Effects of the random magnetic field on the hysteresis behavior of spin-1 Ising nanotube

H. MAGOUSSI, A. ZAIM*, M. KEROUAD*

Laboratoire Physique des Matériaux et Modélisation des Systèmes (LP2MS), Unité Associée au CNRST-URAC: 08, University Moulay Ismail, Faculty of Sciences, B.P. 11201 Zitoune, Meknes, Morocco.

In this work, the hysteresis behavior of the nanotube, consisting of a ferromagnetic core of spin-1 surrounded by a ferromagnetic shell of spin-1 with anti-ferromagnetic interfacial coupling is studied in the presence of a random magnetic field. Based on a probability distribution method, the effective field theory has been used to investigate the effects of the random magnetic field, the interfacial coupling constant and the shell coupling on the hysteresis loops of the nanotube. Some characteristic behaviors have been found.

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Keywords Effective field theory, Ising nanotube, Random magnetic field

1. Introduction

Magnetic nanomaterials have recently attracted considerable attention and intensive research due to their promising applications in diverse areas of high-density magnetic storage media [1, 2], magnetic resonance imaging [3], non-linear optics [4], ferrofluids [5], environmental remediation [6], catalysis [7] and biomedicine [8]. Theoretically, the magnetic properties of nanoparticle have been widely investigated by the use of various techniques, including the mean field theory [9], effective field theory [10-12], Monte Carlo simulations [13-17], Green's function technique [18-19] and Bethe Perils approximation [20]. For example, Zaim et al. [16] have discussed the magnetic behaviour of a ferrimagnetic core/shell nanoparticle. They have found that the system can exhibit one or even two compensation temperatures. Canko et al. [11], have investigated Blume-Capel model on a cylindrical Ising nanotube. They have obtained that tricritical point depends on the coupling constant between core and surface shell. In recent work, Zaim et al. [10] have obtained that the existence of tricritical and critical end points in a ferrimagnetic nanoparticle is dependent on the parameter values.

The hysteresis behaviors in magnetic nanoparticles are a common interest of many works research [21-27]. Recently, Keskin et al. [23] have investigated hysteresis loops of the cylindrical Ising nanowire defined by Kaneyoshi [28], for the reduced temperatures below, around and above the critical temperature. They have observed that the results of hysteresis behaviors of nanowire are in good agreement with both theoretical and experimental results. Some recent works [29] have investigated the magnetic properties and hysteresis loops of magnetic nanowires in a random magnetic field. In Ref. [30], the hysteresis behavior of nanotubes composed of a ferroelectric core with a spin-1/2 surrounded by a ferroelectric shell with a spin-1/2 with ferro- or anti-ferroelectric interfacial coupling has been studied using the transverse Ising model (TIM). Moreover, the dependence of remanence and coercivity on the exchange and dipolar fields of magnetic nanoparticle systems is studied in ref [31]. It is found that both remanence and coercivity decrease with the increase of temperature. Based on Monte Carlo simulation, the effects of size and surface anisotropy on hysteresis loops of a small spherical particle have been investigated [32]. These simulations showed that the hysteresis loops and coercivity are strongly affected by the particle size and the thickness of the surface layer with large anisotropy. By using the effective-field theory with correlations and Glauber-type stochastic approach [33, 34], Deviren et al. have studied hysteresis loop areas and correlations of a cylindrical Ising nanotube or nanowire in an oscillating magnetic field.

As far as we know, the effect of the random magnetic field on the hysteresis behaviours of spin-1 Ising nanotube with core/shell morphology has not been investigated. Therefore, the purpose of this study is to investigate the hysteresis behaviors of an Ising nanotube, using an effective field theory based on a probability distribution method. We also study the temperature dependence of the coercivity and remanent magnetization.

The paper is arranged as follows: In Section 2, we give the model and the formalism. In Section 3, we present the results and discussions, while section 4 is devoted to a brief conclusion.

