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COMMUNICATION

Bi-compartmental responsive polymer particles

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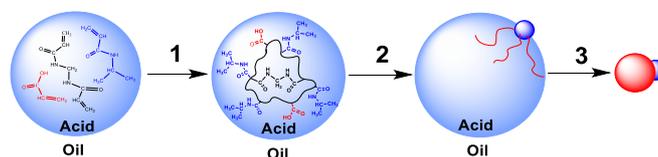
A novel type of bi-compartmental copolymer particles was synthesized in one-pot by controlling the phase separation during the polymerization process. The resulting particles have two distinct compartments, one consisting of mainly poly(acrylic acid) (PAA) and the other of poly(N,N'-isopropylacrylamide) (PNIPAM). The particles exhibit changeable shapes and properties, such as swelling in solvents and deposition on surfaces, and can be used to control emulsification as a function of pH.

Particles that possess two or more distinct compartments have attracted a lot of attention because they allow various applications, e.g. in emulsions,¹ self-assembly,² catalysis,³ and nanomotors.⁴ If a responsive polymer is introduced into these particles, new properties will be obtained. Some responsive bi-compartmental particles have been reported, which were mainly prepared by the surface-selective modification of matrix particles, for example, Au,⁵ SiO₂,⁶ magnetic,⁷ and polymer particles.⁸ A few polymer-based bi-compartmental particles were obtained by microfluidics technology⁹ or phase separation.¹⁰ Here, we report a new one-pot method for preparing asymmetric (Janus-type), bi-compartmental responsive polymer particles by controlling the phase separation during the polymerization process. The ease of the method allows the large-scale preparation of these bi-compartmental particles.

The present investigation of the properties of the responsive Janus particles is mainly focused on the controlled aggregation¹¹ of the particles and the function resulting from this process, i.e. self-assembly,¹¹ and emulsification/demulsification.¹² These functions have been observed in many traditional responsive nanoparticles, such as polymer nanoparticles and inorganic-organic hybrid particles.¹³ However, when one particle consists of two (or more) different compartments, it does not only combine and integrate the properties of the different parts, but it also allows to address the respective properties of each part independently. If one part is a responsive polymer while the other part does not have responsive properties, the different parts will exhibit distinctly different changes in response to external stimuli, which will render the particle properties variable. In the current study, the bi-

compartmental Janus particles exhibit changeable shape and properties due to differences in responsiveness between the two parts.

The copolymerization of N,N'-isopropylacrylamide (NIPAM) and acrylic acid (AA) was carried out in an emulsion, in which the monomers, the crosslinker N,N'-methylenebisacrylamide (MBA) and initiator were put in the aqueous phase, while the surfactant was added into the continuous oil phase (toluene). When the polymerization is carried out at high temperature, the produced poly-NIPAM (PNIPAM) chains are expected to collapse because of their responsiveness to temperature, and move out of the water phase. However, by embedding AA into the polymer chains, the repulsion between the negatively charged carboxyl groups reduces the polymer's responsiveness to temperature¹⁴ and usually leads to an improved Lower Critical Solution Temperature (LCST)¹⁵ so that the collapse of the polymer chains is inhibited. As a result, only spherical particles were obtained under the reaction conditions given above. In contrast, as illustrated in Scheme 1, we added acid to the water phase. Since the acid can protonate the carboxyl groups, the negative charges are removed, which results in the collapse of the polymer chains so that phase separation occurs between the PNIPAM and PAA parts. In this process, the hydrophobic isopropyl groups of PNIPAM become exposed by losing the water cage¹⁶ at high temperature and thereby move to the oil/water interface, while the PAA chains remain hydrophilic and stay in the aqueous phase.



Scheme 1. Synthesis of asymmetric PNIPAM-PAA particles. (1) polymerization in an acidified water/oil emulsion at 70°C; (2) collapse of PNIPAM chains and phase separation during polymerization induced by acid; (3) product collection after washing.

