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# Effect Hyperthermia in $CoFe_2O_4$@$MnFe_2O_4$ Nanoparticles Studied by using Field-induced Mössbauer Spectroscopy

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$CoFe_2O_4$@$MnFe_2O_4$, with a mixed core-shell structure was fabricated by a high temperature thermal decomposition. From the Rietveld refinement, these nanoparticles were found to be cubic spinel with space group $Fd-3m$ and with a Bragg factor ($R_B$) and a structure factor ($R_F$) less than 5%. The size and the shape of the nanoparticles were examined with high-resolution transmission electron microscopy (HR-TEM). The values of the magnetization ($M_S$) and the coercivity ($H_C$) of these nanoparticles at room temperature were 78.95 emu/g and 21.2 mT, respectively. The effect of hyperthermia, measured with a magneTherm device showed that the self-heating temperature of the nanoparticles could reach 133 °C. To determine the applicability of nanoparticles in hyperthermia therapy, we evaluated the in-vitro cell viability of nanoparticles. Based on the probability distribution of cations, we determined the Mössbauer spectra at 4.2 K with two sets of six lines under various applied fields parallel to the direction of the $\gamma$-rays. To separate the A and the B sites, we also obtained the Mössbauer spectra of the nanoparticles under high external field up to 5 T at 4.2 K. From the detailed analysis of the Mössbauer spectra, the spin canting angles and the anisotropy energies at the A and the B sites were determined.

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## I. INTRODUCTION

Ferrites have been used in various industrial applications such as magnetic recording media, biocatalysts, and waste water treatment [1]. Hyperthermia is a treatment for malignant cancer that utilizes the self-heating effect in magnetic nanoparticles exposed to an alternating current (AC) magnetic field [2,3]. Magnetic nanoparticles have been studied for bio applications such as hyperthermia, drug delivery, magnetic resonance imaging reagents, *etc.* [4] due to their small sizes and magnetic properties. Under an AC magnetic field with low frequency, the self-heating effect in the magnetic nanoparticles is caused by Néel and Brown relaxation [5]. $CoFe_2O_4$ is well known to be a hard magnetic ferrite with a large coercivity while $MnFe_2O_4$ is known to be a soft magnetic ferrite with small coercivity [6]. These magnetic materials can couple via an exchange interaction between the hard and the soft core-shell structures, which can lead to a higher thermal effect [7]. In this research, $CoFe_2O_4$@$MnFe_2O_4$ nanoparticles with a mixed core-shell structure were prepared using a high-temperature thermal decomposition [8], and their magnetic properties and the hyperfine structure were investigated to understand the relation between the core-shell structure and the thermal effect.

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## II. EXPERIMENTS AND DISCUSSION

To prepare mixed core-shell nanoparticles with the hard ferrite $CoFe_2O_4$ as a core and the soft ferrite $MnFe_2O_4$ as a shell, we used a high temperature thermal decomposition method [9]. two mmol of Co-acetylacetonate (Co-$(acac)_2$) and 4 mmol of $Fe(acac)_3$ were used as starting materials and were mixed with 6