2. Model and formalism

We consider an Ising nanotube model in a random magnetic field consisting of a spin-1 ferromagnetic core which is surrounded by a spin-1 ferromagnetic surface shell. Each spin is connected to the two nearest neighbor spins on the above and below sections. The Hamiltonian of the model is given by

$$\mathrm{H} = -J_c \sum_{\langle i,j\rangle} S_i S_j - J_s \sum_{\langle m,n\rangle} S_m S_n - J_{\mathrm{int}} \sum_{\langle i,m\rangle} S_i S_m - \sum_i h_i S_i - \sum_m h_m S_m - H\left(\sum_i S_i - \sum_m S_m\right). \tag{1}$$

where the J_c and J_s are the exchange interaction parameters between two nearest neighbor magnetic atoms at the core and surface shell, and J_{int} is the exchange interaction between two neighbor magnetic atoms at the surface shell and the core. S_i is the spin takes the values ± 1; 0 at each site i of the Ising nanoparticle model and a summation index $<i,j>$, $<m,n>$ and $<i,m>$ denote asummation over all pairs of neighboring spins at the core, shell surface and between shell and core, respectively. H is an external magnetic field, h_i and h_m are the random longitudinal magnetic fields acting on S_i and S_m respectively distributed according to a trimodal distribution :

$$P(h_i) = p\delta(h_i) + \frac{1}{2}(1-p)\left(\delta(h_i - h_0) + \delta(h_i + h_0)\right) \tag{2}$$

$$P(h_m) = p\delta(h_m) + \frac{1}{2}(1-p)\left(\delta(h_m - h_0) + \delta(h_m + h_0)\right) \tag{3}$$

Two longitudinal magnetizations on the shell surface, namely m_{s1} and m_{s2} and a longitudinal magnetization on the core, namely m_c within the framework of the effective field theory with a probability distribution, can be obtained as:

$$m_{s_1} = 2^{-5} \sum_{\mu_1=0}^{2}\sum_{\mu_2=0}^{2}\sum_{\mu_3=0}^{1}\sum_{\nu_1=0}^{2-\mu_1}\sum_{\nu_2=0}^{2-\mu_2}\sum_{\nu_3=0}^{1-\mu_3} 2^{(\mu_1+\mu_2+\mu_3)} C_{\mu_1}^{2} C_{\mu_2}^{2} C_{\mu_3}^{1} C_{\nu_1}^{2-\mu_1} C_{\nu_2}^{2-\mu_2} C_{\nu_3}^{1-\mu_3} \left(1-q_{s_1}\right)^{\mu_1}\left(1-q_{s_2}\right)^{\mu_2}\left(1-q_c\right)^{\mu_3}\left(q_{s_1}-m_{s_1}\right)^{\nu_1} \left(q_{s_2}-m_{s_2}\right)^{\nu_2}\left(q_c-m_c\right)^{\nu_3}\left(q_{s_1}+m_{s_1}\right)^{2-\mu_1-\nu_1}\left(q_{s_2}+m_{s_2}\right)^{2-\mu_2-\nu_2} \left(q_c+m_c\right)^{1-\mu_3-\nu_3} F_m\left(x_1, H, h_0\right). \tag{4}$$

$$m_{s_2} = 2^{-6} \sum_{\mu_1=0}^{2}\sum_{\mu_2=0}^{2}\sum_{\mu_3=0}^{2}\sum_{\nu_1=0}^{2-\mu_1}\sum_{\nu_2=0}^{2-\mu_2}\sum_{\nu_3=0}^{2-\mu_3} 2^{(\mu_1+\mu_2+\mu_3)} C_{\mu_1}^{2} C_{\mu_2}^{2} C_{\mu_3}^{2} C_{\nu_1}^{2-\mu_1} C_{\nu_2}^{2-\mu_2} C_{\nu_3}^{2-\mu_3} \left(1-q_{s_1}\right)^{\mu_1}\left(1-q_{s_2}\right)^{\mu_2}\left(1-q_c\right)^{\mu_3}\left(q_{s_1}-m_{s_1}\right)^{\nu_1} \left(q_{s_2}-m_{s_2}\right)^{\nu_2}\left(q_c-m_c\right)^{\nu_3}\left(q_{s_1}+m_{s_1}\right)^{2-\mu_1-\nu_1}\left(q_{s_2}+m_{s_2}\right)^{2-\mu_2-\nu_2} \left(q_c+m_c\right)^{2-\mu_3-\nu_3} F_m\left(x_2, H, h_0\right). \tag{5}$$

