A facile approach to fabricate functionalized superparamagnetic copolymer-silica nanocomposite spheres†

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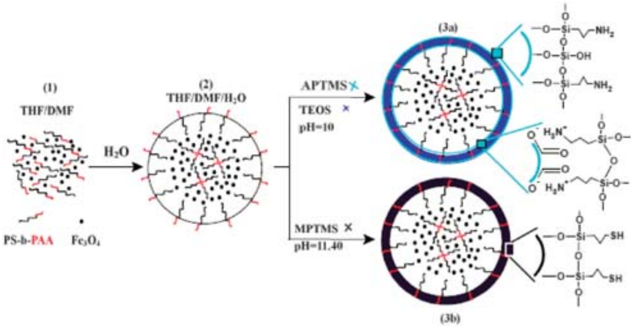
Novel amino- or thiol-functionalized superparamagnetic copolymer-silica nanospheres (NH_2-SMCSNs/SH-SMCSNs), which consist of a magnetic core and a silica cross-linked block copolymer shell, have been fabricated.

Recently, nano-composites with core–shell structures have become an active research field because of their unique physical and chemical properties and great potential for applications in areas of electronics, photonics, catalysis, biology, and nanotechnologies.[1] A typical and important class of materials with the core–shell structure is the spherical 'core–shell' type micelles which can be generated by the self-assembly of amphiphilic block copolymers.[2] However, long-term stability remains a topic of intensive study because block copolymer micelles will spontaneously dissociate at concentrations below their critical micelle concentrations (CMC). In order to improve the micellar stability, the most widely studied method was to cross-link and lock the micellar structure, either in the hydrophobic core region, or in the hydrophilic shell region.[3] Especially, the shell cross-linked micelles (SCL) have become a very attractive class of organic functional nanoparticles.[4] These composite functional micelles displayed a complex structure and great potential for applications in separation and purification of biomolecules, MRI contrast enhancement, biosensoring, and targeted drug delivery.[5] However, in the process of cross-linking, toxic and expensive cross-linking agents were commonly employed.[6]

Very recently, block copolymer micelles have been stabilized using a biomineralisation approach.[7] This biomineralisation method offers two main advantages over covalent polymeric cross-linking: first, inorganic cross-linking occurs relatively quickly in aqueous solution under mild conditions; and additionally, such inorganic overlayers can offer a much stronger barrier to the diffusion of both small molecules and polymers than covalent polymeric cross-linking. Nevertheless, the actual applications of these inorganic cross-linked micelles depend largely on the cross-linked micelles functionalities, *e.g.*, electric or magnetic functions. However, up to now, reports on the synthesis of functional micelles with inorganic cross-linking cannot be found.

Herein, we report a simple route for the fabrication of amino- or thiol-functionalized superparamagnetic copolymer-silica nanospheres (NH_2-SMCSNs/SH-SMCSNs) by embedding nano-sized magnetic particles into the hydrophobic cores with the shell inorganically cross-linked. By uniquely combining the superparamagnetic core and the silica cross-linked shell, not only can the stability of nanocomposite spheres can be significantly enhanced, but also the superparamagnetic characteristics of NH_2-SMCSNs or SH-SMCSNs make them promising candidates for biomedical applications. Importantly, NH_2-SMCSNs or SH-SMCSNs can be further used to facilitate the rapid translation of nanoparticles to a wide range of end applications, such as catalysis and drug delivery.

Scheme 1 illustrates the formation process of NH_2-SMCSNs and SH-SMCSNs. Magnetite nanoparticles (5 nm in average diameter) were obtained according to Sun's reports[8] (Fig. S1 and S2†). Amphiphilic block copolymer PS_{100}-*b*-PAA_{16} (M_n = 11 245 g mol^{-1}; PDI = 1.07) was synthesized *via* atom-transfer radical polymerization as reported[9] (Fig. S3†). The magnetite nanoparticles and the copolymer were dispersed in the co-solvent of tetrahydrofuran (THF) and *N*,*N*-dimethylformamide (DMF) as a precursor solution (step 1); then, water, a non-solvent for PS block, was added gradually to this mixture to de-solvate both the magnetic particles and the hydrophobic polymer block simultaneously. A pale, gray solution formed



Scheme 1 Schematic diagram of the formation process of NH_2-SMCSNs (3a) and SH-SMCSNs (3b).

