Janus Supraparticles by Induced Phase Separation of Nanoparticles in Droplets

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Janus particles are non-centrosymmetric particles with two distinct sides.[1–3] The two sides may differ in surface wettability or in optical, electrical, or magnetic properties. Depending upon the anisotropic properties, these particles can be used as emulsion stabilizers, analogous to surfactant molecules,[4–7] optical probes for chemical, biological, or rheological measurements,[8–11] or building blocks for electronic paper or displays based on particle-actuation.[12–14] The early and most intuitive methods for making Janus particles involved differential surface modification of the two sides of solid particles.[4,15–17] However, uniform surface modification of one side of the particles without affecting the surface of the other side can be challenging. Also, such cosmetically functionalized particles are not truly bicompartmental as they possess a homogeneous core. Bicompartmental Janus particles can be made by spinning disk techniques[14] wherein, a bilayered jet of two dissimilar molten polymers, ejected off the edge of a spinning disk, breaks down into Janus droplets that are cooled and solidified in air. Such particles can also be made by the simultaneous electrohydrodynamic jetting of parallel polymer solutions under the influence of an electrical field.[1,18] A significant limitation of these two techniques is that Janus particles produced using them exhibit a high degree of polydispersity. Alternatively, microfluidic techniques can be used to fabricate bicompartmental Janus particles of different shapes and chemical compositions.[6,12,19–22] These techniques entail co-flowing two dissimilar monomer streams in parallel at low Reynolds numbers. Janus particles are formed within the microfluidic channels by photopolymerizing the droplets formed by the controlled breakup of these parallel streams,[12,19,22] or by photopolymerizing across these streams using continuous flow lithography with a mask-based template.[6] An advantage of the microfluidic techniques is the highly monodisperse Janus particles that can be made with relative ease in one step. However, since these particles are produced one at a time, a single device can generate only a few tens of grams of particles per day. Also, the microfluidic device must be shielded from any perturbations that disturb the laminar flow of the co-flowing streams or cause convective cross-mixing of the monomers within the droplets, since, these effects can lead to formation of particles with undesirable internal morphologies.[12] Moreover, most current fabrication processes offer very limited flexibility in adjusting the relative volumes of the two phases of the Janus particles. Thus, a robust and scalable technique for producing Janus particles with a tunable internal morphology is strongly desirable, as such a technique would expand the portfolio of the properties of such particles and potentially lead to new commercially viable applications.

In this paper, we describe a versatile and robust technique to fabricate Janus particles with a novel, highly anisotropic, and finely tunable internal architecture. We generate microparticles with one side composed of a hydrogel and the other side composed predominantly of aggregated colloidal nanoparticles. The creation of Janus particles with such a unique internal morphology is facilitated by the induced phase separation of colloidal nanoparticles in droplets. By using microfluidic devices, this technique can be used to make extremely monodisperse particles; moreover, this technique can also be combined with bulk emulsification methods, such as membrane emulsification, to produce Janus particles in large quantities for more commercially viable applications. We demonstrate the technique by forming Janus particles with polyacrylamide (PAAm) as the hydrogel and poly(*N*-isopropylacrylamide), PNIPAm, microgels as the nanoparticles. The thermosensitive nature of the PNIPAm microgels offers a means of control for precisely tuning the relative volumes of the two phases. The functional dichotomy of the Janus particles can be further enhanced by embedding different functional materials selectively into any of the two sides of the particles as illuistrated by the incorporation of magnetic nanoparticles in the microgel-rich phase of the particles.