$$m_c = 2^{-7} \sum_{\mu_1=0}^{1}\sum_{\mu_2=0}^{2}\sum_{\mu_3=0}^{4}\sum_{\nu_1=0}^{1-\mu_1}\sum_{\nu_2=0}^{2-\mu_2}\sum_{\nu_3=0}^{4-\mu_3} 2^{(\mu_1+\mu_2+\mu_3)} C_{\mu_1}^{1} C_{\mu_2}^{2} C_{\mu_3}^{4} C_{\nu_1}^{1-\mu_1} C_{\nu_2}^{2-\mu_2} C_{\nu_3}^{4-\mu_3} \left(1-q_{s_1}\right)^{\mu_1}\left(1-q_{s_2}\right)^{\mu_2}\left(1-q_c\right)^{\mu_3}\left(q_{s_1}-m_{s_1}\right)^{\nu_1} \left(q_{s_2}-m_{s_2}\right)^{\nu_2}\left(q_c-m_c\right)^{\nu_3}\left(q_{s_1}+m_{s_1}\right)^{1-\mu_1-\nu_1}\left(q_{s_2}+m_{s_2}\right)^{2-\mu_2-\nu_2} \left(q_c+m_c\right)^{4-\mu_3-\nu_3} F_m\left(x_3, H, h_0\right). \tag{6}$$

Two longitudinal quadrupolar moments on the shell surface, namely q_{s_1} and q_{s_2} and a quadrupolar moment on the core, namely q_c, can be obtained as:

$$q_{s_1} = 2^{-5} \sum_{\mu_1=0}^{2}\sum_{\mu_2=0}^{2}\sum_{\mu_3=0}^{1}\sum_{\nu_1=0}^{2-\mu_1}\sum_{\nu_2=0}^{2-\mu_2}\sum_{\nu_3=0}^{1-\mu_3} 2^{(\mu_1+\mu_2+\mu_3)} C_{\mu_1}^{2} C_{\mu_2}^{2} C_{\mu_3}^{1} C_{\nu_1}^{2-\mu_1} C_{\nu_2}^{2-\mu_2} C_{\nu_3}^{1-\mu_3} \left(1-q_{s_1}\right)^{\mu_1}\left(1-q_{s_2}\right)^{\mu_2}\left(1-q_c\right)^{\mu_3}\left(q_{s_1}-m_{s_1}\right)^{\nu_1} \left(q_{s_2}-m_{s_2}\right)^{\nu_2}\left(q_c-m_c\right)^{\nu_3}\left(q_{s_1}+m_{s_1}\right)^{2-\mu_1-\nu_1}\left(q_{s_2}+m_{s_2}\right)^{2-\mu_2-\nu_2} \left(q_c+m_c\right)^{1-\mu_2-\nu_2} F_q\left(x_1, H, h_0\right). \tag{7}$$

$$q_{s_2} = 2^{-6} \sum_{\mu_1=0}^{2}\sum_{\mu_2=0}^{2}\sum_{\mu_3=0}^{2}\sum_{\nu_1=0}^{2-\mu_1}\sum_{\nu_2=0}^{2-\mu_2}\sum_{\nu_3=0}^{2-\mu_3} 2^{(\mu_1+\mu_2+\mu_3)} C_{\mu_1}^{2} C_{\mu_2}^{2} C_{\mu_3}^{2} C_{\nu_1}^{2-\mu_1} C_{\nu_2}^{2\quad\mu_2} C_{\nu_3}^{2\quad\mu_3} \left(1\quad q_{s_1}\right)^{\mu_1}\left(1\quad q_{s_2}\right)^{\mu_2}\left(1\quad q_c\right)^{\mu_3}\left(q_{s_1}\quad m_{s_1}\right)^{\mu_1} \left(q_{s_2}\quad m_{s_2}\right)^{\mu_2}\left(q_c\quad m_c\right)^{\mu_3}\left(q_{s_1}+m_{s_1}\right)^{2-\mu_1-\nu_1}\left(q_{s_2}+m_{s_2}\right)^{2-\mu_2-\nu_2} \left(q_c+m_c\right)^{2-\mu_3-\nu_3} F_q\left(x_2, H, h_0\right). \tag{8}$$

