Synthesis of Hollow Nanospheres Consisting of Amphiphilic Block Copolymers

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Hollow polymeric nanospheres with shells consisting of inner hydrophilic and outer hydrophobic polymer chains are prepared by a surface-initiated living radical polymerization of 2-trimethylsilyloxyethyl acrylate and methyl methacrylate from initiator-modified silica nanoparticles; these nanospheres are subsequently prepared by intraparticle cross-linking and by dissolution of silica matrices with HF. The translation behavior of hydrophilic substrates from an aqueous phase to an oil phase through the nanocapsules is investigated.

Hollow micro- and nanospheres have attracted considerable attention in the field of material and medical science due to their potential applications including their use as an encapsulator for the controlled release of substrates such as drugs, enzymes, dyes, and ink and as a confined nanovessel of chemical reactions. A variety of materials among ceramics and polymers are used to produce the shells of the hollow spheres.[1] However, nanocapsules exhibiting effective extraction of substrates from the outside to the inside of capsules are still scarce. Thin shells are required for the translation of substrates. In addition, shells multilayered by materials with different chemical properties would help in extracting substrates from the cores, whereas most conventional capsules unfortunately consist of single materials. Atom-transfer radical polymerization (ATRP) has been widely used for the production of polymers with monodispersity and controlled chain length depending on a monomer/initiator ratio; ATRP has been proven to be effective for the production of block copolymer using a wide range of monomers.[2] The ATRP has also been applied to the production of structurally well-defined polymer-grafted nanoparticles and micron-sized polymeric capsules.[3]

Here, we demonstrate the production of hollow nanospheres with shells of block copolymers consisting of hydrophobic and hydrophilic chains, exhibiting an effective extraction behavior. The synthetic procedure of our hollow nanospheres consists of four steps: synthesis of silica nanoparticles (SiNPs) modified with initiators, propagation of block copolymer from the SiNPs by ATRP, intraparticle cross-linking of the polymer chains, and dissolution of the silica matrices with HF (as outlined in Figure 1).

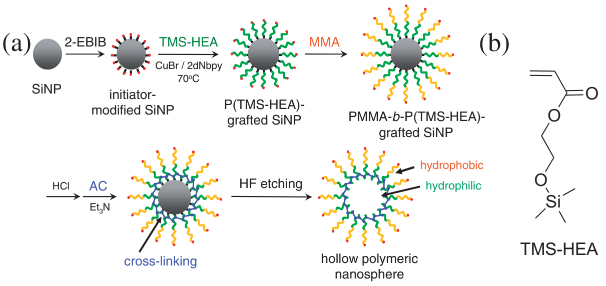

Figure 1. (a) Preparation procedure of hollow nanosphere with shells consisting of hydrophilic and hydrophobic polymer chains. (b) Chemical structure of 2-(trimethylsilyloxy)ethyl acrylate (TMS-HEA).

