a), polymer rounds exhibited in P5A-PNIPAM coated AuNPs (Figure 2b), showing AuNPs were modified with PNIPAM chains. The diameter of P5A-PNIPAM-AuNPs increased from the original 21 nm (Figure 2e) to 58 nm (Figure 2f), which originated from the P5A-PNIPAM protection and some aggregates of AuNPs. The AuNPs possessed many P5A-PNIPAM chains, which made the latter form extended conformation. The relative high local concentration of P5A-PNIPAM chains may cause the entanglement of polymer chains, which contributed to the light scattering intensity. Furthermore, this hybrid AuNPs could also recognize *n*-octylpyrazinium hexafluorophosphate (G) and form complexes. After excess G was added into the aqueous solution of P5A-PNIPAM-AuNPs, the average particle size increased to 106 nm (Figure 2g) and these particles were linked together (Figure 2c), which revealed that the recognition process made the polymers more hydrophobic, and consequently induced the individual particles to aggregate.[27] This could also be detected from UV–vis absorption spectrum. As shown in Figure S16 (Supporting Information), the maximum absorption of P5A-PNIPAM coated AuNPs red shifted from the original 523 to 529 nm. After G was added, this value even increased to 541 nm, indicating the formation of gold aggregates, caused by the host–guest complexation, hydrophobic property of the outer alkyl chain and entanglement of PNIPAM chains. This property may enable the hybrid AuNPs be used as sensors for surface-enhanced Raman spectroscopy detection.

PNIPAM is a well-known thermoresponsive polymer, which dissolved in water below its lower critical solution

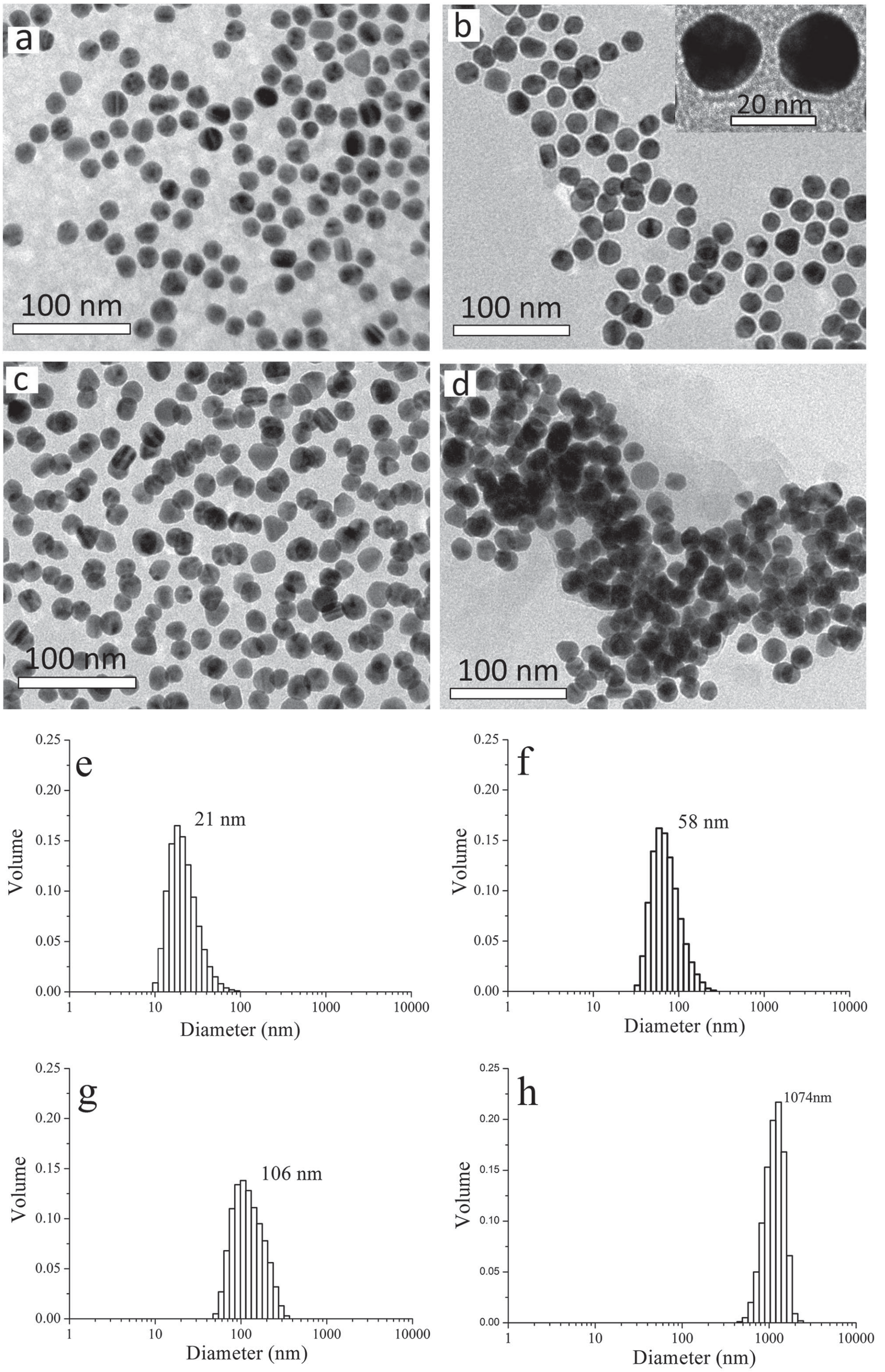


Figure 2. TEM images: a) citrate-AuNPs; b) P5A-PNIPAM-AuNPs; c) P5A-PNIPAM-AuNPs after G was added at room temperature; d) c at 40 °C. e) DLS result of (a); f) DLS result of (b); g) DLS result of (c); h) DLS result of (d).