$$q_c = 2^{-7} \sum_{\mu_1=0}^{1}\sum_{\mu_2=0}^{2}\sum_{\mu_3=0}^{4}\sum_{\nu_1=0}^{1-\mu_1}\sum_{\nu_2=0}^{2-\mu_2}\sum_{\nu_3=0}^{4-\mu_3} 2^{(\mu_1+\mu_2+\mu_3)} C_{\mu_1}^{1} C_{\mu_2}^{2} C_{\mu_3}^{4} C_{\nu_1}^{1-\mu_1} C_{\nu_2}^{2-\mu_2} C_{\nu_3}^{4-\mu_3} \left(1-q_{s_1}\right)^{\mu_1}\left(1-q_{s_2}\right)^{\mu_2}\left(1-q_c\right)^{\mu_3}\left(q_{s_1}-m_{s_1}\right)^{\nu_1} \left(q_{s_2}-m_{s_2}\right)^{\nu_2}\left(q_c-m_c\right)^{\nu_3}\left(q_{s_1}+m_{s_1}\right)^{1-\mu_1-\nu_1}\left(q_{s_2}+m_{s_2}\right)^{2-\mu_2-\nu_2} \left(q_c+m_c\right)^{4-\mu_3-\nu_3} F_q\left(x_3, H, h_0\right). \tag{9}$$

Where

$$x_1 = J_s\left(2-\mu_1-2\nu_1\right) + J_s\left(2-\mu_2-2\nu_2\right) + J_{\mathrm{int}}\left(1-\mu_3-2\nu_3\right)$$
$$x_2 = J_s\left(2-\mu_1-2\nu_1\right) + J_s\left(2-\mu_2-2\nu_2\right) + J_{\mathrm{int}}\left(2-\mu_3-2\nu_3\right)$$
$$x_3 = J_{\mathrm{int}}\left(1-\mu_1-2\nu_1\right) + J_{\mathrm{int}}\left(2-\mu_2-2\nu_2\right) + J_c\left(4-\mu_3-2\nu_3\right)$$

$$F_m\left(x_j, H, h_0\right) = pf_m\left(x_j, H, h_0\right) + \frac{1}{2}(1-p)\left(f_m\left(x_j, H, -h_0\right) + f_m\left(x_j, H, h_0\right)\right) \tag{10}$$

$$F_q\left(x_j, H, h_0\right) = pf_q\left(x_j, H, h_0\right) + \frac{1}{2}(1-p)\left(f_q\left(x_j, H, -h_0\right) + f_q\left(x_j, H, h_0\right)\right) \tag{11}$$

$$j = 1, 2 \textit{ and } 3$$

The functions f_m and f_q are given by:

$$f_m\left(x_j, H, h_0\right) = \frac{2\sinh\left(\beta\, x_j + H + h_0\right)}{1 + 2\cosh\left(\beta\, x_j + H + h_0\right)} \tag{12}$$

$$f_q\left(x_j, H, h_0\right) = \frac{2\cosh\left(\beta\, x_j + H + h_0\right)}{1 + 2\cosh\left(\beta\, x_j + H + h_0\right)} \tag{13}$$

with $\beta = \frac{1}{K_B T}$, T is the absolute temperature and K_B is the Boltzmann factor. C_k^l denotes the binomial coeffient, $C_k^l = \frac{l!}{k!(l-k)!}$.