SiNPs with amino groups on the entire surface were prepared by microemulsion.[4] Spherical SiNPs of 37.1 ± 4.4 nm in diameter, determined from scanning electron microscopic (SEM) images, were used as sacrificial cores. The surface was chemically modified with ethyl 2-bromo-isobutyrate (2-EBIB) through glucono-1,5-lactone. X-ray fluorescence analysis indicated that the EBIB-modified SiNPs contained 5.26 wt % bromine, which corresponded to a grafting density of 3 initiators/nm^2. The stepwise ATRP of 2-(trimethylsilyloxy)ethyl acrylate (TMS-HEA) and methyl methacrylate (MMA) from the EBIB-modified SiNPs was conducted to produce block copolymers at 70 °C in anisole using the complex of Cu$^{\mathrm{I}}$Br and 4,4′-dinonyl-2,2′-bipyridine (dNbpy) as a catalyst, according to the literature.[2] Here, the 20- and 10-fold amounts of TMS-HEA and MMA relative to those of the initiator were in turn added. Treatment with HCl produced amphiphilic polymer chains due to the deprotection of hydroxy groups from the TMS-HEA units. The poly(2-hydroxyethyl acrylate) chains partially cross-linked with adipoyl chloride (AC). The resulting powder of the nanoparticles was easily dispersed in good solvents for PMMA. The cross-linked polymer-grafted nanoparticles were dispersed in benzene and treated with 2.5% aqueous HF solution and tetraoctylammonium bromide, a phase transfer catalyst, in a two-phase system to dissolve the silica. It is worth noting that the two-phase system apparently maintained a clearly separated state during the etching process. This suggests the successful intraparticle linking with AC. Because the two phases combined into a single homogeneous phase, indicating a bicontinuous phase constructed by free amphiphilic polymer chains when unlinked polymer-grafted nanoparticles were treated with HF in the same manner. The nanocapsules thus prepared were purified by repeated centrifugation and dispersion in acetone. Fourier transform infrared spectra (FT-IR) of the products after HF etching showed the disappearance of a broad band at around 1080 cm^{-1} due to a Si–O stretch of silica, whereas the band at 1730 cm^{-1} derived from the polymer shell still remained. (Figure S1).[5]

The SEM observation of the products exhibits the spherical shapes of the nanoparticles (Figure 2a). The transmission electron microscopic (TEM) observation revealed that monodisperse hollow nanospheres were successfully produced (Figure 2b). The average diameters of the outer surface and the hollow core were $d_{\mathrm{out}} = 46.5 \pm 11.1$ nm and $d_{\mathrm{in}} = 27.8 \pm 2.1$ nm, respectively. The size of the hollow core was considerably smaller than that of SiNPs used as the sacrificial core ($d_{\mathrm{s}} = 37.1$ nm), indicating the shrinking of the polymer chains while drying in vacuum; however, the shell thickness (ca. 9 nm) of the nanocapsules was

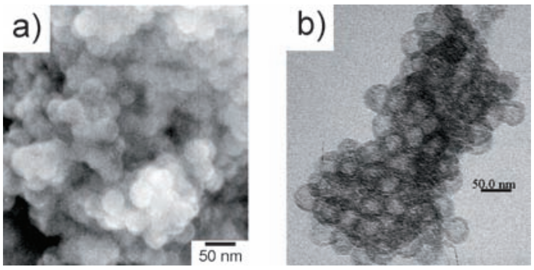

Figure 2. (a) SEM and (b) TEM image of the purified nanocapsules. Average diameters of the outer surface and the inner core were $d_{\mathrm{out}} = 46.5 \pm 11.1$ nm and $d_{\mathrm{in}} = 27.8 \pm 2.1$ nm, respectively.

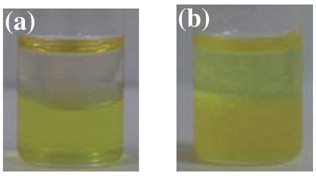

Figure 3. Photographs of two phases of 2 mL of benzene solution containing the nanocapsules (2.4 mg mL^{-1}) and 2 mL aqueous solution of $NaAuCl_4$ (0.1 M) after stirring for (a) 0 h and (b) 5 h.

comparable to the length of the stretched polymer chains, calculated from a CPK model. This can be explained by the dense packing of the polymer chains upon the evaporation of the solvent. The steric crowding during the shrinking will force the chains to stretch away.

The extraction behavior of the nanocapsules was examined to characterize the shell structures. Figure 3a shows a photograph of two phases of benzene solution containing the nanocapsules (2.4 mg mL^{-1}; upper) and aqueous solution of $NaAuCl_4$ (0.1 M; lower). The nanocapsules were dispersed easily in hydrophobic solvents such as benzene, but they did not disperse in water. This shows the hydrophobic outer surface of the nanocapsules. After stirring for 5 h, the benzene solution changed from colorless to pale yellow due to the translation of $AuCl_4^-$ ions from the aqueous phase to the benzene phase (Figure 3b). The yellow-colored benzene phase can be explained by the dispersion of the nanocapsules that received $AuCl_4^-$ ions in the hydrophilic core at an interface of the benzene/aqueous phase. The results described above exhibit that the shells of the nanocapsules consists of inner hydrophilic and outer hydrophobic polymer chains.

