Controlled Phase Behavior of Thermally Sensitive Poly(N-isopropylacrylamide/ionic liquid) with Embedded Au Nanoparticles

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ABSTRACT: We have synthesized a series of poly(N-isopropylacrylamide/ionic liquid) with deposited Au nanoparticles. The size of the nanoparticle range was varied from 10 to 35 nm, and these were characterized by transmission electron microscopy analysis. Ionic liquids (IL) were chosen by varying the polymerizable unit to be both in cationic (allyl) and anionic (acrylate) moiety. One-pot polymerization was done with N-isopropylacrylamide and IL using ammonium persulphate as the initiator, which we added already prepared Au NPs. These thermally sensitive composites formed, possessed reversible swelling/deswelling abilities in water, and demonstrated a reversible visible phase transition, which was detected by differential scanning calorimetric measurements. The lower critical solution temperature (LCST) showed dependency on the size of nanoparticles and the IL independently. It was seen that the LCST of PNIPAM-based composite films can be tuned from 32 °C to a range of 23−67 °C by choosing the desired Au NP size, its concentration and kind of IL.

INTRODUCTION

Extremely productive and versatile classes of environmentally responsive materials have been studied since ages which can change their physical, chemical, or electronic conformations on stimuli like light, temperature, pH, ions, electric/magnetic fields, or biological agents. Temperature is one such stimuli present naturally and artificially, making thermo-responsive polymers a fascinating category for examination. These tend to show phase transitions like lower critical solution temperature (LCST) where the polymer shows decreased solubility at elevated temperatures. A simple, intensively effective, and rigorously investigated temperature-sensitive polymers include poly(N-isopropylacrylamide) or PNIPAM. It exhibits a sharp LCST at exactly 31−33 °C in aqueous media, near to physiological body temperature which makes it of tremendous use in biological applications. It undergoes coil-to-globule transition in the presence of water because of changes in conformation around its hydrophobic part. As the temperature of the system is increased, hydrophobic interactions of nonpolar backbone and isopropyl groups becomes dominant, causing the polymer structure to collapse in a globule separated from water. This is visually seen as a turbid occasion. As PNIPAM’s LCST does not depend on the polymer concentration or its molecular weight, tuning of this class of polymer is done widely by adding different salts or entities, by changing the functionalities or via co-polymerization. These tuned LCST of composites/hybrids gives potential for utilization in drug deliveries, sensors, catalysis, bioengineering, separation, and so forth.

One such method to tune the LCST of polymers can be the use of green solvents, ionic liquids (IL) as co-monomers. Its general properties include low vapor pressure, high electrical and chemical stability, high conductivity, and most importantly, their designability on the basis of hydrophilic/hydrophobic parts, providing tunability. Other versatile properties of these environmentally benign solvents depend on the class of ILs being utilized. For example, pyrrolidinium-based ILs have high energy storage capacity, making them suitable for heat transfer media, while phosphonium-based ILs lack acidic protons and are less dense than water, which make them apt for separation. Meanwhile, imidazolium-based ILs are the best candidates when polarity or hydrophobicity/hydrophilicity needs to be tailored for a chosen application. Kohno and Ohno have already reported the important role of hydrophobicity, making it the key factor to show LCST/UCST of amino-acid based ILs in aqueous media. Thus, ILs become an important class of materials based on the phase transitions. Our group has previously reported the tuning of LCST of PNIPAM by copolymerizing with imidazolium based ILs. We have observed the tuning of random co-polymers of PNIPAM/IL which showed clear dependency on hydrophobicity of cations and nature of anions.

