AIP Journal of Applied Physics

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Citation: Journal of Applied Physics **109**, 076104 (2011); doi: 10.1063/1.3573518
View online: http://dx.doi.org/10.1063/1.3573518
View Table of Contents: http://scitation.aip.org/content/aip/journal/jap/109/7?ver=pdfcov
Published by the AIP Publishing

Vortex core scattering and pinning by impurities in nanomagnets

D. Toscano,[1,a)] S. A. Leonel,[1,b)] R. A. Dias,[1,c)] P. Z. Coura,[1,d)] and B. V. Costa[2,e)]
[1]*Departamento de Física, Laboratório de Simulação Computacional, ICE, Universidade Federal de Juiz de Fora, 36036-330 Juiz de Fora, MG, Brazil*
[2]*Departamento de Física, Laboratório de Simulação, ICEX, Universidade Federal de Minas Gerais, 30123-970 Belo Horizonte, MG, Brazil*

(Received 17 December 2010; accepted 5 March 2011; published online 8 April 2011)

The dynamical behavior of a magnetic nanoparticle contaminated by pointlike impurities is studied by using a spin dynamics numerical simulation. It was observed that the impurities can behave both as pinning (attractive) and as scattering (repulsive) sites. A Gaussian profile was observed for the interaction potential energy ranging up to two lattice parameters. Using the known values of the parameters for Permalloy-79 we have calculated the interaction energy of the vortex core with a single defect. We estimated the interaction range as approximately 10nm. Both results agree quite well with experimental measurements. © *2011 American Institute of Physics*. [doi:10.1063/1.3573518]

Recently it was discovered that some magnetic nanostructures can present interesting properties that may lead to building efficient new storage devices.[1–4] In a magnetic nanodevice like a nanodisk, the competition between the magnetostatic energy and the exchange interaction is responsible for the formation of a magnetic vortex in the ground state.[5] The static vortex has a planar configuration parallel to the plane of the disk, except at the center of the vortex where the magnetic moments point out in a direction perpendicular to the disk plane, the z direction, which can be up or down ($\pm z$ respectively).[6,7] The system is twofold degenerated, since configurations up and down have the same energy.[8] The manipulation of the vortex and a way to control the core magnetization are subjects of paramount importance, since the Z_2 symmetry of the vortex core can be used as a bit in storage devices. It was observed in numerical simulations that switching can be induced by vortex–hole interaction[9] or by the application of a time-dependent external magnetic field which induces a vortex gyrotropic motion.[10,11]

The interaction of the vortex core with lithographically inserted defects has been the subject of intense investigation in the last few years.[12,13] For example, in Ref. 14 the authors showed that vortices are attracted and pinned by nonmagnetic impurities. It is known that even in pure samples, such as nanodisks made of Permalloy, structural defects are distributed randomly through the material. In Ref. 15, the authors found a density of defects of up to $\approx 2 \times 10^{11}/\text{cm}^2$ for the pinning sites in Permalloy nanodisks, which affect the vortex dynamics. In Ref. 16 the authors used Lorentz transmission electron microscopy to investigate the pinning behavior of magnetic vortices. In a recent work, Compton *et al.*[17] used time-resolved Kerr microscopy to study the vortex-core dynamics in individual magnetic disks. They observed fluctuations in the frequency of the gyrotropic mode in nanodisks of Permalloy. They argued that the fluctuations were due to a distribution of nanoscale defects pinning the vortex core. The authors estimated the average interaction energy of the vortex core with a single nanoscale defect to be approximately 2eV. In Ref. 18 the authors discussed two possible types of pointlike defects acting as pinning or scattering sites. The question pointed out was: It is known that nonmagnetic impurities act as pinning sites, but what could act as a scattering site? In this work we use spin dynamics simulations to study a model for both magnetic pinning and scattering sites. In the model we developed the interaction between the magnetic sites in the nanodisk and the defects depends only on the exchange energy. Following Ref. 19, we consider the magnetic nanodisks modeled by magnetic moments with dipole–dipole and exchange interactions. We can write a model Hamiltonian for the nanodisk with magnetic impurities using a pseudospin language as

$$H = J\left\{-\frac{1}{2}\sum_{\langle i\neq i',j\rangle}\vec{S}_i\cdot\vec{S}_j - \frac{J'}{2J}\sum_{\langle i',j\rangle}\vec{S}_{i'}\cdot\vec{S}_j + \frac{D}{2J}\sum_{i\neq j}\left[\frac{\vec{S}_i\cdot\vec{S}_j - 3\left(\vec{S}_{i}\cdot{}_{ij}\right)\times\left(\vec{S}_{i}\cdot{}_{ij}\right)}{\left(r_{ij}/a^3\right)}\right]\right\}. \quad (1)$$