We begin with *N*-isopropylacrylamide, NIPAm, monomer which is subsequently polymerized by precipitation polymerization in an aqueous phase to yield an aqueous suspension of ≈500–nm-diameter PNIPAm microgels. Allylamine (5 mol%) is copolymerized along with the NIPAm monomer to incorporate reactive amine groups into and onto the microgel particles. The cationic nature of the microgels was confirmed by measuring the electrophoretic mobility of the particles which was found to be $0.9 \times 10^{-8}\,m^2\,v^{-1}s^{-1}$. To this microgel suspension we add a small amount of an oppositely charged water soluble polymer, a high molecular weight polyacrylic acid (PAAc), to induce clustering of the microgels by electrostatic interactions between the ammonium ions of the microgels and the carboxyl groups of PAAc.[23] We also dissolve 10 wt% acrylamide in the microgel suspension along with a crosslinker (methylene-bis-acrylamide) and a

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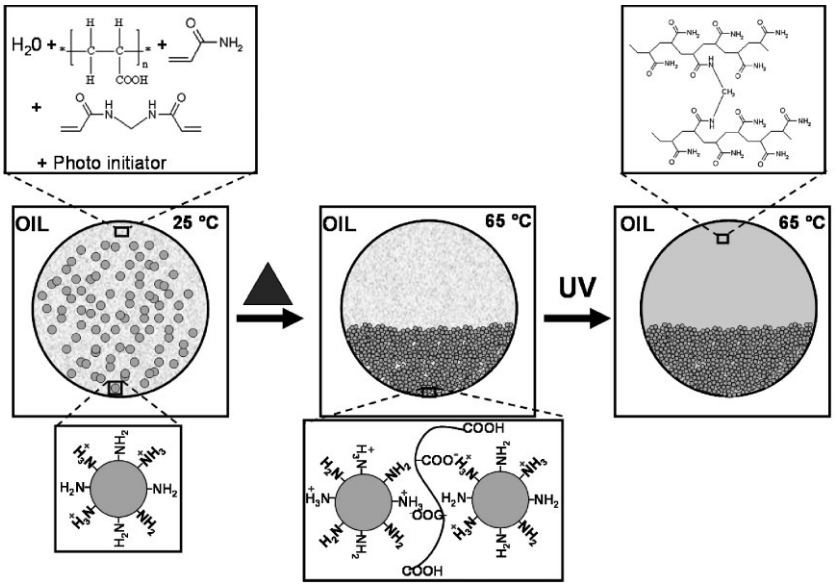

Figure 1. Schematic representation of the process employed for making Janus supraparticles. Aqueous droplets containing the cationic PNIPAm microgels, polyacrylic acid, acrylamide, methylene bisacrylamide, and a photoinitiator are formed in a silicon oil. Upon heating, the microgels shrink and aggregate on one side of the droplet under the combined influence of the high temperature and the electrostatic interactions between them and polyacrylic acid. The acrylamide monomer forced into the other side of the droplets is then polymerized and gelled using ultraviolet light to form Janus gel particles whose one side is composed of acrylamide and other side is composed of PNIPAm microgels.

photoinitiator. This aqueous mixture is emulsified in an oil and heated at 65 °C in an oven. PNIPAm is a thermosensitive polymer that exhibits a phase transition at ≈ 32 °C;[24–26] the microgels are hydrophobic above this transition temperature and hydrophilic below this temperature. When the emulsion is heated to 65 °C, the weakly associated PNIPAm microgel aggregate shrinks and becomes compacted on one side of the droplets by pushing the acrylamide containing water to the other side, thus forming phase-separated Janus droplets. The acrylamide monomer is then polymerized and cross-linked by exposure to ultraviolet (UV) radiation, forming Janus supraparticles with a PNIPAm microgel-rich side and an PAAm-rich side. The overall scheme is presented in Figure 1.

Since the particles are generated by inducing phase separation in preformed droplets, the technique can be combined with any emulsification method to produce Janus particles. Thus, bulk emulsification methods, such as membrane emulsification, can be employed to produce Janus particles on a large scale. However, since the particles use the droplets as templates, the polydispersity of the Janus particles is set by that of the droplets. For applications that require extremely monodisperse particles, monodisperse droplets made using microfluidic techniques should be used as templates. Drop formation in microfluidic devices results from a balance of the interfacial tension between the two phases and the shear exerted by the continuous phase on the dispersed phase. Since the interfacial tension between the two fluids is constant and the shear rate can be precisely adjusted in these devices, droplets with less than 1% polydispersity can be efficiently made.[27] Here, we demonstrate the fabrication of monodisperse Janus particles using a capillary based microfluidic device.