Nowadays, nanoparticle (NP) chemistry is a hot topic and is currently under intense research. Gold NPs (Au NPs) display...
distinctive physiochemical properties\textsuperscript{24} based on different shape,\textsuperscript{25} size,\textsuperscript{26} solubility,\textsuperscript{27} and pH.\textsuperscript{28} They show localized surface plasmon resonance (LSPR) and a strong absorption in UV–vis–NIR range.\textsuperscript{29} Hence, they become very effective in the utility of electronics\textsuperscript{29} catalysis,\textsuperscript{30} optics,\textsuperscript{31} diagnosis,\textsuperscript{32} biomedicine,\textsuperscript{33} and sensing.\textsuperscript{34} It was already known that citrate-protected NPs are susceptible to easy aggregation.\textsuperscript{35} To overcome this problem, very recently, modification on PNIPAM is under way with the use of Au NPs.\textsuperscript{36,37} Different methods like grafting-to and grafting-from have been developed to create PNIPAM brushes /shells /nanocomposite\textsuperscript{37} coated over Au NPs. Hoogenboom et al.\textsuperscript{38} reported the use of PNIPAM-coated Au NPs in salt and its colorimetric sensing. Yuan et al.\textsuperscript{39} have used the PNIPAM-modified Au NP for bioactivity modulation. Many other groups are studying the mechanistic and kinetics of the variety of growth method, shell responses, and phase transitions over NPs.\textsuperscript{40–43} It was also reported by Hu et al.\textsuperscript{44} that plasmonic NPs like Au improve the thermal and light sensitivity of thermo-sensitive polymers because they act as anchors to restrict the hydrophobic chains of the polymers from rotating at an early stage, thereby inducing a greater demand of thermal energy to collapse. However, systematic dependence on the NP size has not been studied yet.

Taking inspiration from the above research perspectives, it seems quite interesting to incorporate distinct sizes of Au NP in PNIPAM/IL copolymers and study its effect. It is believable that the polymerized IL can stabilize the Au NPs and in turn, NPs could enhance the light to thermal efficiency of the thermos-sensitive polymer. This would double the opportunity of its use in different applications.\textsuperscript{45,46} Thus, in our study, hydrophilic citrate-coated Au NPs ranging from 10 to 35 nm in size have been prepared according to the literature. Further, in the presence of these NPs, copolymerization of N-isopropylacrylamide (NIPAM) with polymerizable N,N′-di-substituted imidazolium-based ILs was done using ammonium persulphate to form a polymer film which showed tunable reversible LCST behavior in water. How the size of NPs and structure of IL affect the LCST and how they can be further tuned were studied as the key points of understanding.

\section*{RESULTS AND DISCUSSION}

For the synthesis of Au NPs, different reaction conditions were employed to create particles in the range 10–35 nm (Figure 1). Many factors including temperature were varied in the reaction procedure to obtain the desired diameter of the particles. Transmission electron microscopy (TEM) showed that monodispersed NPs were formed with the polydispersity lying between 1.5 and 7.3%. The in situ copolymerization of Au@PNIPAM-co-IL was done using ammonium persulphate as the initiator for the free-radical polymerization. A 10 mol % of bisacrylamide was added, while the reaction proceeded to ensure the formation of a 3D polymer network. The synthesis was confirmed by \textsuperscript{1}H NMR in DMSO-\textsubscript{d}\textsubscript{6} (Figure 2). Matrix-assisted laser desorption ionization time-of-flight (MALDI-TOF) measurements showed the molecular weight of the matrix to be in the order of \~1050 g/mol. Hence, a low-molecular weight oligomer framework was synthesized for PNIPAM-co-IL. TEM analysis was also carried out which showed the Au NPs being distinctively embedded and dispersed into the copolymer matrix of NIPAM and IL (Figure 3b). The size of the Au NP remained almost the same after the polymerization, which suggested the absence of aggregation of particles once incorporated into the matrix. This emphasises the fact that IL-containing copolymer chains acted as a stabilizing ligand for the particles.\textsuperscript{41}

For the LCST temperature determination, 1 mg of the copolymer was dissolved in 2 mg water and dissolved solution made above after sonication was taken and subjected to differential scanning calorimetry at a rate of 1 °C/min for 15–90 °C. Thus, the effect of structure of polymerizable ILS and size of Au NPs was studied on the LCST of this polymer matrix.