Here the sites i and j are sites of the pure sample, i' are for sites that contain impurities; $\vec{S}_i$, $\vec{S}_j$, and $\vec{S}_{i'}$ are dimensionless vectors with fixed length representing classical spins located in the sites i, j, and i' and satisfying the condition $|\vec{S}| = 1$; J (in units of energy) is the exchange coupling constant between $\vec{S}_i$ and $\vec{S}_j$; J' is the exchange coupling constant between $\vec{S}_{i'}$ and $\vec{S}_j$; $r_{i,j}$ is the distance between sites i and j measured in units of length; $\hat{r}_{ij} = \vec{r}_{ij}/r_{ij}$; and D is the dipole strength. The parameter a is the lattice parameter defined as the distance between the first neighbors sites in the lattice. The sums in the first and second terms are over nearest neighbors. The Hamiltonian (1) can be rewritten as $H = JH$, where H is the dimensionless term in curly brackets. We

[a)]Electronic address: danilotoscano@yahoo.com.br.
[b)]Author to whom correspondence should be addressed. Electronic address: sidiney@fisica.ufjf.br.
[c)]Electronic address: radias@fisica.ufjf.br.
[d)]Electronic address: pablo@fisica.ufjf.br.
[e)]Electronic address: bvc@fisica.ufmg.br.

follow Ref. 20 to build the simulated nanodisk. The dynamics of the system is followed by solving numerically the discrete version of the Landau–Lifshitz–Gilbert (LLG) equation[21,22] given by

$$\frac{d\vec{S}_i}{d\tau} = -\left[\vec{S}_i \times \frac{\partial \mathcal{H}}{\partial \vec{S}_i}\right] + \alpha\left[\vec{S}_i \times \vec{S}_i \times \frac{\partial \mathcal{H}}{\partial \vec{S}_i}\right], \qquad (2)$$

where τ is the dimensionless simulation time. The Hamiltonian time, t, measured in seconds is obtained by $t = \tau/\omega_0$ (Ref. 24). For Permalloy-79, $\omega_0 = 2.13 \times 10^{11}\ s^{-1}$.[20] The equations of motion were integrated forward by using a fourth-order predictor-corrector scheme with a damping parameter $\alpha = 0.01$ and time step $d\tau = 0.01$ ($dt = 4.7 \times 10^{-14}$s for Permalloy-79). The spin dynamics simulations were done in a nanodisk with diameter $d = 25a$ and thickness $l = a$. Initially the vortex was set at the center of the nanodisk in the presence of a magnetic impurity two sites away. The simulations were performed with no cutoff in the dipolar energy term. The estimated value for the ratio (D/J) for Permalloy-79, $(D/J) = 0.0708$, was used.[20] We observed that if $J' < J$ the vortex core moves toward the magnetic impurity site, indicating an effective attractive potential of interaction between the vortex and the magnetic impurity, as shown in Fig. 1 (see supplementary material[23]). If $J' > J$ the vortex core moves away of the magnetic impurity site, indicating an effective repulsive potential of interaction between the vortex and the magnetic impurity, as shown in Fig. 2 (see supplementary material[23]). We have also calculated numerically the interaction energy per site ($E_{\rm int}$) between the vortex core and the magnetic impurity as a function of the relative distance (r/a) between them. The vortex core was put at the center of a nano-disk with diameter $d = 30a$ as shown in Fig. 3. A Gaussian profile for the interaction energy, $E_{\rm int}(r) = E_0 \exp[-0.5(r/\sigma)^2)]$, was observed for all values of the ratio J'/J. Here $E_0 = E_{\rm int}(r = 0)$ is the interaction energy when the center of the vortex coincides with the impurity site. From Fig. 3 we see that if $J' < J$ the potential is attractive, if $J' > J$ the potential is repulsive. We also observed that the interaction energy exhibits a maximum (if repulsive) or a minimum (if attractive) at $r = 0$, decaying rapidly to zero for $|r| > 2a$. The model for describing structural pointlike defects in nanoscaled ferromagnetic materials presented in Ref. 18 agrees very well with the obtained

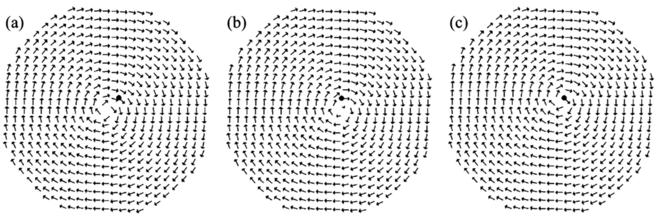

FIG. 1. Snapshots of the dynamical behavior of a vortex core near an attractive magnetic impurity ($J' < J$). (a) A typical initial configuration with the vortex core at the center of the nanodisk. The black circle symbol represents a magnetic impurity located two sites away from the center. (b) Configuration after 120 simulating time steps. (c) Configuration after 350 time steps showing the vortex core at the impurity site. The simulation for later times shows that this is an equilibrium position. See the supplementary material[23] for a video of the vortex core motion in the presence of a magnetic attractive impurity (enhanced online).

