

## Surface Modification of Fe<sub>3</sub>O<sub>4</sub> Nanoparticles for the Preparation of Magnetic Responsive Hydrogels

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**Abstract.** A novel approach was developed to synthesize polymerizable vinyl group functionalized Fe<sub>3</sub>O<sub>4</sub> nanoparticles with high aqueous dispersion stability. Firstly, the Fe<sub>3</sub>O<sub>4</sub> nanoparticles were synthesized via chemical co-precipitation method. Then, azide-functional Fe<sub>3</sub>O<sub>4</sub> nanoparticles were obtained by a two-step chemical modification process. Finally, a quaternized 2-(Dimethylamino) ethyl methacrylate (QDMA) with alkyne moiety were directly reacted with azide-functional Fe<sub>3</sub>O<sub>4</sub> nanoparticles to obtain Fe<sub>3</sub>O<sub>4</sub>@QDMA nanoparticles. The Fe<sub>3</sub>O<sub>4</sub>@QDMA nanoparticles with a mean diameter 12.2 nm possess positive charges and can be well dispersed in water media for further preparation of particle-crosslinked magnetic nanocomposite hydrogels.

### Introduction

Over the past decade, magnetic responsive hydrogels have been drawn tremendous attentions due to the non-contacting control of hydrogels by external magnetic field and potential applications in the field of drug delivery [1] and hyperthermia [2]. For the production of magnetic responsive hydrogels by in situ polymerization in the presence of magnetic nanoparticles, three aspects should be considered: (1) the stability of magnetic nanoparticles in aqueous, (2) surface functionalization of magnetic nanoparticles and (3) the incompatibility of polymer matrix and magnetic nanoparticles. Recently, numerous studies have been strived to address these issues. Among these studies, one of the most general methods is the modification of magnetic nanoparticles with reactive vinyl groups that allows the direct covalent coupling between the polymer matrix and magnetic nanoparticles by grafting-through method [3, 4]. Although dispersed and stable in nonaqueous solution, magnetic nanoparticles modified with vinyl groups may form larger aggregates and generate precipitation in aqueous due to the hydrophobicity of vinyl groups. In this case, structurally homogeneous hydrogels with unique mechanical properties are unable to achieve.

Therefore, a quaternized 2-(dimethylamino) ethyl methacrylate (QDMA) with “clickable” alkyne moiety was synthesized by the quaternization of DMA with propargyl bromide. The QDMA combines the vinyl and quaternary ammonium ionic groups that enable polymerizable functionality and dispersion stability in water of

magnetic nanoparticles. Then, the QDMA was effectively connected onto azide-functionalized  $\text{Fe}_3\text{O}_4$  nanoparticles via Copper (I) catalyzed click chemistry. The obtained  $\text{Fe}_3\text{O}_4$ @QDMA nanoparticles were utilized as cross-linkers to prepare novel magnetic nanocomposite hydrogels for realizing the combination of high mechanical properties and magnetic responsibility.

## **Experimental**

### **Materials**

$\text{Fe}_3\text{O}_4$  nanoparticles and quaternized 2-(dimethylamino) ethyl methacrylate (QDMA) were synthesized according to literature procedures [5, 6]. All other chemicals were purchased from Sigma-Aldrich and used as received.

### **Synthesis of Azide-functionalized $\text{Fe}_3\text{O}_4$ Nanoparticles**

The  $\text{Fe}_3\text{O}_4$ @Cl nanoparticles were prepared based on the method of Schmidt [7]. Desired amount of water-based  $\text{Fe}_3\text{O}_4$  dispersion was added to dry ethanol to make a dispersion containing 195 mL ethanol and 5 mL water at a concentration of 2 mg/mL. Then 3-chloropropyltriethoxysilane (3.6 mmol/1 g  $\text{Fe}_3\text{O}_4$  nanoparticles) was added dropwise to the above dispersion. After reacted at ambient temperature for 16 h, the dispersion was distilled under reduced pressure to promote the condensation of siloxane groups. The product ( $\text{Fe}_3\text{O}_4$ @Cl) was washed three times with ethanol and dried overnight. Subsequently, the obtained  $\text{Fe}_3\text{O}_4$ @Cl nanoparticles (0.400 g),  $\text{NaN}_3$  (4.68 mmol) and tetrabutylammonium iodide (0.05 mmol) were dispersed in DMF (100 mL). Then, the reaction was mechanically stirred with nitrogen protection at 50 °C for 24 h. The obtained particles were washed three times with deionized water and dried overnight.