\textbf{Effect of Polymerizable IL on LCST of Au@PNIPAM-co-IL Composites.} Under constant size of Au NPs (sample 1: 10 nm), structures of IL were changed and the results of LCST measurements were as procured in Table 1. It is seen clearly that the phase transition temperature depends on the hydrophobicity/hydrophilicity of the IL as excepted. For example, Au(10 nm)@PNIPAM-co-A1mCl has the LCST of 41 °C, whereas Au(10 nm)@PNIPAM-co-AO1mTFSI has it at 23 °C. A1mCl is the most hydrophobic moiety among the IL
structures we examined, where chloride ions and short alkyl chains (allyl and methyl) have strong ion-dipole forces to overcome the hydrogen bonds between water molecules. Hence, it takes enough energy to surpass this condition and for hydrophobicity of the allyl group to become dominant, thereby delaying the phase transition temperature from 32 °C of pure PNIPAM to 41 °C. As we increase the hydrophobicity in the IL moiety by increasing the chain length from hexyl-methyl to allyl-octyl, the LCST temperature decreased. Thus, Au(10 nm) @PNIPAM-co-HMImAcr has LCST of 39 °C, while Au(10 nm)@PNIPAM-co-AOImBr has 33 °C. As it is already known that TFSI is a bulky anion water-repellent in nature, it became interesting to note that the LCST when using this IL becomes lower even than the pure PNIPAM. As more of the hydrophobic moieties are introduced in water, because of the hydrophobic effect, there happens a greater interference with the hydrogen bonding. Hence, the LCST temperature is lowered. Hence, both cation and anion play a key role in the phenomenon of phase behavior.

Thus, keeping the size of NPs constant, hydrogen bonding of the polymer chains water plays a significant role toward LCST. This suggests that changing the hydrophobic/hydrophilic nature of the IL can help in the fine-tuning of the LCST of these copolymers. Here, just by changing the structure of the IL, the LCST can be customized from 32 to 23−41 °C. This trend is systematic and was similarly observed in all the ILs irrespective of any NP size. Not to forget, different sized NPs will yield different results, which can be used to further tune the phase behavior of systems and will be discussed in the subsequent sections. Effect of Au NP size on LCST of Au@PNIPAM-co-IL composites was studied.

In this research work, the diameters of the spherical NPs were varied from 10 to 32 nm in 6 different sizes (Table 2). The normalized DSC profiles showed distinguished endo-thers because of the LCST temperature (Figure 4). The LCST temperatures are listed in Table 2. It is observed that LCST increased as the size of the NPs increased irrespective of the IL structure. This can be clearly perceived upon discussing each case particularly. Starting with the results for Au@PNIPAM-co-AMImCl, with the enlarged sized induction of...
Table 2. LCST Temperatures Obtained by DSC for (a) Au@PNIPAM-co-AOImTFSI, (b) Au@PNIPAM-co-AOImBr, (c) Au@PNIPAM-co-HMImAcr, and (d) Au@PNIPAM-co-AMImCl

| NP name | size (nm) | LCST (°C) |
|---------|-----------|-----------|
| Au-1    | 10        | 23        |
| Au-2    | 17        | 32        |
| Au-3    | 20        | 33        |
| Au-4    | 23        | 36        |
| Au-5    | 24        | 38        |
| Au-6    | 32        | 43        |

| NP name | size (nm) | LCST (°C) |
|---------|-----------|-----------|
| Au-1    | 10        | 33        |
| Au-2    | 17        | 40        |
| Au-3    | 20        | 42        |
| Au-4    | 23        | 44        |
| Au-5    | 24        | 46        |
| Au-6    | 32        | 51        |

| NP name | size (nm) | LCST (°C) |
|---------|-----------|-----------|
| Au-1    | 10        | 39        |
| Au-2    | 17        | 45        |
| Au-3    | 20        | 50        |
| Au-4    | 23        | 54        |
| Au-5    | 24        | 56        |
| Au-6    | 32        | 64        |

| NP name | size (nm) | LCST (°C) |
|---------|-----------|-----------|
| Au-1    | 10        | 41        |
| Au-2    | 17        | 47        |
| Au-3    | 20        | 51        |
| Au-4    | 23        | 53        |
| Au-5    | 24        | 58        |
| Au-6    | 32        | 67        |