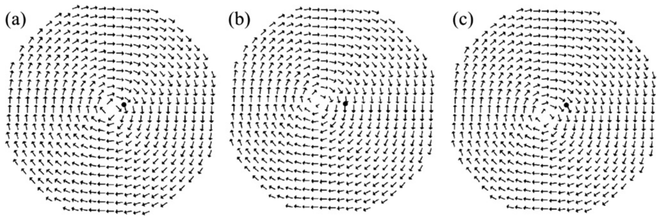

FIG. 2. Snapshots for the dynamical behavior of a vortex core near an repulsive magnetic impurity ($J' > J$). Symbol is the same as in Fig. 1. (a) A typical initial configuration with the vortex core located at the center of the nanodisk in the presence of a magnetic impurity. (b) Configuration after 300 simulation time steps. (c) Configuration after 600 simulation time steps showing the equilibrium position of the vortex core four sites away from the impurity. See the supplementary material[23] for a video of the vortex core motion in the presence of a magnetic repulsive impurity (enhanced online).

gaussian profile. In a micromagnetic approach the nanodisks can be partitioned into cubical working cells of dimensions $a \times a \times a$. Each site represents the center of a working cell. As in Ref. 20 we consider $a = 5$nm and the known exchange stiffness $A = 8.125 \times 10^7$eV/m for Permalloy-79-made samples. In the micromagnetic simulations J is considered as the effective exchange coupling between neighboring cells given by $J = 2Aa = 8.125 \times 10^{-1}$eV. An estimate of the range of the interaction gives $|r| \approx 2a \approx 10$nm, which is in close agreement with the experimental results in Refs. 15 and 16. An estimate of the interaction energy (E_0) of the vortex core with a single pinning impurity or defect can be done as follows. Our model of nanodisks had approximately $N = 717$ sites (cells). For $J' = 0.1J$, $E_0 = -4.18 \times 10^{-3} \times 717 \times 8.125 \times 10^{-1} eV = -2.43$eV and for $J' = 0.5J$, $E_0 = -1.35$eV. These energy values are of the same order of magnitude as those estimated in Ref. 17 (approximately 2eV). Our results indicate that the possible origins of the pinning and scattering defects in thin films could be the local reduction or increase in the exchange constant respectively, caused by a local nanoscaled structural

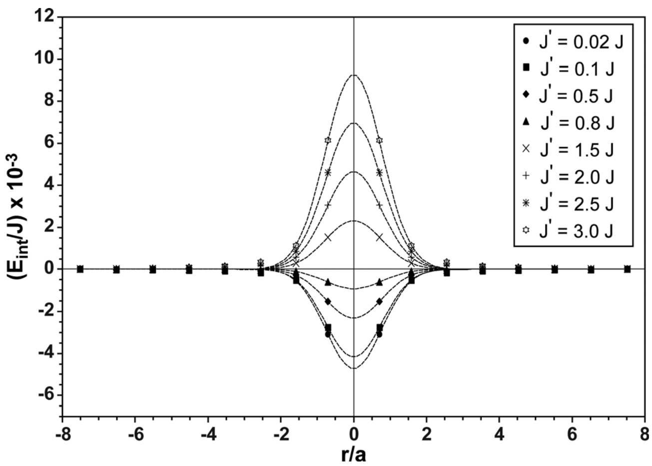

FIG. 3. Interaction energy per site ($E_{\rm int}/J$) as a function of the relative distance, (r/a), between the vortex core and the magnetic impurity considering the vortex core located at the center of the nanodisk ($r = 0$). The dotted lines are adjustments of the Gaussian $E_{\rm int}/J = (E_0/J)\exp[-0.5(r/\sigma)^2]$ for several values of J'/J as shown in the inset. The corresponding values for $E_0/J(\times 10^3)$ are: $-4.70, -4.18, -2.32, -0.93, 2.32, 4.63, 6.96, 9.29$, and $\sigma = 0.77a$ for all J'/J.

deformation. We believe that not all structural defects produced in the samples are pinning defects, structural scattering defects can also be produced and certainly will affect the gyrotropic frequency as pointed out in Ref. 17. It should be very interesting to have more investigation on this subject so that one could validate (or not) our findings.