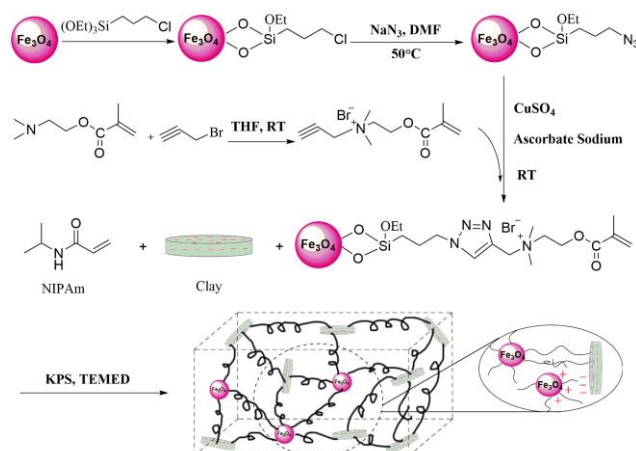
### **Synthesis of $\text{Fe}_3\text{O}_4$ @QDMA Nanoparticles**

The obtained  $\text{Fe}_3\text{O}_4$ @ $\text{N}_3$  nanoparticles (0.400 g) and QDMA (0.397 g) were dispersed in 40 mL deionized water. Then  $\text{CuSO}_4$  (0.040 g) and sodium ascorbate (0.080 g) were added to the  $\text{Fe}_3\text{O}_4$  dispersion respectively. The mixture was mechanically stirred at room temperature for 24 h. The product was washed three times with water and collected by a magnet, then dried overnight.

### **Characterization**

TEM images of  $\text{Fe}_3\text{O}_4$  nanoparticles were taken using a JEM-1200EX (120Kv). Fourier transform infrared spectra (FTIR) of the products were recorded using a Nicolet 6700 spectrophotometer. Stability in water at was studied using zeta potential as a function of pH from 3 to 11.

## Results and Discussion



Scheme 1. Synthetic Route for the Preparation of Fe<sub>3</sub>O<sub>4</sub>@QDMA nanoparticles and particle-crosslinked magnetic nanocomposite hydrogels.

### Synthesis of Fe<sub>3</sub>O<sub>4</sub>@QDMA Nanoparticles

The synthesis route of Fe<sub>3</sub>O<sub>4</sub>@QDMA nanoparticles is illustrated in Scheme 1. The surface chemical composition and morphology of Fe<sub>3</sub>O<sub>4</sub> nanoparticles were fully analyzed by TEM and FTIR. The prepared Fe<sub>3</sub>O<sub>4</sub>@QDMA nanoparticles showed a spherical morphology, and a mean diameter of 12.2 nm was extracted from log-normal distribution fitting of the histogram obtained from Fig. 1. FTIR spectra of bare Fe<sub>3</sub>O<sub>4</sub>, Fe<sub>3</sub>O<sub>4</sub>@Cl, Fe<sub>3</sub>O<sub>4</sub>@N<sub>3</sub> and Fe<sub>3</sub>O<sub>4</sub>@QDMA nanoparticles are displayed in Fig. 2. The characteristic vibrations of magnetite nanoparticles are the broad and intense peak of O-H groups around 3400 cm<sup>-1</sup> and strong Fe-O-Fe vibration peak at 588 cm<sup>-1</sup>. The peaks between 1172 and 943 cm<sup>-1</sup> in curve b-d is attributed to the asymmetric -Si-O-Si- vibration of the composite, which demonstrates the successful modification with 3-chloropropyltriethoxysilane. The adsorption peak at 2102 cm<sup>-1</sup> in curve c can be assigned to asymmetric stretch of azide groups, which indicates the successful functionalization of N<sub>3</sub> on the surface of magnetite nanoparticles. FTIR spectra in curve d shows the disappearance of characteristic azide vibration at 2102 cm<sup>-1</sup> and the appearance of the vibrational absorption of vinyl groups at 1720 cm<sup>-1</sup>. This demonstrates that QDMA was successfully grafted onto the magnetite nanoparticles.