The ratio of oil/water was kept at 10 while various copolymerization were carried out using NIPAM, AA and MBA in different ratios. As a typical example, NIPAM, AA and MBA were used in a 15:5:1 ratio and polymerized for 2 h in an acidified water/toluene emulsion (pH=0). The copolymer particles were collected by centrifugation and washed with toluene, ethanol and water. The particles were re-dispersed in Milli-Q water before characterization. Their average hydrodynamic size in water was 109 ± 37 nm at room temperature, as determined by dynamic light scattering (DLS) (Fig. S1). The composition of the dried particles was assessed by infrared (IR) and nuclear magnetic resonance spectroscopy (^1H NMR). The peak of the carboxyl group at 1717 cm^{-1} and peaks of the amide groups at 1626 , 1547 cm^{-1} in the IR spectra indicated that the particles were typical P(NIPAM-AA) crosslinked copolymer particles (Fig. S2A). Signals for the isopropyl groups were found at 1.2 and 4.0 ppm in the NMR spectrum, confirming the presence of PNIPAM (see Fig. S2B). Scanning electron microscope (SEM) images of the particles showed their unique asymmetric shape: every particle consisted of two distinct parts with clearly different contrasts (see Fig. 1A, 1B and S3A). The bright parts have a nearly spherical shape while the dark parts are irregular and adhering onto the spherical parts.

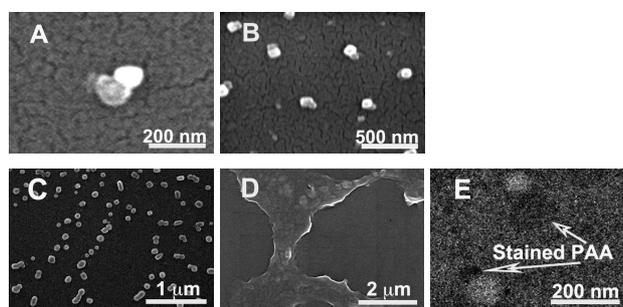


Fig. 1 SEM images (A, B) of asymmetric bi-compartmental particles showing different contrasts for the two compartments; SEM images of pure PNIPAM (C) and pure PAA (D) particles (the latter showing a weak contrast to the substrate); E) TEM image of a bi-compartmental PNIPAM-PAA particle stained with uranyl acetate. Asymmetric particles were prepared by polymerization at 70°C with a feed ratio of NIPAM to AA of 3:1. All particles were prepared in acid emulsion polymerization with the same feed ratio of MBA at 5% relative to the monomer(s). All particle samples were dispersed in water before drying.

In order to assign the contrast observed by SEM to the composition of the two parts of the asymmetric particles, pure PNIPAM and PAA particles were synthesized by acidic emulsion polymerization of the respective monomer (NIPAM or AA) and 5 mol% MBA as crosslinker under the same reaction conditions as the bi-compartmental particles. The PNIPAM particles exhibited a homogeneous and spherical shape, and the particles looked bright in the SEM (Fig. 1C). In contrast, the PAA particles were apparently soft and showed a tendency to spread onto the substrate, while they looked darker in the SEM (Fig. 1D). By using the substrate as a reference in the SEM images, the contrast of the PNIPAM particles is apparently brighter than PAA. Although it is possible that every polymer compartment may contain a fraction of the other monomer, these results indicate that the bright parts in Fig. 1A/B correspond to the PNIPAM-rich compartment while the dark parts contain mainly PAA. This is consistent with the origin of the SEM images (secondary electrons) and the different conductivities of the two parts. The tendency of the PAA particles to spread is also consistent with the irregular shape and adhesion observed for the dark parts of the copolymer particles.

Transmission electron microscopy (TEM) was carried out for further characterizing the composition of the bi-compartmental particles. The particles were dropped onto a copper grid and dried, followed by staining with uranyl acetate. This agent is known to stain the carboxyl groups selectively. As seen in Fig. 1E and S3B, one compartment shows a bright contrast compared to the substrate, and the size of these compartments was similar to the bright PNIPAM parts shown in the SEM images of Fig. 1A/B. As expected, the PAA parts were stained and showed up darker. So, it can be concluded that the bright parts in the bi-compartmental particles is mainly PNIPAM while the dark parts contain mainly PAA, that is, the particles have a PNIPAM-PAA structure.