Furthermore, let us define the longitudinal magnetization per site of the shell surface M_{sh}, and the total magnetization per site M_t as follows

$$M_{sh} = \frac{1}{2}\left(m_{s_1} + m_{s_2}\right) \tag{14}$$

$$M_t = \frac{1}{3}\left(m_{s_1} + m_{s_2} + m_c\right) \tag{15}$$

3. Results and discussions

Our investigations in this work are for ferrimagnetic case. Hence, $J_{int} < 0$ (negative core-shell coupling) correspond to the antiferromagnetic interfacial couplings. In this section, we investigate the effects of the interfacial coupling, the random magnetic field and the shell coupling on the hysteresis loops of a ferrimagnetic nanotube with core/shell morphology.

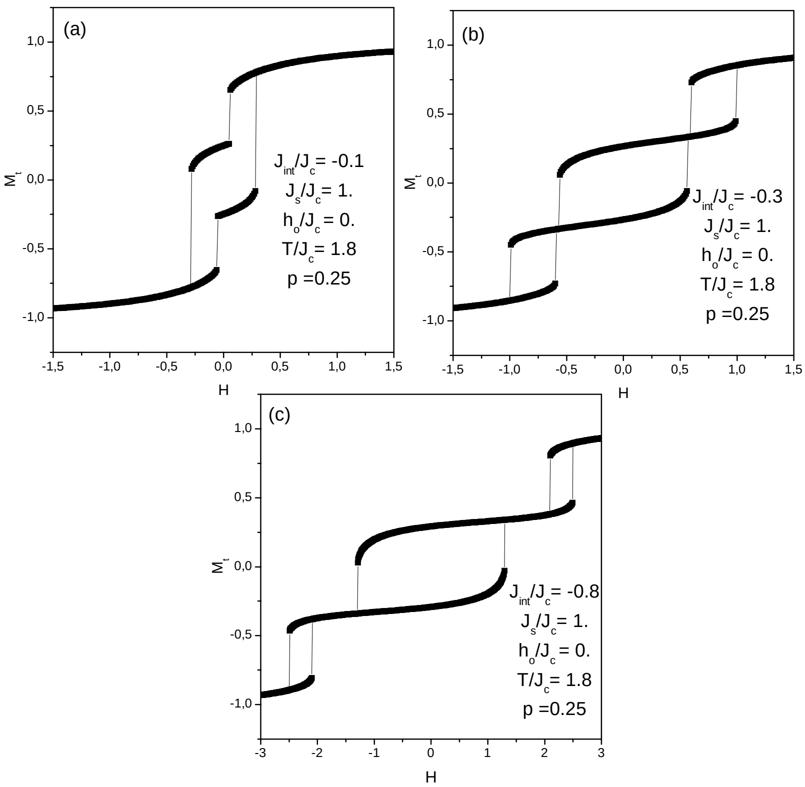

Fig. 1. The magnetic hysteresis curve of the ferrimagnetic nanotube for the fixed parameters $h_0/J_c=0$, $J_s/J_c=1$, $T/J_c=1.8$ and $p=0.25$, and for different values of the antiferromagnetic interfacial coupling constant. a) $J_{int}/J_c=-0.1$, b) $J_{int}/J_c=-0.3$, and $J_{int}/J_c=-0.8$.

In Fig. 1, we show the dependence of the hysteresis loops of a ferrimagnetic nanotube on the antiferromagnetic interfacial coupling constant J_{int}/J_c at $T/J_c=1.8$ for $J_s/J_c=1$, $h_0/J_c=0$ and $p=0.25$. We can see that if the antiferromagnetic coupling constant is small (Fig. 1a), only a central loop opens. The central loop involves two steps due to the different ferromagnetic properties of the core and the shell. This phenomenon illustrates that the behavior of the nanotube approaches that of a ferromagnetic behavior as the absolute value of the antiferromagnetic interfacial coupling constant decreases. It is shown that when $|J_{int}|/J_c$ increases (Fig. 1b and 1c) the hysteresis curve changes from one central loop to triple loops. The larger the antiferromagnetic coupling constant is, the more difficult for the applied magnetic field to change the direction of the magnetization at two interfacial layers in core and shell is. So the outer loops stretch further out horizontally with increasing $|J_{int}|/J_c$. It implied that the behaviors of the system are ferromagnetic like for smaller $|J_{int}|/J_c$, and antiferromagnetic like for larger $|J_{int}|/J_c$. These results mentioned above are qualitatively in a good agreement with hysteresis loops of a ferrimagnetic core/shell nanocube [27].