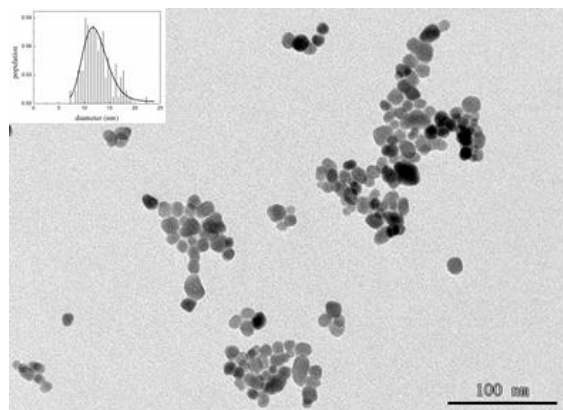


Figure 1. TEM image of Fe<sub>3</sub>O<sub>4</sub>@QDMA nanoparticles with size distribution histogram.

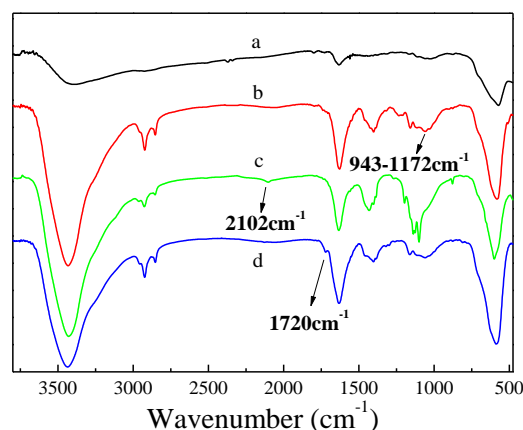


Figure 2. FT-IR spectra of bare  $\text{Fe}_3\text{O}_4$  nanoparticles (a),  $\text{Fe}_3\text{O}_4@\text{Cl}$  (b),  $\text{Fe}_3\text{O}_4@\text{N}_3$  (c) and  $\text{Fe}_3\text{O}_4@\text{QDMA}$  (d) .

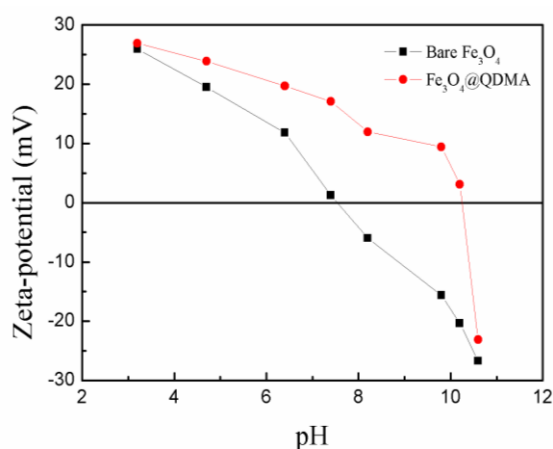


Figure 3. Zeta-potential of bare  $\text{Fe}_3\text{O}_4$  and  $\text{Fe}_3\text{O}_4@\text{QDMA}$  nanoparticles.

### Particle Stability Analysis

Particle stability was studied using zeta potential as a function of pH from 3 to 11. As shown in Fig. 3, the  $\text{Fe}_3\text{O}_4$  nanoparticles coated with QDMA have positive charges over almost the entire pH range due to the presence of quaternary ammonium ions, demonstrating that  $\text{Fe}_3\text{O}_4@\text{QDMA}$  nanoparticles are stable in water at neutral condition.

### Conclusion

Polymerizable vinyl group functionalized  $\text{Fe}_3\text{O}_4$  nanoparticles with high aqueous dispersion stability was synthesized via click chemistry. The  $\text{Fe}_3\text{O}_4@\text{QDMA}$  nanoparticles with a mean diameter 12.2 nm have positive charges and can be homodispersed in water. The obtained  $\text{Fe}_3\text{O}_4@\text{QDMA}$  was then utilized as a cross-linker to prepare novel magnetic nanocomposite hydrogels with unique properties and thus enable covalent attachment to hydrogel matrix. The novel magnetic hydrogels with combination of thermal and magnetic responsibility have potential for dual hyperthermia and drug delivery applications and related study is ongoing.

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