Since the two distinct PNIPAM and PAA compartments have different properties (e.g. wettability and responsiveness), the particle shape can change when the morphologies of the two parts are being altered asynchronously. The particles were dispersed in acetone, and a droplet of the solution was deposited onto a silicon wafer and dried to create SEM and atomic force microscopy (AFM) images. As shown in Fig. 2A/B and S4A, the shape of the asymmetric particles changed drastically compared to the aqueous deposited particles (Fig. 1A/B). Notably, this morphology change is reversible (Fig. S4B). The compartments of the particles in Fig. 2 displayed opposite shape changes: the dark parts became round and flattened, while the bright parts became spherical bright dots. Clearly, the diameter of the dark parts is much bigger than that of the bright parts, in large contrast to the particles observed in Fig. 1A/B. The flattening of the PAA part indicates a better interaction with the surface and suggests that the PNIPAM part lies on top of it. In addition, the bright part of most particles deviates from the center of the dark part; in many cases the bright part of the particles lie at the rim. The distance (D) between the centers of the bright and dark parts was measured and compared to the radius (R) of the respective particle. The ratio D/R mainly concentrated on 30-50% (Fig. 2C). Published particles with core-shell structures¹⁷ do have much smaller D/R ratios, which implies that the particles do not have a core-shell architecture and thus further confirm the Janus structure observed in Fig. 1A/B.

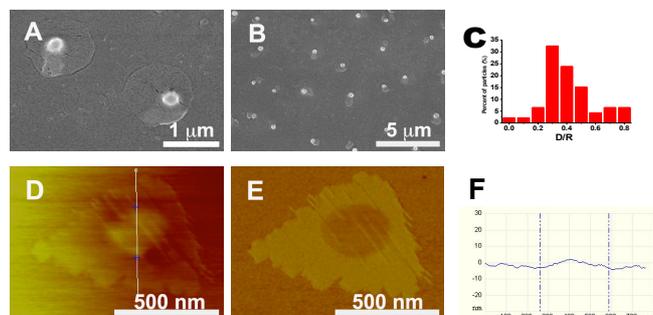


Fig. 2 Changing the morphology of bi-compartmental particles by deposition from acetone: A, B) SEM images showing the bright spots to be off-center compared to the dark parts; C) analysis of the deviation of centers of the bright parts (R is the radius of the whole particle while D is the distance between the centers of the bright and dark parts); D, E) AFM height and phase images of a particle; F) AFM height profile of the line scan shown in D.

For further characterization, a sample prepared from acetone was scanned by AFM. In the AFM height image (Fig. 2D), the two parts were clearly observed. It, together with the line scan (Fig. 2F), indicates a wide flat compartment (up to 1 nm height) and a higher (2-3 nm) compact part. Combined with the

contrast observed in SEM (Fig. 2A/B), it can be concluded that the former is the PAA-rich domain, while the latter is the PNIPAM part. The AFM phase image (Fig. 2E) shows two different phases in one particle, resulting from different interactions with the AFM tip, which confirms the difference of compositions between two compartments and the presence of the PNIPAM at the surface in the compact part.

The relative sizes of the two compartments can be varied by changing the feed ratio. While keeping the fraction of MBA at 5 mol%, a series of asymmetric particles with different ratios of NIPAM to AA were synthesized. The content of AA was measured by potentiometric titration according to literature,¹⁸ resulted in 20%, 38% and 58% of AA for the different samples. As shown in Fig. S5, all of particles changed their shape to the asymmetric off-centered structures when deposited from acetone. The diameter of the bright part became smaller when increasing the AA fraction. In contrast, the diameter of the dark area increased correspondingly. The diameter ratio of the two parts (R/r , where r is the radius of the bright part) is dependent on the content of AA (Fig. S5G), and increased with increasing amounts of AA. Moreover, the ratio of bright to dark parts remained unaffected when changing the fraction of crosslinker MBA while fixing the ratio of NIPAM to AA (Fig. S6). All-in-all, these results show that the relative sizes of the compartments can be controlled simply by varying the monomer ratio in the feed.