NPs from 10 to 17 nm in the matrix, LCST increased from 41 to 47 °C. With increasing NP size subsequently to 32 nm, the attained maximum LCST was at 67 °C. This reason can be well deciphered if we understand the mechanism at the subatomic level. Because the NPs are well distributed in the matrix, Au NPs can act like anchors and control the movement of the polymer chains. They reduce the rotation of polymer chains and IL moieties to restrict the formation of the hydrophobic globule. This delays the molecular conformational change of polymers and thus, a greater amount of energy is required to overcome this restriction, which fosters an increase in the LCST temperature. As we keep the concentration of the NPs constant, it can also be presumed that as the size of the NP is increased, the limitation of the bond rotations increases.

When the IL is changed to hydrophilic one, that is, HMImAcr, for the copolymers Au@PNIPAM-co-HMImAcr, the lowest LCST of 39 °C was achieved when the spherical diameter was smallest and it further increased to 64 °C as the size of NPs increased. The trend is the same as observed for Au@PNIPAM-co-AMImCl. However, the LCST of Au@PNIPAM-co-HMImAcr was lower than Au@PNIPAM-co-AMImCl because of the more hydrophobic nature of HMImAcr. Later, keeping the bromide ion as the anion, the chain length of IL was increased from hexyl—methyl to allyl—octyl, which was apt enough to show the LCST similar to that of PNIPAM at 10 nm of Au size. Then, the same dependency was observed on the NP size.

The results became more fascinating when we further decreased the hydrophilicity in the IL structure and changed it to AOImTFSI. For Au@PNIPAM-co-AOImTFSI, the general trend remained same, but when the Au NP size was 10 nm, its LCST was even lowered compared to that of PNIPAM. The reason for this circumstance can be that AOImTFSI has a long alkyl chain (octyl) and bulky bis(trifluoromethanesulfonyl)-imide anion, both of which are much hydrophobic in nature. Thus, hydrophobicity of both the cation and anion in the IL became so dominant that the LCST was lowered from 32 to 23 °C.

To picture the image of how captivating the dependency of NP size and IL structure is on the LCST of these Au@PNIPAM-co-ILs, a three-dimensional plot was created as represented as in Figure 5. The LCST is contingent upon the Au NP size and IL structure. Careful investigation of the 3D plot portrayed the increase in phase transition temperature of the film can be seen as a function of the size of NPs. Thus, this conveys the fact that LCST is independently yet synergistically dependent on both the factors. Both can be individually or equally worked upon to tune the LCST of the colored copolymer film. Hence, it is possible to widen the temperature range of PNIPAM from 32 to 23−67 °C. As four of the ILs showed a similar trend, it becomes viable to assume the trend might be followed by another types of ILs. This can aid in the customization of the phase behavior of the materials tailored to the user’s needs.

To study the effect of change on concentration of NPs in the hybrid, different concentrations of NPs (Table 3) were added while preparing the hybrids. The DSC was performed and evaluated as in Figure 6. It was seen that as the concentration of NPs increases, the LCST temperature increases (Figure 7). As expected, if the concentration of NPs in the hybrid is high, the frequency to act as anchors is enhanced, thereby delaying the formation of hydrophobic globules. Hence, it was seen that concentration of NPs does play an important role in determining the phase transition temperature of these NP-based hybrids.

To investigate the mechanism of Au NPs on the film further, control experiments were also carried out wherein, no NPs were added while synthesizing the films. Therefore, the films obtained were PNIPAM-co-IL and their LCST was recorded as shown in Table 4. As already observed by our group in previous reports, Au@PNIPAM-co-IL can also alter the LCST of PNIPAM up to a certain limit, which was observed in this case as well. This study reveals that Au NPs do play an important role in modifying the LCST of copolymer. It was very keen to discover that all PNIPAM-co-IL films show LCST as if they were induced with the Au NP of size 20−24 nm. This becomes interesting as there might be the threshold of rotation caused by the hydrophobic bonds. Irrespective of the kind of IL used, the LCST lies as if size of diameter is in this range. This reason can be followed by another types of ILs. This can aid in the customization of the phase behavior of the materials tailored to the user's needs.
temperature play an important role for the swelling/shrinking/aggregation and cloud point (LCST) of the systems. Gibson et al.\textsuperscript{13} have prepared PNIPAM-coated NPs with molecular weight being 2800, 5700, and 11300 g/mol while varying the NP size from 15 to 40 nm. They showed that there is no LCST when the molecular weight is 2800 g/mol, while with 5700 g/mol, it was 74°C. This showed that molecular weight is an important factor to determine the LCST of this system. Our results showed that Au@PNIPAM-co-AOIm-IL show LCST even when the molecular weight is low enough because of strong plasma resonance.

