Available online at www.sciencedirect.com

ScienceDirect

Physics Procedia 54 (2014) 75 – 80

Physics Procedia

International Conference on Magnetic Materials and Applications, MagMA 2013

Magnetization switching of interacting ferromagnetic nanocluster assemblies

Brinis Drifa [1, 2,]*, Ledue Denis [2], Laggoun Ali [1], Patte Renaud [2]

[1]Unité de recherche MPE, Université de Boumerdes, 35 000 Algérie
[2]Groupe de Physique des Matériaux, UMR 6634 CNRS - Université de Rouen, Avenue de l'Université,BP 12, 76801 Saint-Etienne-du-Rouvray, France

Abstract

We have calculated by Monte Carlo simulation (MC) the temperature variation of the ac-susceptibility of cobalt nanoclusters, located at the vertices of periodic lattices, and interacting via dipolar interactions. Our study focuses on the dimensionality effect, so one or two dimensional assemblies have been considered. Opposite effects on the peak height and location of the two ac-susceptibility components have been observed, depending on the easy axis is in the plane of the assembly or perpendicular to it. Furthermore, we have investigated the energy barrier distribution in the presence of dipolar interactions.

Peer-review under responsibility of Department of Physics, Indian Institute of Technology Guwahati
Keywords: nanoclusters; superparamagnetic; ac-susceptibility; Monte Carlo simulation; dipolar interactions.

1. INTRODUCTION

In recent years, ferromagnetic nanoclusters have received a great interest due to their potential applications especially in the field of high density magnetic recording. Indeed, thanks to their nanometer size, storage densities of about 1 Tbits/in² could be reached. In such assemblies, dipolar interactions (DI) cannot be neglected. In order to understand the role of DI, several models have been proposed sometimes leading to contradictory results. For example, the DBF model given by Dormann et al (1988) predicts an increase of the energy barrier, of the relaxation time and hence of the blocking temperature due to DI whereas in the MT model given by Morup et al (1994) the opposite effect is expected. These two models were strongly debated by Hansen et al (1998) and Dorman et al (1999) but most of the

* Corresponding author. Tel.: 00213179714; fax: +0-000-000-0000 .
E-mail address: brinisd@yahoo.fr

Peer-review under responsibility of Department of Physics, Indian Institute of Technology Guwahati
doi:10.1016/j.phpro.2014.10.039

experimental data are better explained by the DBF model. These contradictions arise from approximations made to simplify the problem, especially the mean field approach. Indeed, the dipolar field is not uniform and depends on time since it expression is given by equation (1).

$$\vec{B}_i = \frac{\mu_0}{4\pi} \sum_{j \neq i} \frac{-\vec{m}_j + 3\left(\vec{m}_j . \vec{e}_{ij}\right)\vec{e}_{ij}}{r_{ij}^3} \tag{1}$$

Where

$\vec{m}_{ij}$	magnetic moment of nanocluster *j*
r_{ij}	distance between nanocluster *i* and *j*
$\vec{e}_{ij} = \vec{r}_{ij} / r_{ij}$	
μ_0	magnetic permeability of vacuum

It is worth noting that experimental works do not allow to disentangle DI effect from others, such as the spatial distribution of nanoclusters, the size distribution, the orientation of the anisotropy axes and the damping (Masunga et al (2009), De Toro et al (2012) and Barbeta et al (2010)). As regards the analytical calculation, only weak DIs have been studied by Azzeggh et al (2007), Jönsson et al (2001), Kachkachi et al (2005), Kachkachi et al (2000). So, numerical investigations, such as those made by Anderson et al (1997) and Berkov et al (2001), are important tools since they allow to consider stronger DI.
Here, we propose to investigate the DI effect on the ac-susceptibility using Monte Carlo (MC) simulations. Our study is focused on the dimensionality effect which may come from DI, and the distribution of energy barriers arising from DI due to the thermal fluctuations of the magnetic moments.