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spontaneously, indicating the formation of magnetic micelles (step 2); after dialysis, the PAA blocks (the outer shell) of the assembled copolymer micelles were cross-linked under different conditions. Taking a mixture of 3-aminopropyltrimethoxysilane (APTMS, $pK_a \approx 10.6$) and tetraethyl orthosilicate (TEOS) as the silica source and adjusting the pH value to around 10 with a solution of sodium hydroxide (step 3a), NH_2-SMCSNs were obtained. For SH-SMCSNs, the outer shell of the polymeric micelles was cross-linked with 3-mercaptopropyltrimethoxysilane (MPTMS) alone at pH = 11.40, which was adjusted by aqueous ammonia (step 3b).

Fig. 1 presents the FE-SEM and TEM images of the magnetic polymeric micelles as well as TEM images of NH_2-SMCSNs and SH-SMCSNs. Fig. 1a shows the SEM image of the magnetic polymeric spheres without shell cross-linking. It reveals that the magnetic polymeric spheres are relatively uniform in size with an average diameter of around 125 nm. The TEM image of the magnetic polymeric spheres (Fig. 1b) indicates that several tens of monodisperse magnetite nanocrystals were encapsulated in the cores of polymeric micelles. This encapsulation can be attributed to the hydrophobic nature of the magnetite nanoparticles[8] and their much smaller size (*ca.* 2.5 nm) compared to the dimensions of the polymer chains ($R_g \approx 3$ nm for PS_{100}-*b*-PAA_{16}) in the present work, so the magnetite nanoparticles could act as solutes during the process of self-assembly between the block copolymers and magnetic nanoparticles.[10] From the TEM image, it also can be seen that the spheres have a uniform polymer shell with an average diameter of 12 nm. Note that the morphologies of the magnetic micelles reported herein are different from the previously reported composites in which hydrophobic nanoparticles were evenly embedded in PAA-*b*-PS block copolymer micelles.[4] In our work, the size of the core region is larger than the length of a fully stretched PS segment (25 nm) and the contrast of the core region does not change obviously, indicating that the morphology of the polymer core is composed of aggregates of reverse micelles, as illustrated in Scheme 1 (step 2), and magnetic nanoparticles dispersed uniformly in the hydrophobic regions of reverse micelles, which is similar to that reported by Park *et al.*[11]

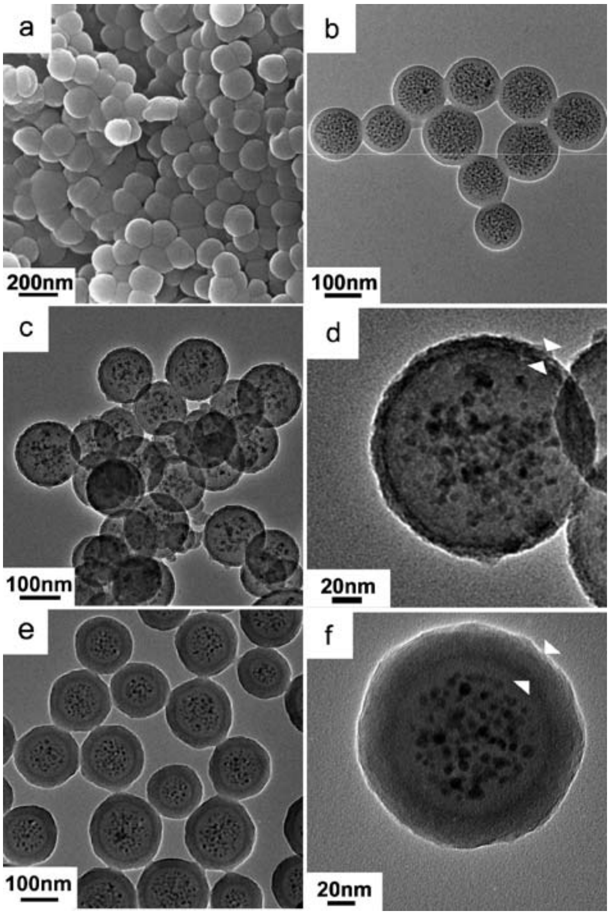

Fig. 1 FE-SEM image of magnetic micelles (a) and TEM images of magnetic micelles (b), NH_2-SMCSNs (c, d), and SH-SMCSNs (e, f), respectively.