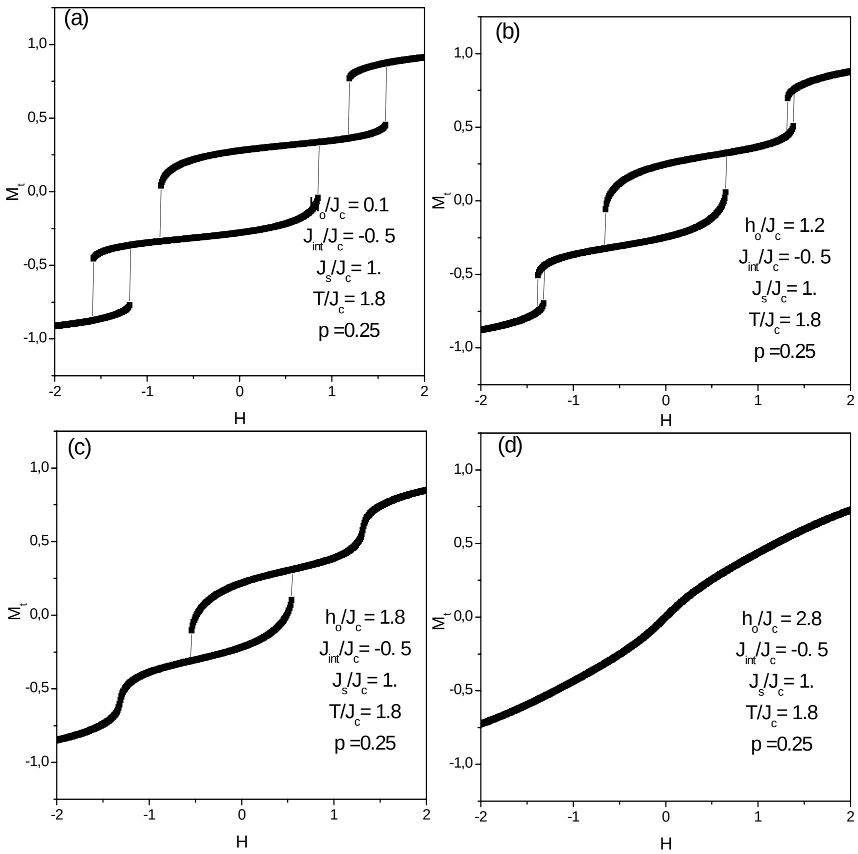

Fig. 2. The magnetic hysteresis curve of the ferrimagnetic nanotube for the fixed parameters J_{int}/J_c=-0.5, J_s/J_c=1, T/J_c=1.8 and p=0.25, and for different values of the random magnetic field. a) h_0/J_c=0.1, b) h_0/J_c=1.4, c) h_0/J_c=1.8, and d) h_0/J_c=2.8.

To better understand the effect of the random magnetic field on the hysteresis loops, we plot in Fig. 2, the magnetization M_t curves versus the applied magnetic field H for $J_s/J_c=1$, $J_{int}/J_c=-0.5$, $T/J_c=1.8$ and for different values of the random magnetic field ($h_0/J_c=0.1$, 1.2, 1.8 and 2.8). From this figure, we can see that the size of the outer loops and that of the central loop reduce when the random magnetic field varies from 0.1 to 1.2. As shown in Fig. 2c, for $h_0/J_c=1.8$, the outer loops disappear and the central loop reduce. When $h_0/J_c=2.8$ in Fig. 2d, the hysteresis loops disappears.

In order to investigated the effect of the shell coupling, we plot in Fig. 3, the magnetization M_t curves versus the applied magnetic field H for $h_0/J_c=0.5$, $J_{int}/J_c=-0.3$, $T/J_c=1.8$, $p=0.25$ and for different values of shell coupling ($J_s/J_c=0.85$, 1.2, and 1.8). It is observed that the shapes of the hysteresis loops changed from triple hysteresis loops to one central loop and that when J_s/J_c increases, the area of the central loop increases. Moreover the triple hysteresis loops behaviors have been seen for different system, such as in single chain magnets with antiferomagnetic interchain coupling [35] and in molecular-based magnetic materials [36]. More than the triple hysteresis loops behaviors have been also seen experimentally in CoFeB/Cu, CoNip/Cu, FeGa/py and FeGa/CoFeB multilayerad nanowire [37].