2. MODEL AND SIMULATION

A. MODEL

In our model we have considered self-organized assemblies, i.e. the nanoclusters are located at the vertices of a periodic lattice. Each nanocluster is assigned a common easy axis parallel to the *z*-axis. During the simulation, an oscillating field is applied at each temperature along the *z*-axis, $H(l) = H_0 \cos(2\pi\, l/n)$ where *l* is the number of the MC step and *n* the total number of MC steps. The ac susceptibility $\chi = \chi' - i\,\chi''$ is given by :

$$\chi'(\omega) = \frac{2}{n\, H_0} \sum_{l=1}^{n} M(l) \cos(\omega\, l\, \delta t_0) \tag{2-a}$$

$$\chi''(\omega) = \frac{2}{n\, H_0} \sum_{l=1}^{n} M(l) \sin(\omega\, l\, \delta t_0) \tag{2-b}$$

Where

$M(l)$	magnetization of the assembly at the MC step number *l*
$\omega = 2\pi f$	pulsation of the applied field and *f* it's frequency
δt_0	the physical time associated to one MC step

B. SIMULATION TECHNIQUE

In our work, we have used the MC method (Heermann (1990) and Binder et al (1990)). In this work, we have used a transition probability proportional to $\exp(-\Delta E/(k_B T))$ where ΔE is the energy barrier.

3. RESULTS AND DISCUSSION

A. Study without dipolar interaction

First, we investigated the magnetization reversal without DI. For good accuracy of our results, we have considered a large enough number of nanoclusters. Furthermore, we found that the ac-susceptibility curves (Fig. 1) depend strongly on the amplitude H_0 of the applied field. We have to take care that H_0 is large enough for a good accuracy, but small enough for a linear response, and this is in agreement with Anderson et al (1997). By comparison with analytical results of Ledue et al (2012), we found that the value of $\mu_0 H_0 = 0.00521$ T is the appropriate choice. Following this, we have deduced the time associated to one MC step:

$$\delta t_0 = \frac{1}{n_{MCS}\, f} = 8.33\times10^{-13}\ \text{s}$$

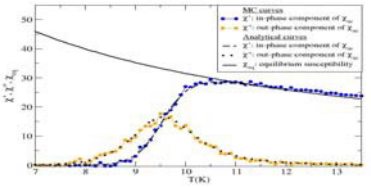

Fig. 1: Comparison of simulated and analytical curves ($f = 10^4$ Hz) of the ac-susceptibility without DI.

According to our model, the value of the prefactor τ_0 of the relaxation time equals to $\tau_0(MC) = \frac{\delta t_0}{2}$, which gives

$$\tau_0 = 4.165\text{x}10^{-13}\, s$$

The independence of τ_0 on the temperature arises from the fact that we ignore the intra-well fluctuations. In the Brown model (1963), τ_0 is given by $\tau_0 = \frac{1}{2\lambda\gamma H_K}\left(\frac{\pi k_B T}{KV}\right)^{1/2}$ and it is equal to 4×10^{-13} s (for $T = 9{,}5$ K and $\lambda = 10$) which is very close to our value.

B. Dipolar interactions effect

B. 1- 1D lattice parallel to the *z*-axis

Albeit the 1D lattice is not realistic, but we insist on it for its simplicity because DI effect is well understood in such assembly. Indeed, DI tend to align the magnetic moments parallel to each other (ferromagnetic order) without frustration, thus increasing the response to an applied field (fig. 2) with a shift of the peaks of the in-phase component χ' and the out-of-phase component χ'' of the ac susceptibility towards higher temperatures. This shift suggests that the relaxation time is increased in the presence of DI which should be due to an increase of the energy barriers. So, we have plotted the distribution of these energy barriers (fig 3). In the blocked state, the distribution exhibits mainly one peak and indicate that the energy barrier increases with the intensity of DI (fig 3-a). In the region in the vicinity of T'_{max} and superparamagnetic states (fig 3-b) and (fig 3-c), other peaks appear in the presence of DI because of the fluctuations of the magnetic moments.

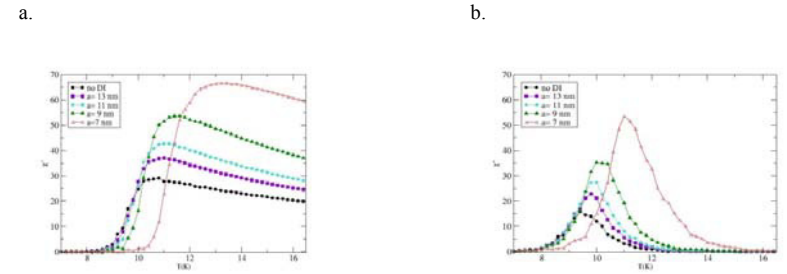

Fig. 2: Thermal variation of the ac susceptibility of the 1D lattice parallel to the *z*-axis for various strengths of the DI. (a): in-phase component. (b): out-of phase component