Our microfluidic device is composed of coaxially aligned glass microcapillaries.[27] The outer capillary has a square cross-section and the inner capillary has a round cross-section. The coaxial alignment is achieved by matching the outer dimensions of the round capillary with the inner dimensions of the square capillary. Prior to its placement within the square capillary, the round capillary is heated and pulled using a pipette puller to create a gradual taper that culminates in a much finer circular orifice. The square capillary serves as a flow channel for the two individual fluid streams while the circular capillary serves as a collection tube for the emulsion. A schematic representation of the device and a camera image of the actual device are included in the Supporting Information (Fig. S2). The surfactant-containing silicon oil flows from one end of the square capillary and focuses the monomer-containing aqueous phase flowing from the opposite end into the orifice of the collection tube. The aqueous phase breaks into monodisperse droplets upon entering the collection tube to form an emulsion of monodisperse droplets as shown in Figure 2a. Once collected, the emulsion is heated at 65 °C

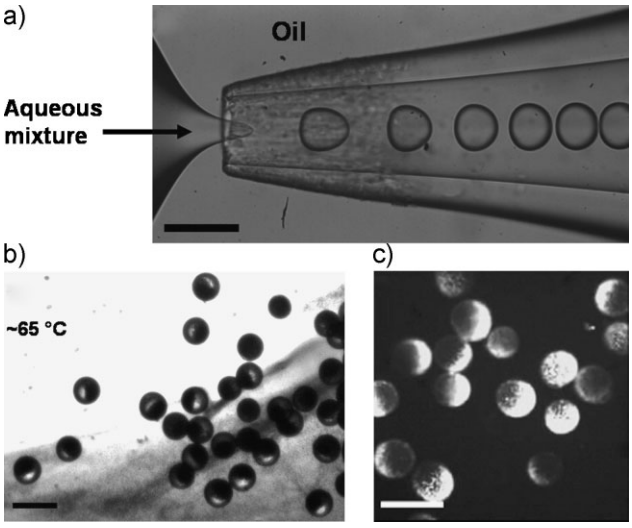

Figure 2. a) Formation of monodisperse droplets in a microfluidic device with a flow focusing geometry. The dispersed phase is an aqueous suspension composed of cationic PNIPAm microgels, polyacrylic acid, and photopolymerizable monomers while the continuous phase is silicon oil containing a surfactant. b) Aggregation and compaction of the PNIPAm microgels on one side of the droplets upon heating the emulsion at ≈65 °C. c) A fluorescent microscope image of Janus particles formed by photopolymerizing the monomers in the phase separated droplets. The PNIPAm microgels are tagged with Rhodamine B to enhance visual contrast between the two phases. The scale bars are 200 μm.

in an oven, which causes the microgels to shrink and compact on one side of the droplets, thus forming monodisperse Janus droplets (Fig. 2b). Monodisperse Janus gel microparticles are formed when the acrylamide is polymerized by exposing the phase separated droplets to UV radiation. At this point, the dimensions and the positions of the microgels become fixed and their volume does not change in response to changes in the external temperature. A fluorescent microscope image of the Janus particles is presented in Figure 2c. The PNIPAm microgels are tagged with rhodamine B to enhance visual contrast between the two phases. Since, the phase separation process occurs downstream of the microfluidics process, the problems associated with the convective mixing of the monomers, often encountered during the co-flow microfluidic techniques for making Janus particles, are eliminated.[12] This technique is not just limited to the fabrication of spherical Janus particles but can also be extended to other shapes. We demonstrate the versatile applicability of this technique by forming a Janus structure in bulk by separating the two hydrogel phases in a glass vial (Supporting Information Fig. S3).