temperature (LCST), and aggregated above its LCST.[28] This endowed the hybrid AuNPs good temperature responsibility (Figure S17, Supporting Information). As the temperature increased (Figure S17a, Supporting Information), the absorbance dramatically increased and the peak of the surface plasmon resonance (SPR) underwent a red shift, caused by the contraction of PNIPAM chains leading to an increase of scattered light and aggregation of gold nanoparticles. The TEM images gave visual evidence. Aggregated gold nanoparticles were observed (Figure 2d) when the temperature increased to 40 °C. The average diameter of these aggregates was ≈1074 nm from DLS characterization (Figure 2h). When the temperature decreased (Figure S17b, Supporting Information), the absorbance decreased and the peak of SPR underwent a blue shift, for polymer chains were soluble in water again. Thus as expected, the hybrid P5A-PNIPAM-AuNPs exhibited good thermoresponsivity, which could be used as recyclable catalyst. We can perform a chemical reaction using hybrid P5A-PNIPAM-AuNPs as the catalyst, then after increasing temperature above 40 °C, the monodispersed nanoparticles will aggregate and precipitate, leading to easy separation from the reaction system and could be used again. In the present work, the borohydride reduction of *p*-nitrophenol was carried out five times to evaluate the performance of P5A-PNIPAM-AuNPs. The conversion decreased within 3% (Figure S18, Supporting Information), demonstrating that P5A-PNIPAM-AuNPs exhibited good reversibility and catalytic efficiency.

The host–guest complexation may affect the phase transitions. Cloud point (*T*% = 50), dependent on molecular weight, polydispersity, and end group, is always used to understand the phase transition behavior of dilute aqueous PNIPAM solutions.[29] As shown in Figure 3, the transmittance of P5A-PNIPAM decreased when temperature increased from 25 to 35 °C, and this value maintained 25% at 35 °C, revealing a slow phase transition. However, when P5A-PNIPAM was coated to gold surface, the transmittance dropped quickly within 3 °C, and the cloud point decreased from 31 to 30.5 °C. After G was added to the P5A-PNIPAM coated AuNPs, the transmittance decreased within 0.5 °C, revealing a fast phase transition took place. Moreover, the cloud point decreased from 30.5 to 29 °C after G was added. The lower cloud point and more sensitive to temperature revealed that the gold nanoparticles act as a "crosslinker," and the guest G inserted into the cavity of P5A, leading to more hydrophobic end group of PNIPAM chain, in accordance with the literatures.[29,30] The fast phase transition of P5A-PNIPAM-AuNPs could be utilized to detect G and separate it. As shown in Figure S19 (Supporting Information), after increasing temperature to 40 °C, P5A-PNIPAM-AuNPs with most of G precipitated, and only a little G left in the liquid.

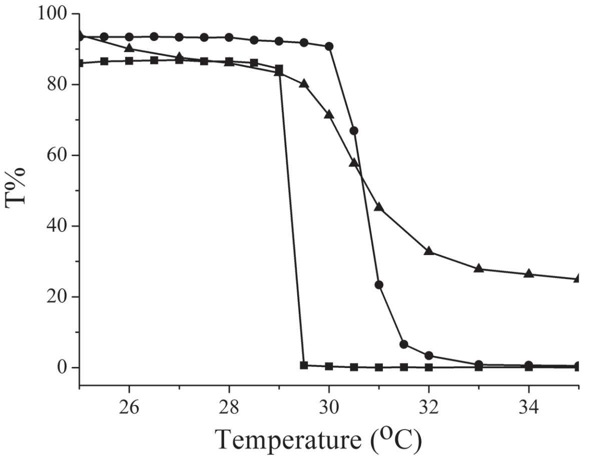


Figure 3. LCST of P5A-PNIPAM (triangle), P5A-PNIPAM-AuNPs before (circle) and after (square) G was added.

4. Conclusions

Narrow-disperse thermoresponsive polymer end capped with pillararene (P5A-PNIPAM) was first synthesized via RAFT polymerization by using P5A-CTA as the effective chain transfer agent. This work provides a new way to introduce pillararenes into polymers, expanding the field of pillararene studies. This polymer could self-assemble to micelles and form vesicles after G was added. Moreover, this functional polymer could be applied to prepare hybrid AuNPs. Such hybrid AuNPs integrated the molecular recognition of pillararene and thermoresponsivity of PNIPAM, which could be utilized as recycle catalyst. After *n*-octylpyrazinium hexafluorophosphate was added, these AuNPs aqueous solution showed lower cloud point, and increased sensitivity to temperature, which could be applied to separate G. Further studies on pillararene-containing polymers and their applications as sensors for surface-enhanced Raman spectroscopy detection are currently underway in our laboratory.

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

Acknowledgements: National Natural Science Foundation of China (No. 21204022), Research Fund for the Doctoral Program of Higher Education of China (No. 20120076120005), the Fundamental Research Funds for the Central Universities, and the Large Instruments Open Foundation of East China Normal University (No. 2014-15) are acknowledged for their financial supports.

Received: March 18, 2015; Revised: May 3, 2015; Published online: ; DOI: 10.1002/marc.201500167

Keywords: gold nanoparticles; host–guest interaction; pillararene; supramolecular chemistry; thermoresponsive polymers

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