In summary, we have used spin dynamics simulations to study a model for magnetic pinning and scattering sites. We found that if the coupling between the defect with the magnetic atoms (J') in the crystal is smaller than the coupling between the magnetic atoms, the interaction potential between the vortex and the impurity is attractive. On the other hand if ($J' > J$) a repulsion is observed. Using the known values of the parameters for Permalloy-79 we have found that our results are in very good agreement with experimental estimate. We observe that a potential technological application can be the use of magnetic impurities lithographically inserted in magnetic nanodisks to control the gyrotropic mode and the core magnetization.

ACKNOWLEDGMENTS

This work was partially supported by CNPq and FAPEMIG (Brazilian agencies). Numerical work was done at the Laboratório de Simulação Computacional do Departamento de Física da UFJF.

[1] K. Y. Guslienko, R. H. Heredero, and O. Chubykalo-Fesenko, Phys. Rev. B **82**, 014402 (2010).
[2] Y. Gaididei, V. P. Kravchuk, D. D. Sheka, and F. G. Mertens, Phys. Rev. B **81**, 094431 (2010).
[3] R. P. Cowburn, D. K. Koltsov, A. O. Adeyeye, M. E. Welland, and D. M. Tricker, Phys. Rev. Lett. **83**, 1042 (1999).
[4] T. Shinjo, T. Okuno, R. Hassdorf, K. Shigeto, and T. Ono, Science **289**, 930-932 (2000).
[5] N. A. Usov and S. E. Peschany, J. Magn. Magn. Mater. **118**, L290 (1993).
[6] A. Hubert, and R. Schafer, *Magnetic Domains* (Springer, Berlin, 1998).
[7] J. E. R. Costa and B. V. Costa, Phys. Rev. B **54**, 994 (1996); J. E. R. Costa, B. V. Costa, and D. P. Landau, Phys. Rev. B. **57**, 11510 (1998).
[8] B. V. Costa, Braz. J. Phys. **41**, 1 (2011).
[9] R. L. Silva, R. C. Silva, A. R. Pereira, W. A. Moura-Melo, N. M. Oliveira-Neto, S. A. Leonel, and P. Z. Coura, Phys. Rev. B. **78**, 054423 (2008).
[10] K. Y. Guslienko, B. A. Ivanov, V. Novosad, Y. Otani, H. Shima, and K. Fukamichi, J. Appl. Phys. **91**, 8037 (2002).
[11] J.P. Park, P. Eames, D. M. Engebretson, J. Berezovsky, and P. A. Crowell, Phys. Rev. B. **67**, 020402 (2003).
[12] M. Rahm, J. Stahl, and D. Weiss, Appl. Phys. Lett. **87**, 182107 (2005).
[13] A. R. Pereira, A. R. Moura, W. A. Moura-Melo, D. F. Carneiro, S. A. Leonel, and P. Z. Coura, J. Appl. Phys. **101**, 034310 (2007).
[14] A. R. Pereira, L. A. S. Mól, S. A. Leonel, P. Z. Coura, and B. V. Costa, Phys. Rev. B. **68**, 132409 (2003).
[15] R. L. Compton and P. A. Crowell, Phys. Rev. Lett. **97**, 137202 (2006).
[16] T. Uhlig, M. Rahm, C. Dietrich, R. Hollinger, M. Heumann, D. Weiss, and J. Zweck, Phys. Rev. Lett. **95**, 237205 (2005).
[17] R. L. Compton, T. Y. Chen, and P. A. Crowell, Phys. Rev. B **81**, 144412 (2010).
[18] F. A. Apolonio, W. A. Moura-Melo, F. P. Crisafuli, A. R. Pereira, and R. L. Silva, J. Appl. Phys. **106**, 084320 (2009).
[19] J. C. S. Rocha, P. Z. Coura, S. A. Leonel, R. A. Dias, and B. V. Costa, J. Appl. Phys. **107**, 053903 (2010).
[20] D. Toscano, S. A. Leonel, R. A. Dias, P. Z. Coura, J.C.S. Rocha, and B.V. Costa, J. Appl. Phys. **109**, 014301 (2011).
[21] Y. Gaididei, V. P. Kravchuk, and D. D. Sheka, Int. J. Quantum Chem. **110**, 83 (2010).
[22] L. D. Landau and E.M. Lifshitz, "On the theory of the dispersion of magnetic permeability in ferromagnetic bodies", Phys. Z. Sowjetunion, **8**, pp. 153 (1935); also in *L. D. Landau, Collected Papers*. edited by D. ter Haar (Gordon and Breach, New York, 1967), p. 101.
[23] See supplementary material at E-JAPIAU-109-067107 for videos of the vortex core motion in the presence of a magnetic attractive/repulsive impurity.
[24] L. Berger, Y. Labaye, M. Tamine, and J. M. D. Coey, Phys. Rev. B **77**, 104431 (2008).