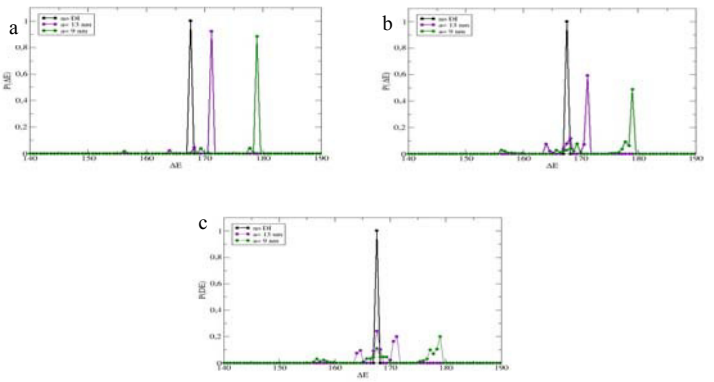

Fig. 3: Distribution of energy barriers in the 1D lattice parallel to the *z*-axis for various strengths of the DI. (a) blocked state; (b) in the vicinity of T'_{max}; (c) superparamagnetic state.

B.2- 2D assemblies

In this section, we have considered two cases: 2D assemblies parallel to the *xy*-plane for which the magnetic moments are perpendicular to the assembly, or 2D assemblies parallel to the *yz*-plane for which the magnetic moments are in the plane of the assembly. Let us remind that in these 2D assemblies DI bring about magnetic frustration.

Assemblies parallel to the xy-plane

In Fig. 4, we can see that the DI effect on the in-phase χ' and out-of-phase χ'' components of the ac susceptibility is opposite to the 1D lattice parallel to the *z*-axis. Actually, in such lattice, DI favor antiferromagnetic order with frustration, thus decreasing the response to an applied field. The shift of the peaks of χ' and χ'' towards lower temperatures suggests that the relaxation time decreases in the presence of DI. On the other hand, we have plotted the distribution of these energy barriers (fig 5). We found that, because of frustration, DIs broaden the energy barriers distributions.

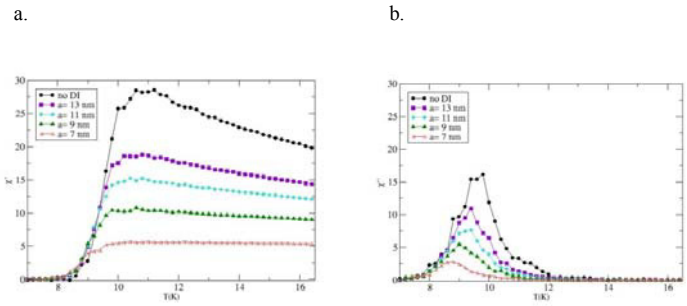

Fig. 4: Thermal variation of the ac susceptibility of the 2D lattice (xy plane) for various strengths of the DI. (a) in-phase component; (b) out-of phase component

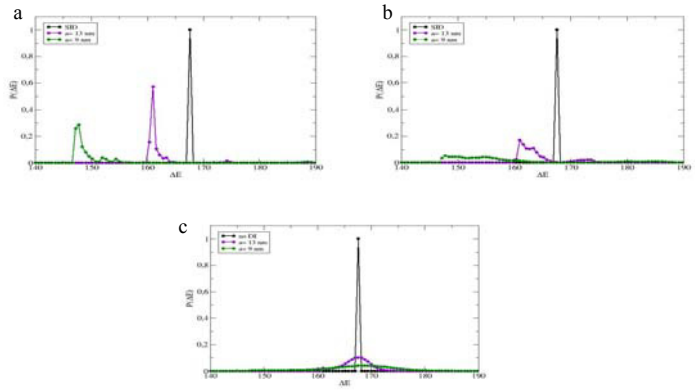

Fig. 5: Distribution of energy barriers in 1D lattice parallel to the *z*-axis for various strengths of the DI. (a) blocked state; (b) in the vicinity of T'_{max}; (c) superparamagnetic state.

Assemblies parallel to the yz-plane

In Fig. 6, we have plotted the thermal variation of the ac susceptibility for various intensities of the DI. The DI effects are qualitatively the same as for the 1D lattice parallel to the *z*-axis but less marked. This indicates that, in such assembly, DI play finally a magnetizing role.

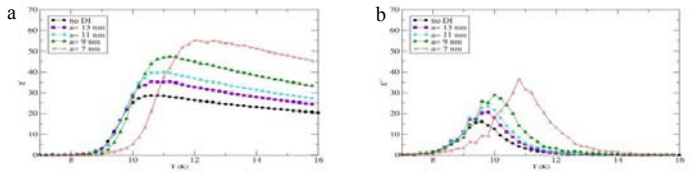

Fig. 6: Thermal variation of the ac susceptibility of the 2D lattice (yz plane) for various strengths of the DI.