Fig. 1c and d show TEM images of NH_2-SMCSNs, which were cross-linked with the mixture of APTMS and TEOS. As can be seen in Fig. 1c, monodispersed spheres with magnetic nanoparticles in the cores were obtained and the average diameter of the NH_2-SMCSNs is around 150 nm. From the single sphere shown in Fig. 1d, a uniform silica shell is clearly observed with an average diameter of 10 nm. FT-IR spectrum (Fig. S4†) of NH_2-SMCSNs confirms the co-existence of silica, APTMS and block copolymer. As shown in Fig. S4(b),† the strong IR band at 1066 cm^{-1} is the characteristic of the Si–O–Si vibrations, while the transmissions around 1640 cm^{-1} and 800 cm^{-1} match well with N–H vibrations and Si–C stretching vibrations, respectively. During the process of silica cross-linking, APTMS plays an important role due to the quaternization of amino-silane at pH = 10, so we hypothesize that silica cross-linking occurred based on the electrostatic interaction between anionic surfactants and silica precursors following a $S^-N^+ \sim I^-$ pathway,[12] where S, N, and I stands for the block copolymer surfactants (PS-*b*-PAA), the silane coupling agent, and the silica precursors (TEOS), respectively. To further confirm the hypothesis, SMCSNs were prepared under almost the same conditions as the NH_2-SMCSNs but without using APTMS. As expected, a silica cross-linking layer could not be found without adding APTMS (Fig. S5).†

Fig. 1e and f show the TEM images of SH-SMCSNs cross-linked with MPTMS. In Fig. 1e, well mono-dispersed SH-SMCSNs were presented and the average diameter of SH-SMCSNs is around 180 nm. In Fig. 1f, a uniform silica shell with an average diameter of 25 nm was illustrated. EDS analysis results (Fig. S6†) verify the presence of Si and S on the outer shells of SH-SMCSNs. Compared with NH_2-SMCSNs, the SH-SMCSNs could be synthesized more simply and conveniently. Moreover, the thickness of the silica shell can be facilely tuned by altering the amount of MPTMS (Fig. S7†). To further confirm the presence of thiol groups on the surface of SH-SMCSNs, the samples of Pd-SH-SMCSNs were prepared. It is found that Pd nanoparticles with diameters of 1–2 nm are highly dispersed on the surface of SH-SMCSNs (Fig. S8†). Such a material would be a promising magnetically recoverable catalyst in nanocatalysis, and the catalytic activity of Pd-SH-SMCSNs will be investigated in our further work.

The room-temperature magnetization curve (Fig. 2a) shows that the NH_2-SMCSNs are essentially superparamagnetic with

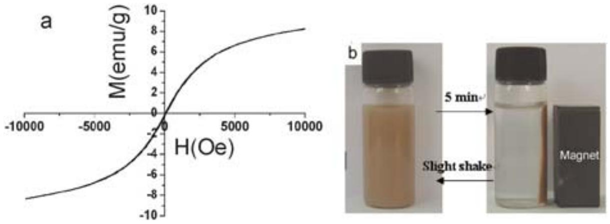

Fig. 2 The magnetic properties of NH_2-SMCSNs: (a) room temperature magnetization curve, and (b) separation from solution under an external magnetic field.

negligible hysteresis, which suggests the monodispersity and minimal agglomeration of magnetite nanoparticles in the cores of the composite spheres. The saturation magnetization value of NH_2-SMCSNs with spherical morphology (10-nm thickness of silica shell) is as high as 8.3 emu g^{-1}, which is significantly higher than the saturation magnetization of $\sim$4 emu g^{-1} of magnetomicelles,[4] but lower than that of mesoporous organosilica magnetic hollow spheres (17.6 emu g^{-1}).[13] The magnetic separability of such superparamagnetic copolymer-silica nanoparticles was tested in water by placing a magnet near the glass bottle. The grey particles were attracted toward the magnet within several minutes, and then could be easily redispersed with slight shaking (Fig. 2b), demonstrating directly that the core–shell nanospheres possess magnetic properties.

In conclusion, we have successfully fabricated novel kinds of amino- or thiol-functionalized superparamagnetic copolymer-silica nanospheres (NH_2-SMCSNs and SH-SMCSNs), which consist of a magnetic core and a silica cross-linked block copolymer shell. The magnetic core is composed of tens of well-dispersed nano-magnetite particles, which provide the superparamagnetic properties with a magnetization intensity higher than 8 emu g^{-1}. It may be possible to encapsulate other species such as quantum dots or biologically active molecules and we intend to address this possibility in future work. Due to their well-defined nanostructures, low cost of production, high biocompatibility and convenient surface functionalization, these materials may have potential applications in biolabeling, biodiagnostics, drug delivery, bio-imaging, *etc*.

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