| concentration of Au NPs/m moles | LCST (°C) |
|---------------------------------|-----------|
| 7.8 × 10\textsuperscript{-12}   | 42        |
| 6.9 × 10\textsuperscript{-11}   | 45        |
| 1.4 × 10\textsuperscript{-9}    | 57        |
| 2.1 × 10\textsuperscript{-9}    | 60        |

Figure 4. DSC profiles for LCST determination of (a) Au@PNIPAM-co-AOImTFSI, (b) Au@PNIPAM-co-AOImBr, (c) Au@PNIPAM-co-HMImAcr, and (d) Au@PNIPAM-co-AMImCl (in graph—Au is plotted by varying the size of NPs).

Figure 5. 3-D plot depicting the simultaneous dependence of type of IL in copolymers and size of Au on LCST of Au NP-induced copolymers.

Table 3. LCST of Au-20@PNIPAM-co-AOImBr by Varying the Concentration of Au NPs

Figure 6. DSC profiles for LCST determination of Au@PNIPAM-co-AOImBr by changing the concentration of Au NP in the hybrid.
CONCLUSIONS

Novel Au NP-embedded PNIPAM-co-IL polymers were systematically designed and elucidated for their phase transition properties. NP size was varied from 10 to 35 nm. Structures of polymerizable IL were varied by changing both the cation and anion specifically. LCST can be altered by varying the size of NPs used or the concentration of the NPs used or changing the hydrophobicity/hydrophilicity in the IL structure. All the factors played an essential role in tuning the LCST and that can widen the range to 23−67 °C. The results can be utilized for the profound understanding of the LCST behavior of PNIPAM-based materials, its mechanism, and effect of NPs. The present tuning provides a fruitful strategy for custom-designed thermo-sensitive materials and their applications.

EXPERIMENTAL SECTION

Materials. 1-Methylimidazole, acetonitrile, diethylether, bromooctane, allylchloride, trisodium citrate, and bis-acrylamide (Wako Co. Ltd.); acrylic acid, NIPAM, 1-allylimidazole, lithium bis(trifluoromethanesulfonyl)imide, and N,N,N′,N′-tetramethylenenediamine (TEMED) (Tokyo Chemical Industry Co. Ltd.); bromohexane, ammonium persulphate, l(+)-ascorbic acid, and gold chloride (Sigma-Aldrich); all were used as received.

Instrumentation. Nuclear magnetic spectroscopy (400 MHz) was performed on Ultrashield PLUS Bruker, Z10135S, used to characterize ILs. A JASCO V-630 UV−visible spectrometer was employed for NP absorbance measurements and LCST confirmation. TEM was carried out on a Hitachi H-7100 model at 100 kV to characterize the NP size and composite formation. LCST determination was done on a differential scanning calorimeter Shimadzu DSC-60Plus. MALDI-TOF was carried out on a PerSeptive Biosystems (now Applied Biosystems Inc.) Voyager DE RP.

Synthesis of ILs. The ILs synthesized were, namely, 1-allyl-3-methylimidazolium chloride (AMImCl), 1-hexyl-3-methylimidazolium acrylate (HMImAcr), 1-allyl-3-octylimidazolium bromide (AOImBr), and 1-allyl-3-octylimidazolium bis-(trifluoromethanesulfonyl)imide (AOImTFSI). The synthesis was done as already reported in literature55 (Scheme 1a). All the ILs were characterized by 1H NMR.

