

Synthesis of Core/Shell $\text{MnFe}_2\text{O}_4/\text{Au}$ Nanoparticles for Advanced Proton Treatment

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1. Introduction

Magnetic nanoparticles have been intensively studied for their versatile biomedical applications [1, 2], such as magnetic resonance imaging (MRI), hyperthermia, drug delivery and cell signaling. Recently metallic nanoparticles have been shown for therapeutic applications in radiation oncology [3]. The surface modification of the nanomaterials is required for the biomedical use to give physiological stability, surface reactivity and targeting properties. Among many approaches for the surface modification with materials, such as polymers, organic ligands and metals, one of the most attractive ways is using metals.

The fabrication of metal-based, monolayer-coated magnetic nanoparticles has been intensively studied. However, the synthesis of metal-capped magnetic nanoparticles with monodispersities and controllable sizes is still challenged.

Recently, gold-capped magnetic nanoparticles have been reported to increase stability and to provide biocompatibility [4, 5]. Magnetic nanoparticle with gold coating is an attractive system, which can be stabilized in biological conditions and readily functionalized through well-established surface modification (Au-S) chemistry. The Au coating offers plasmonic properties to magnetic nanoparticles. This makes the magnetic/Au core/shell combinations interesting for magnetic and optical applications.

Herein, the synthesis and characterization of Au coated-manganese ferrite ($\text{Au-MnFe}_2\text{O}_4$) that has a high MR contrast effect have demonstrated. The core/shell nanoparticles were transferred from organic to aqueous solutions for biomedical applications.

2. Methods and Results

Methods and results parts are divided into four sections. First, the synthesis of magnetic core nanoparticles (MnFe_2O_4) is described. Second, the synthesis of Au-coated MnFe_2O_4 is mentioned. Third, characterization of the resulting nano-structured materials is discussed. At last, phase transfer of the products ($\text{Au-MnFe}_2\text{O}_4$) is described. As mentioned in Figure 1, the core/shell nanoparticles prepared in organic solvents were transferred into aqueous solutions for biological applications.

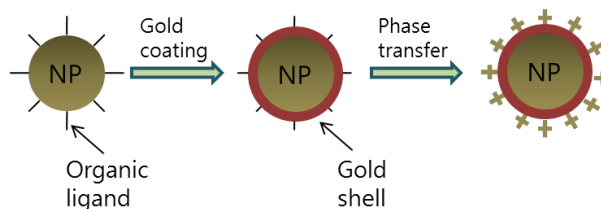


Fig. 1. Schematic illustration of core-shell nanoparticles. Magnetic cores (MnFe_2O_4) were prepared using a thermal decomposition method and coated with gold. The gold-capped MnFe_2O_4 nanoparticles were transferred into aqueous solutions for biological applications.

2.1 Synthesis of manganese ferrite nanoparticles

MnFe_2O_4 nanocrystals were prepared with a thermal decomposition method [6]. Briefly, to prepare monodisperse MnFe_2O_4 nanoparticles, $\text{Mn}(\text{acac})_2$ and $\text{Fe}(\text{acac})_3$ were mixed in benzyl ether with 1,2-hexadecanediol, oleic acid and oleylamine under nitrogen gas. The solutions were heated to reflux for 1 h. After cooled to room temperature, ethanol was added to the reaction mixture to precipitate the magnetic nanoparticles for the characterization. The resulting solutions were centrifuged to give 7-nm MnFe_2O_4 nanocrystals. As shown in Fig. 2A, TEM analysis was performed with the resulting product dissolved in hexane.

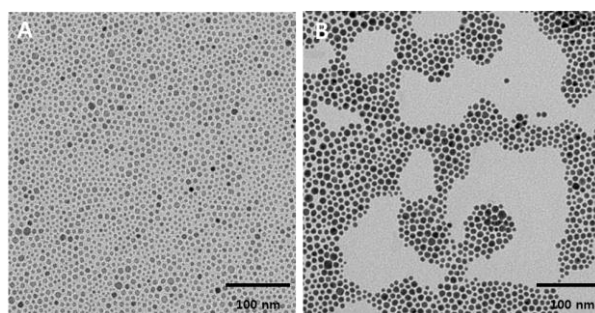


Fig. 2. TEM images of manganese-doped iron oxide nanoparticles (A) and the gold-coated nanoparticles (B) in organic solvents.

2.2 Synthesis of Au-capped manganese ferrite nanoparticles

The resulting magnetic nanoparticles were used as seeds for gold coating. The reaction solution of magnetic nanoparticles in benzyl ether was mixed with

gold acetate, oleic acid, oleylamine and 1,2-hexadecanediol. Gold acetate as a gold source was added into the reaction mixture. The reaction solution was heated to $\sim 180^\circ\text{C}$ and was kept at this temperature for 1.5 h. After cooled to room temperature, ethanol was added to the solution. The dark-purple materials were precipitated and separated by centrifuging. The resulting product was washed with ethanol and redissolved in hexane solutions to give 8-nm Au-MnFe₂O₄ nanocrystals (Fig. 2B). As shown in Fig. 3, the Au-coated magnetic nanoparticles showed a clear band at around 525 nm.