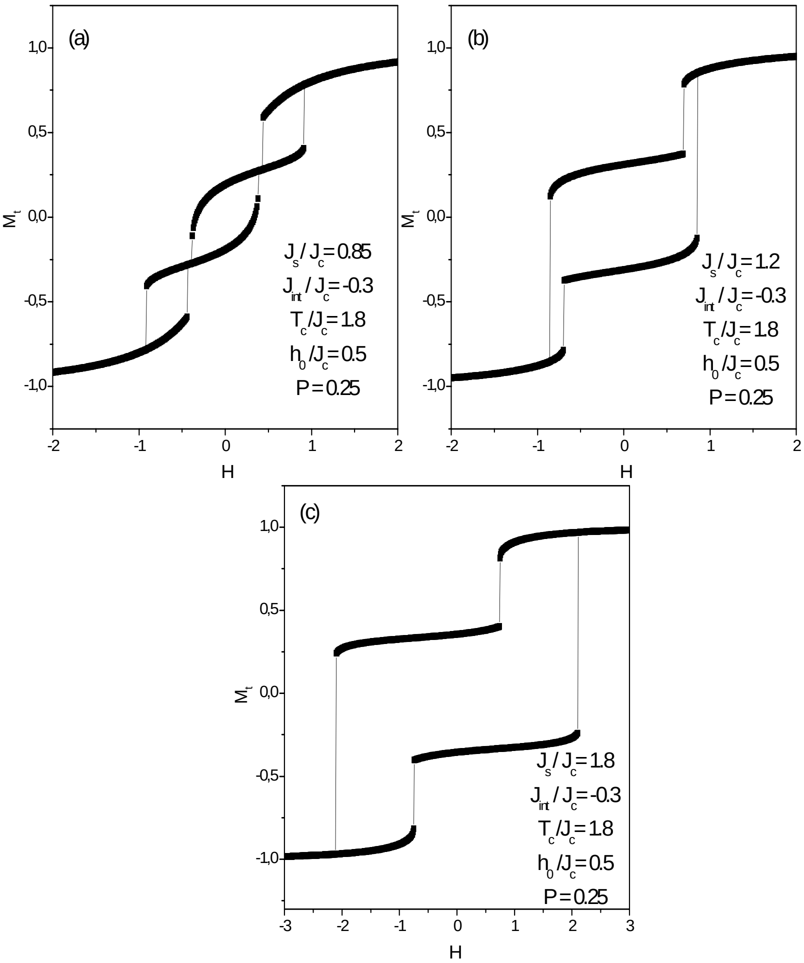

Fig. 3. The magnetic hysteresis curve of the ferrimagnetic nanotube for the fixed parameters J_{int}/J_c=-0.3, h_0/J_c=0.5, T/J_c=1.8, p=0.25, and for different values of the shell coupling. a) J_s/J_c=0.85, b) J_s/J_c=1.2, and c) J_s/J_c=1.8.

4. Conclusions

In conclusions, we have studied the hysteresis behavior of the spin-1 Ising nanotube with core/shell morphology in a random magnetic field where we have taken a coupling constant J_c and J_s for the core and the shell respectively, and an interfacial coupling constant J_{int} between nearest-neighbors spin across the core-shell. Using an effective field theory based on a probability distribution method, we have discussed for ferrimagnetic cases, the influence of the random magnetic field, the shell coupling and the interfacial coupling constant on the hysteresis behaviors. It is shown that, the size of the outer loops and that of the central loop reduce when the random magnetic field increase. It is clear that the triple hysteresis loops occurs for the larger the antiferromagnetic coupling constant.

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*Corresponding authors: ah_zaim@yahoo.fr , kerouad@fs-umi.ac.ma