The microstructure and phase boundaries of these particles were further probed using a scanning electron microscope (SEM). A larger sized Janus particle (≈ 2 mm diameter) was used for this purpose to visually allow suitable orientation of the particle on the SEM specimen stub. The images reveal a rougher surface for the PNIPAm phase in contrast to a relatively smooth surface for the PAAm phase (Fig. 3a). A high magnification micrograph of the PNIPAm phase reveals a raspberry like structure formed by the aggregation of the PNIPAm microgels (Fig. 3b). The surfaces of both sides reveal wrinkles and stretch marks caused by the dehydration of the hydrogels during sample preparation for electron microscopy. The micrographs also reveal a somewhat continuous phase surrounding the PNIPAm microgels, suggesting that not all of the acrylamide gets pushed to the opposite side of the drop but some of it gets trapped and is subsequently polymerized between the microgels. This explains why the volume of the microgel-aggregate does not change with temperature once the phase-separated droplets are UV-irradiated.

The thermosensitive nature of the PNIPAm microgels can be effectively exploited to adjust the relative volumes of the two phases of these Janus particles. When the phase-separated Janus droplets are cooled from 65 °C to below the phase transition temperature of PNIPAm, the microgels become hydrophilic and begin to absorb water from the other side of the drop. As a result, the internal morphology of the Janus droplets evolves dynamically during the cooling process. The PNIPAm phase compacted on one side of the drops swells and increasingly occupies a larger volume of the droplet with time as shown in Figure 4 and Movie S1 of the Supporting Information. Thus, by controlling the elapsed time between heating the emulsion and exposing it to UV radiation, the relative volumes of the two phases can be effectively tuned. This range of phase ratios can be further expanded by varying the concentration of the microgels in the aqueous mixture. Alternatively, the size ratios of the two phases can also be adjusted by varying the crosslinker concentration of the PNIPAm microgels. Microgels with a lower crosslinker concentration exhibit a greater equilibrium size change compared to those with a higher crosslinker concentration.[28] Hence, the use of PNIPAm microgels with a lower crosslinker concentration will result in Janus particles with a wider range of phase ratios as compared to those made using microgels with a higher crosslinker concentration.

Different materials can be selectively incorporated into the two phases to enhance the functional dichotomy of the particles and to tailor them to suit specific applications. To illustrate this we make magnetically anisotropic particles by embedding magnetic nanoparticles only in the PNIPAm rich side of the Janus particles. Anionic magnetic beads are added to the aqueous mixture of the PNIPAm microgels and other monomers. Since the microgel

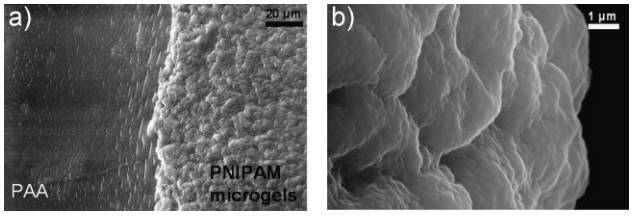

Figure 3. Scanning electron micrographs of a Janus supraparticle. a) Low magnification image shows the interface between the PNIPAm and the poly(acrylamide) phases. b) High magnification image shows closely packed PNIPAm microgels forming a raspberry like structure on one side of the Janus particle. The particle surface has buckled due to the dehydration of the hydrogels during sample preparation for SEM analysis. A 2 mm diameter particle was used to visually allow suitable orientation of the particle on the SEM specimen stub.