To estimate the extraction ability of the nanocapsules, we investigated the extraction process of hydrophilic fluorescent molecules. Figure 4a shows fluorescence (FL) spectra of the benzene phase (2 mL) containing the nanocapsules (2.4 mg mL^{-1}) as a function of time after the addition of 2 mL of aqueous solution containing fluorescein (0.6 mM). The FL intensity increased with time and almost reached near saturation after 5 h (Figure 4b). The relatively slow extraction rate when compared to chelate agents appears to be caused by the diffusion limitation of the substrates through the shells. An extraction efficiency (E_{eff}) is estimated according to eq 1,

$$E_{\mathrm{eff}} = \frac{I_{\mathrm{b}}}{\pi d_{\mathrm{s}}^3/6 \cdot N_{\mathrm{p}}/\upsilon_{\mathrm{b}} \cdot I_{\mathrm{aq}}} \tag{1}$$

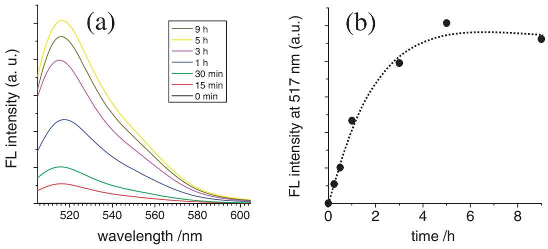

Figure 4. (a) FL spectra and (b) intensities at $\lambda_{\mathrm{max}} = 517$ nm of benzene phase containing nanocapsules as a function of time after the addition of 0.6 mM aqueous fluorescein solution. Aliquots of the benzene phase were taken and diluted in benzene at given times to measure FL spectra.

where I_{aq} and I_{b} are FL intensity at $\lambda_{\mathrm{max}} = 517$ nm of the 0.6 mM aqueous fluorescein solution and the benzene phase containing the nanocapsules after 9 h, respectively. The number of nanocapsules, N_{p}, $(=6W_{\mathrm{p}}/\pi\rho(d_{\mathrm{out}}^3 - d_{\mathrm{in}}^3))$ is estimated from the added weight (W_{p}) of nanocapsule powder, the density of the block polymers using the bulk density of PMMA ($\rho = 1.18$ g cm^{-3}) for simplicity, and the outer and inner diameters (d_{out} and d_{in}) assuming spherical shape. The υ_{b} is the volume of the benzene phase. The average volume of a hollow core filled with aqueous solution is estimated from $\pi d_{\mathrm{s}}^3/6$ using the size of the sacrificial cores (d_{s}). The FL intensity at 9 h corresponds to $E_{\mathrm{eff}} = 1.0$, suggesting that all the nanocapsules retained 0.6 mM aqueous fluorescein solution in the core. This also suggested that the shrunken nanocapsules swelled again on exposure to the solvent because an extraordinary value of E_{eff} (>2.3) was obtained if calculated from the shrunken diameter, as shown in Figure 2b. Effective extraction of the substrates might be enabled by swollen, porous shell structure.

In conclusion, monodisperse nanocapsules consisting of hydrophilic and hydrophobic chains were successfully prepared by ATRP of TMS-HEA and MMA using 2-EBIB-modified SiNPs as macroinitiators; these monodisperse nanocapsules were prepared by intraparticle cross-linking and by dissolution of the silica matrices with HF. The nanocapsules exhibited effective extraction of hydrophilic substrates such as $NaAuCl_4$ and fluorescein from the aqueous phase to the oil phase, implying a potential application for use as confined reaction nanovessel to construct new nanostructures and nanocomposites.

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References and Notes

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5 Supporting Information is available electronically on the CSJ-Journal Web site, http://www.csj.jp/journals/chem-lett/index.html.

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