Synthesis of Au NPs. Different methods were used to prepare different sizes of Au NPs.26,56−58 Trisodium citrate was used as the main reducing and capping agent. However, to prepare smaller particles, a second reducing agent, that is, ascorbic acid was used. The concentration was measured using the absorbance values from UV−visible spectroscopy, and size distribution was analysed by TEM. The spherical diameters were obtained via size distribution curves (Figure 1) and are mentioned in Table 2.

Preparation of samples 2−5: 0.2 mL of 0.066 mM gold chloride(III) solution was taken in 50 mL water in a 100 mL round bottom flask. It was then heated to boiling for 15 min with a constant stirring at 600 rpm. Respective volume (Table 5) of 0.040 mM trisodium citrate solution was added, and the reaction was stirred at same rpm for 1 h at 80 °C. The solution was cooled to room temperature and further subjected to characterizations.

Preparation of samples 1 and 6: 2.2 mM trisodium citrate solution was prepared in 150 mL water. (0.1 mL 2.5 mM ascorbic acid was added to sample 1 to reduce the size of NPs formed). The solution was heated to 70 °C (sample 1) and 150 °C (sample 6) for 15 min under vigorous stirring. Then, 1 mL 25 mM gold chloride solution was added, and the resulting

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Table 4. LCST for PNIPAM-co-IL

| name                     | LCST (°C) |
|--------------------------|-----------|
| PNIPAM-co-AMImCl         | 56        |
| PNIPAM-co-HMImAcr        | 53        |
| PNIPAM-co-AOImBr         | 44        |
| PNIPAM-co-AOImTFSI       | 34        |

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Scheme 1. Synthetic Schemes for (a) ILs and (b) Au@PNIPAM-co-IL
mixture was stirred at 90 °C for an hour. The solution was cooled to room temperature and further subjected to characterizations.

Syntehsis of Au NP-Embedded Copolymers of NIPAM and ILs Au@PNIPAM-co-IL (Scheme 1b). A modified synthetic scheme has been employed, and 1.5 mmol of NIPAM and 0.15 mmol of IL (AMImCl/AOImBr/AOImTF-SI/HMImAc) were mixed in 1 mL water. Bisacrylamide (10 mol %, 25 mg, 1.65 mmol) and TEMED (5 mol %, 10 mg, 0.086 mmol) were added to the solution and were sonicated for 5 minutes to completely solubilize, and 7.8 × 10⁻³ mmol Au solution (of required size) was added. (Different concentrations of NPs viz., 6.9 × 10⁻¹¹, 1.4 × 10⁻⁹, 2.1 × 10⁻⁹ mmol were added to study the concentration dependence). The resulting mixture was put to a plastic vial, and 80 μL of 5 wt % APS as a polymerization initiator was added. The mixture was heated in a vacuum oven at 60 °C till the solvent evaporates. After 3 days, a colored polymer film (blue to red) was obtained, which was rigid in nature.

Table 5. Reaction Concentrations, Size, and Wavelength Measurements for Au NPs

| sample name | AuCl₃ conc. | sodium citrate conc. | additive | size of NP | absorbance/nm |
|-------------|-------------|----------------------|----------|------------|---------------|
| Au-2        | 0.2 mL, 0.066 mM | 0.2 mL, 0.040 mM | 50 mL water | 17.5 ± 0.5 | 520.5 |
| Au-3        | 0.2 mL, 0.066 mM | 0.4 mL, 0.040 mM | 50 mL water | 20.0 ± 0.3 | 523.0 |
| Au-4        | 0.2 mL, 0.066 mM | 0.8 mL, 0.040 mM | 50 mL water | 23.7 ± 1.5 | 526.5 |
| Au-5        | 0.2 mL, 0.066 mM | 1.6 mL, 0.040 mM | 50 mL water | 24.3 ± 1.1 | 529.5 |
| Au-1        | 1.0 mL, 25 mM    | 150 mL, 2.2 mM     | 0.1 mL, 2.5 mM ascorbic acid  | 10.9 ± 0.8 | 536.0 |
| Au-6        | 1.0 mL, 25 mM    | 150 mL, 2.2 mM     | water     | 32.9 ± 2.0 | 525.5 |

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