The shape changes described above can be ascribed to independent alteration of the two compartments because of their different interactions with different solvents. This result is consistent with earlier literature on NIPAM copolymers containing acid group,¹⁹ which show an increase of swelling upon increase of the fraction of carboxyl groups. In contrast, the more the content of PNIPAM was, the stronger the polymer collapsed.

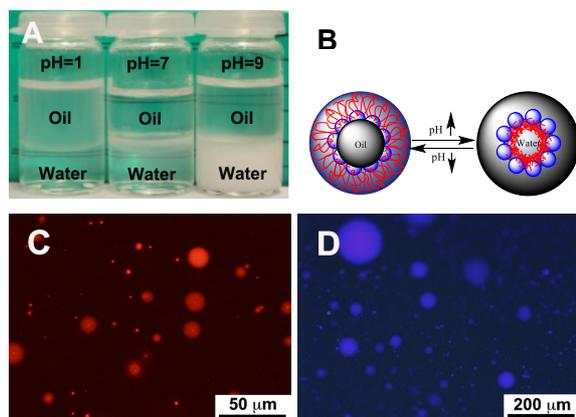


Fig. 3 Reversible transformation of emulsions produced by bi-compartmental particles. A) photograph of 1-octadecene/water emulsion system at different pH values in the absence of a fluorescent dye (right: pH 9, middle: pH 7, left: pH 1), where the background line can not be seen through the upper emulsion of the left bottle, nor the lower emulsion of the right bottle; B) cartoon of the emulsion transformation between oil-in-water and water-in-oil induced by the responsive bi-compartmental particles; C) Fluorescence microscope image of water droplets with rhodamine B at pH 1 in the 1-octadecene phase; D) Fluorescence microscope image of 1-octadecene droplets with anthracene in the water phase at pH 9. The mixtures consisted of water, 1-octadecene and around 1×10^{-4} wt.% of bi-compartmental particles.

The feature that each part of one particle can independently change can provide particles with new functions. Here we used these particles to emulsify oil/water mixtures. As shown in Fig. 3, the

particles were put at low concentrations (about 1×10^{-4} wt.%) into water with different pH values, and then mixed with oil (1-octadecene) by sonication for 5 min. At pH 9, 1-octadecene was emulsified into water and formed an oil-in-water emulsion, where the bottom half became a white emulsion and the background line could not be seen anymore, while the upper oil phase remained transparent (the right sample in Fig. 3A). At pH 7, the emulsion became unstable and separated, and both water and oil phases became transparent. At pH 1, water was emulsified into oil and formed a water-in-oil emulsion (left bottle of Fig. 3A); the water phase became transparent in 3 h while the upper oil phase remained opaque and stable. The controlled emulsification is caused by the pH-dependent alteration of the particles (the alteration of particles could be proven by their aggregation at different pH, not shown here) and is schematically shown Fig. 3B. When rhodamine B or anthracene was used as a fluorescent indicator for water or oil droplets, respectively, fluorescent droplets were formed. At pH 1, a large amount of fluorescent water droplets with rhodamine B were observed in the oil phase (Fig. 3C) while no fluorescent 1-octadecene droplets with anthracene were found in water after the emulsion stood for 8 h. At pH 9, a large amount of 1-octadecene droplets with the fluorescent anthracene were observed in water as the continuous phase (Fig. 3D), while fluorescent water droplets could hardly be found in the oil phase. Furthermore, this transformation was shown to be reversible upon changing the pH from low to high or vice versa.

Conclusions

In conclusion, we synthesized a novel type of bi-compartmental particles by inducing phase separation in a one-pot emulsion polymerization process. This method is potentially suited for producing other asymmetric responsive particles in large quantities. These particles can change their shape and exhibit the controlled emulsification of an oil/water mixture, which can reversibly transit between oil-in-water and water-in-oil by changing the pH. This kind of different responsiveness between two compartments in particles can render the particles versatile for various applications, e.g. in self-assembly or for controlled drug release.

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Notes and references

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