2.3 Characterization of the resulting nanomaterials

The hexane solutions or aqueous solutions containing the nanoparticles were dropped onto a carbon-coated copper grid, and then dried at room temperature for Transmission Electron Microscopy (TEM) analysis. The nanoparticle solution dispersed in hexanes was also measured with a dynamic light scattering method for size determinations. Ultraviolet visible (UV) spectra of the nanoparticles with/without gold coating were acquired with a UV 2550 spectrophotometer (Shimadzu) over the range of 400-700 nm.

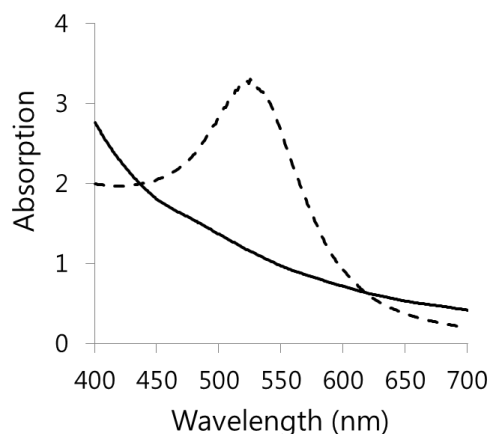


Fig. 3. UV-Vis spectra of manganese ferrite nanoparticles (solid) and the nanoparticles with the Au coating (dashed).

2.4 Phase transfer of gold-capped magnetic nanoparticles

The hexane solutions containing Au-MnFe₂O₄ nanoparticles were removed and then the resulting nanoparticles were dispersed in 4 mL of chloroform. After adding cetyltrimethylammonium bromide (CTAB) and sodium citrate solutions into the chloroform solution, the reaction mixture was stirred to form the microemulsion system for overnight. Next day, the reaction mixture was heated to 60°C to remove the remained chloroform. As shown in Fig. 4, the phase transfer of Au-MnFe₂O₄ nanocrystals was successfully achieved. Interestingly, MnFe₂O₄ nanoparticles were aggregated during the phase transfer (data not shown).

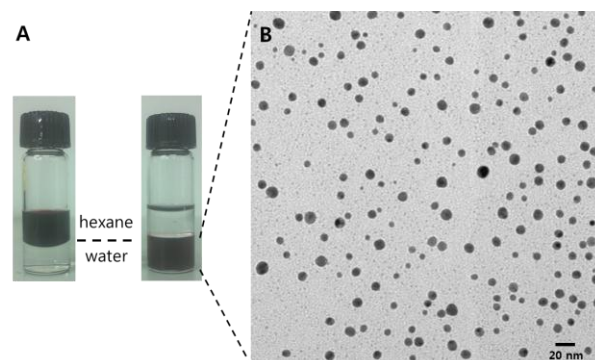


Fig. 4. The pictures of Au-MnFe₂O₄ nanocrystals in hexanes (A, left) and aqueous solutions (A, right) and the TEM images of Au-MnFe₂O₄ nanoparticles (B) in aqueous solutions.

3. Conclusions

The core/shell structured MnFe₂O₄/Au nanoparticles have been prepared and transferred from organic phase to aqueous solutions. The resulting Au-coated nanocrystals may be an attractive system for biomedical applications, which are needed both magnetic resonance imaging and optical imaging. The phase transferred core/shell nanoparticles can be decorated with targeting moiety, such as antibodies, peptides, aptamers, small molecules and ligands for biological applications. The proton treatment with the resulting Au-MnFe₂O₄ nanoparticles is undergoing.

REFERENCES

- [1] Y. Jun, Y Huh, J. Choi, J. Lee, H. Song, S. Kim, S. Yoon, K. Kim, J. Shin, J. Suh, and J. Cheon, Nanoscale Size Effect of Magnetic Resonance Imaging, *Journal of American Chemical Society*, Vol.127, p. 5732, 2005.
- [2] D. Ling and T. Hyeon. Chemical Design of Biocompatible Iron Oxide Nanoparticles for Medical Applications. *Small*, Vol.9, p.1450, 2013.
- [3] J.-K. Kim, S.-J. Seo, K.-H. Kim, T.-J. Kim, M.-H. Chung, K.-R. Kim and T.-K. Yang. Therapeutic application of metallic nanoparticles combined with particle-induced x-ray emission effect. *Nanotechnology*, Vol.21, p.425102, 2010.
- [4] L. Wang, H. Park, S. I. Lim, M. J. Schadt, D. Mott, J. Luo, X. Wang, and C. Zhong. Core@shell nanomaterials: gold-coated magnetic oxide nanoparticles. *Journal of Materials Chemistry*, Vol.18, p.2629, 2008.
- [5] J. Gallo, I. Garcia, D. Padro, B. Arnaiz and S. Penades. Water-soluble Magnetic Glyconanoparticles Based on Metal-Doped Ferrites Coated with Gold: Synthesis and Characterization. *Journal of Materials Chemistry*, Vol.20, p.10010, 2010.
- [6] S. Sun, H. Zeng, D. B. Robinson, S Raoux, P.M. Rice, S. X. Wang, and G. Li. Monodisperse MFe₂O₄ (M = Fe, Co, Mn) Nanoparticles, *Journal of American Chemical Society*, Vol.126, p. 273, 2004.