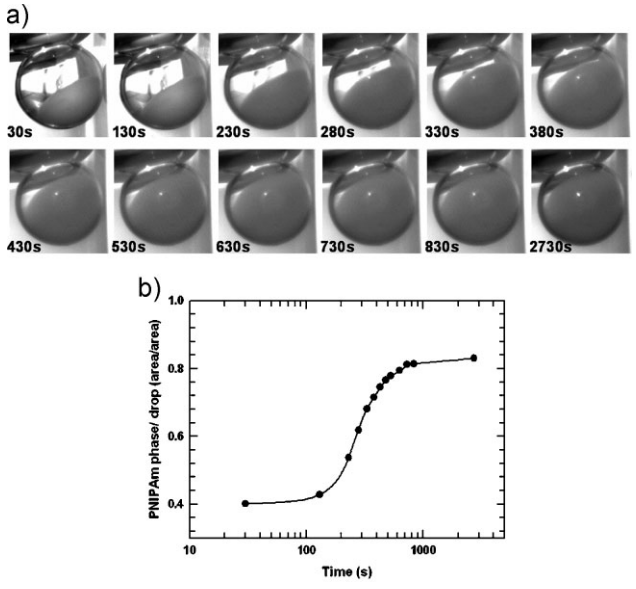

Figure 4. a) Temporal evolution of the internal morphology of a Janus droplet while cooling down from 65 °C. A 25 μL drop of the aqueous mixture was pipetted in 1 g of silicon oil in a glass vial. Phase separation within the droplet was achieved by heating the vial in an oven at 65 °C for 45 min. The sample was then taken out of the oven and placed in front of a camera for imaging at room temperature. The time at which the sample is removed from the oven is set as the temporal origin. b) Swelling kinetics of the PNIPAm phase within the drop upon upon cooling to room temperature. The ordinate represents the ratio of the area of the PNIPAm phase to that of the entire drop as determined by an image processing software. The data implies that the relative volumes of the two phases of the Janus particles can be finely tuned by controlling the cooling time of the droplets prior to UV irradiation.

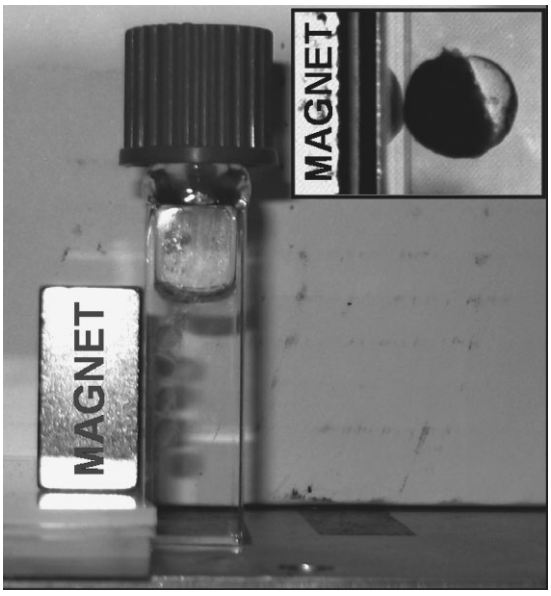

Figure 5. Magnetically anisotropic Janus particles generated by embedding oppositely charged iron oxide particles selectively into the PNIPAm microgel rich phase. The inset shows a magnified image of a single particle with the PNIPAm side attracted to a magnet.

particles are cationic, the magnetic beads electrostatically bind to the surface of the microgels, and are thus trapped only in the PNIPAm phase of the Janus particles as shown in Figure 5. Such magnetically anisotropic particles can be used to make magnetically actuated displays or other applications that require directional orientation or transportation of particles. We expect cationic materials that will get repelled by the cationic PNIPAm microgels to be successfully embedded into the PAAm gel of the Janus particles.

To summarize, this study presents a novel method to fabricate hierarchal Janus structures by the directed assembly of nanoparticles. Central to this approach is the use of nanoparticles that can be aggregated on one side of the aqueous droplets. Since the phase separation of the nanoparticles, and, thus, the formation of Janus droplets occurs downstream of the microfluidic process, problems associated with the convective cross-flow of the monomer fluids within Janus droplets, encountered during the co-flow microfluidic techniques for making Janus particles, are eliminated. The technique is highly versatile as it can be used in conjunction with microfluidics or any other emulsification method, which increases the ease of large-scale production of these particles. Although, here we have only demonstrated the fabrication of spherical Janus microparticles, the concept can be extended to generate Janus structures of various shapes as exemplified in the Supporting Information.