(a) in-phase component; (b) out-of phase component

3. Conclusion

In this work, we have evidenced opposite DI effect depending on the direction of the magnetic moments relatively to the sample plane. Our results shown that the peak shift of the imaginary component of the ac-susceptibility toward higher (lower) temperature, is related to the magnetizing (demagnetizing) nature of the DI also evidenced that the energy barrier distributions are not the same in the different states (blocked, in the vicinity of T'_{max} and superparamagnetic state) because of the fluctuation of the magnetic moments.

REFERENCES

Dormann, J.L., Bessais, L., and Fiorani, D., 1988. A dynamic study of small interacting particles: superparamagnetic model and spin-glass laws. J. Phys. C 21, 2015-2033.

Morup, S and Tronc, E., 1994. Superparamagnetic Relaxation of Weakly Interacting Particles. Phys. Rev. Lett. 72, 3278-3281.

Hansen, M.F. and Morup, S, 1998. Models for dynamics of interactingmagnetic nanoparticles. J. Magn. Magn. Mater. 184, 262-274.

Dormann, J.L., Fiorani, D., and Tronc, E., 1999. On the models for interparticle interactions in nanoparticle assemblies: comparison with experimental results. J. Magn. Magn. Mater. 202, 251-267.

Masunga, S. H, Jardim, R. F., Fichner, P. F. P., and Rivas, J., 2009. Role of dipolar interactions in asystem of Ni particles studied by magnetic susceptibility measurements. Phys. Rev. B 80, 184428, 1-7.

De Toro, J.A., Gonzalez, J.A., Normile, P.S., Muniz, P., Andrés, J.P., Lopez Anton, R., Canales-Vazquez, J., and Riveiro, J. M., 2012. Energy barrier enhancement by weak magnetic interactions in Co/Nb granular films assembled by inert gas condensation. Phys. Rev. B 85, 054429, 1-7.

Barbeta, V.B. Jardim, R.F. Kiyohara, P.K. Effenberger F.B.and RossiL.M., 2010. Magnetic properties of Fe3O4 nanoparticles coated with oleic and dodecanoic acids. J. Appl. Phys. 107, 073913, 1- 7.

Azzeggh, M., Kachkachi, H., 2007. Effects of dipolar interactions on the zero-field-cooled magnetization of a nanoparticle assembly. Phys. Rev. B 75, 174410.

Jönsson, P. E., Garcia-Palacios, J. L., 2001. Relaxation time of weakly interacting superparamagnets. Europhys. Lett., 55 (3), 418-424.

Kachkachi, H., Azeggagh, M., 2005. Magnetization of magnet assemblies: Effects of anisotropy and dipolar interacrions. Eur.Phys J B 44, 299-420.

Kachkachi, H., Coffey, W. T., Crothers, D. S. F., Ezzir. A., Kennedy, E. C., Noguès, M., Tronc, E,. 2000. Field dependence of the temperature at the peak of the zero-field-cooled magnetization. J. Phys.: Condens. Matter 12, 3077-3090.

Anderson, J. O., Juburg, O., Jonsson, T., Svedlindh, P., and Nordblad, P.,. 1997. Monte Carlo studies of the dynamics of an interacting monodispersive mzgnetic pzrticle system. Phys. Rev. B 56, 21, 13983-13988.

Berkov, D. V., and Gorn, N. L., 2001. Susceptibility of the disordered system of fine magnetic particles: a Langevin-Dynamics study. J. Phys. Cond. Matter. 13, 9369-9381.

Heermann, D, W., 1990, Computer Simulation Methods in theoretical Physics, 2nd Edition, Springer, Berlin.

Binder, K., Heermann, D, W. 1990, Monte Carlo Simulation in Statistical Physics, 2nd Edition, Springer, Berlin.

Metropolis, N., Rosenbluth, A, W., Rosenbluth, M, N., Teller, A, H., 1953. Equation of State Calculations by Fast Computing Machines. J.Chem.Phys.21, 6, 1087-1092.

Ledue, D., Patte, R., Kachkachi, H., 2012. Dynamical Susceptibility of Weakly Interacting Ferromagnetic Nanoclusters., J.N.N Vol. 12, 1-8.

Néel. L, 1949. , Ann; Géophys, Théorie du trainage magnétique des ferromagnétiques en grains fins avec applications aux terres rares cuites, 99-136.

Brown, W. F, 1963. Thermal Fluctuations of aSingle-Domain Particle. Phys. Rev. 13