Experimental

Microgel Synthesis: The PNIPAm microgels were synthesized by precipitation polymerization [29]. NIPAm monomer (4 g, 99% purity, Acros) was dissolved along with *N*,*N*′-methylene bisacrylamide (0.16 g, 99.5% purity, Fluka) and allyl amine (0.14 mL, Sigma–Aldrich) in deionized water (150 mL). The solution was filtered with a 1-micrometer filter to remove any particulate impurities and then transferred to a round bottom flask (250 mL) fitted with a stirrer, glass thermometer, condenser, and a nitrogen purge line. The solution was heated to 70 °C and allowed to equilibrate for 5 minutes under nitrogen. A fluorescent dye, methacryloxy thiocarbonyl rhodamine B (0.0002 g) and a reaction initiator, $K_2S_2O_8$ (0.12 g, 99% purity, Sigma–Aldrich) dissolved in water (5 mL), were then added to the heated solution. The monomers were allowed to polymerize for ≈90 minutes. After polymerization, the microgel suspension was filtered using a filter cloth (100 μm mesh size) and quickly cooled down to room temperature using a water bath. The suspension was dialyzed for 72 h to remove the unreacted monomers. The microgel particle size was determined using dynamic light scattering (ALV 5000, 532 nm laser, 90° scattering angle) and fluorescence optical microscopy (Leica TCS-SP5 scanning confocal microscope). A fluorescent micrograph of the synthesized microgels is included in the Supporting Information (Fig. S1).

Microfluidics: A detailed description of the fabrication technique of glass capillary based microfluidic devices was presented in previous publications [27,30]. A schematic and an image of an actual capillary based microfluidic device with a flow focusing geometry used for making single emulsions are included in the Supporting Information (Fig. S2). The aqueous phase for microfluidic emulsification was prepared by dissolving PAAc (2×10^{-3} wt%, 1.25×10^6 g mol^{-1}, Carbopol 941, Noveon), acrylamide (10 wt%, 99 wt% purity, Sigma–Aldrich), *N*,*N*′- methylene bisacrylamide (1 wt%, 99.5% purity, Fluka), and a photoinitiator (5×10^{-1} wt%, Darocur 1173) in the microgel suspension. The continuous phase was poly-(dimethylsiloxane) fluid (500 cSt, Sigma–Aldrich) containing a surfactant (0.3 wt%, DC749) for emulsion stabilization and the photoinitiator (5×10^{-1} wt%, Darocur 1173). The addition of the photoinitiator to the oil phase was necessary to prevent the diffusion of the photoinitiator, which is soluble in both water and oil, out of the drops into the continuous phase. The fluids were pumped into the microfluidic device using syringe pumps (Harvard PHD 2000 series). The flow rates for the continuous and the dispersed fluids were set at 3000 and 500 μL h^{-1}, respectively. The collected emulsion was heated in an oven at 65 °C for 45 minutes and was then placed under a UV lamp (Rad-Free, Schleicher & Schuell, 365 nm wavelength). The solidified Janus particles were removed from the silicon oil and repeatedly flushed with isopropanol to remove any adsorbed oil. The particles were then washed and stored under water. The microfluidics process was monitored using an inverted optical microscope (DM-IRB, Leica) fitted with a fast camera (Phantom V5, Vision Research).

Characterization: The images for the phase-separated droplets and the Janus particles were taken using an inverted optical microscope fitted with an EMCCD camera (Rolera MGi, QImaging). SEM images were taken using a Zeiss Ultra55 field emission microscope (FESEM). To enhance image contrast, the samples were coated with ≈ 5–10 nm of gold after dehydration prior to SEM analysis. To effectively capture the temporal evolution of the internal morphology of a Janus drop, a large drop was made by pipetting 25 μL of the aqueous mixture in 1g of silicon oil (DC550, 125 cSt, 1.07 g cm^{-3}, Dow corning) in a glass vial. After thermally inducing phase separation, the vial was immediately placed in front of a Pulnix TM-200 camera mounted with a Pextax-FA 1:3.5 macro lens and images were taken at regular intervals of 10 s each. An image-processing software, ImageJ, was used to calculate the ratio of the area occupied by the PNIPAm phase to that occupied by the entire drop for each image. Magnetically anisotropic particles were fabricated by dissolving a ferro-fluid (EMG 708, Ferrotec) in the aqueous mixture. For ease of visualization, large Janus particles made using 25 μL droplets as templates were used for this purpose.

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