Predicted defect-induced vortex core switching in thin magnetic nanodisks

R. L. Silva,* A. R. Pereira,† R. C. Silva, and W. A. Moura-Melo‡
Departamento de Física, Universidade Federal de Viçosa, Viçosa, 36570-000 Minas Gerais, Brazil

N. M. Oliveira-Neto
Departamento de Física, Universidade Estadual do Sudoeste da Bahia, Jequié, 45200-000, Bahia, Brazil

S. A. Leonel and P. Z. Coura
Departamento de Física ICE, Universidade Federal de Juiz de Fora, Juiz de Fora, 36036-330 Minas Gerais, Brazil

(Received 1 April 2008; revised manuscript received 30 May 2008; published 18 August 2008)

We investigate the influence of artificial defects (small holes) inserted into magnetic nanodisks on the vortex core dynamics. One and two holes (antidots) are considered. In general, the core falls into the hole; but, in particular, we would like to note an interesting phenomenon not yet observed, which is the vortex core switching induced by the vortex hole interactions. It occurs for the case with only one hole and for very special conditions involving the hole size and position as well as the disk size. Any small deformation in the disk geometry such as the presence of a second antidot completely changes the vortex dynamics, and the vortex core eventually falls into one of the defects. After trapped, the vortex center still oscillates with a very high frequency and small amplitude around the defect center.

DOI: 10.1103/PhysRevB.78.054423 PACS number(s): 75.75.+a, 75.40.Gb, 75.60.Ch, 75.60.Jk

I. INTRODUCTION AND MOTIVATION

As it is well known, magnetic vortex states are experimentally observed in ferromagnetic disk shaped nanostructures. These topological objects exhibit a planarlike configuration of spins outside the core where a perpendicular magnetization (up or down polarization) is observed.[1–3] As long as one could manipulate these vortices, several possibilities would emerge. Therefore, studies taking into account the application of external potentials such as static and sinusoidal magnetic fields are nowadays very common in the literature.[4–9] For instance, the simplest effect induced by an external field is the gyrotropic mode, which is the lowest excitation of the vortex structure. This mode is simply the elliptical vortex core motion (with the resonance frequency) around the disk center. The sense of gyration in an elliptic trajectory (clockwise or counterclockwise) is determined only by the vortex core polarization. External potentials such as magnetic fields or (dc) spin polarized currents can also stimulate dramatic effects such as the switching behavior.[4–7] However, no internal mechanisms that were able to induce the core switching were reported neither experimentally nor theoretically. Such a chance would only occur if the vortex could interact with possible inhomogeneities present in the nanostructure. For instance, a possibility of triggering this process could be obtained by removing some small portions of the magnetic nanodisk in such a way that the cavities (antidots) thus created work by attracting and eventually affecting the vortex structure.[10–16] Recently, Rahm and co-workers[10–12,17] experimentally studied the cases of one, two, three, and four antidots artificially inserted in a disk with a diameter ~500 nm and separated by around 150–200 nm. Their results did not only confirm the previous statement about vortex pinning around the hole defects[13–16] but have also put forward the possibility of using these stable states as serious candidates for magnetic memory and logical applications.[18] Although experimental results are provided for such systems, it is worthy to notice that a broad theoretical analysis is still lacking. In this paper, we argue that the defects present in the dots may induce interesting possibilities for the magnetization dynamics, including the switching behavior of vortex structures. This is a very interesting topic and open possibilities for technologies and experiments. Indeed, a very recent work[19] has shown that magnetization dynamics and evolution are deeply modified when cavities are introduced. Their samples are consist of Co-made elongated ring-shaped nanomagnets, which similar to permalloy has negligible magnetostatic anisotropy. What is clearly observed in these experiments is that the reversal pathway of the so-called diagonal onion state is drastically affected by the inserted holes once they attract and sometimes pin the transient vortexlike domain-wall configurations. Actually, not only the presence but also the sizes and locations of the cavities (two or four in their hollowed samples) remarkably change magnetization evolution and eventually lead to its reversal. We will follow a different line in which the magnetization reversal takes place due to the effects produced by the hole on the vortex core motion. No further agent is necessary in the switching process, such as those that occurred to other usual methods where external fields are one of the main ingredients.

Before starting our analysis, it would be useful to describe how a magnetic vortex can arise in nanodisks. Indeed, a small revision will help to justify the magnetic model used here. The vortex state in magnetic nanodot materials is the result of the competition between exchange and magnetostatic interactions. Particularly, in finite systems such as magnetic dots, densities of "magnetic charges" are induced in their volumes and surfaces. Considering the magnetization $\vec{M}$, the volumetric and superficial densities are defined as $\rho = -\vec{\nabla}\cdot\vec{M}$ and $\sigma=\vec{M}\cdot\hat{n}$, respectively, where $\hat{n}$ is the unit vectors normal to the surfaces of the dot at each point. Therefore, in order to minimize the magnetostatic energy, the magnetization tends to point parallel to the dot surfaces and it is one of the properties responsible for the formation of the vortex ground state. However, for as long as we go toward the vortex center, exchange energy density gradually increases such as r^{-2}. Then, in order to regularize exchange contribution, the magnetic moments around the center tend to revolve—developing out-of-plane projection so that exactly at the vortex center it is perpendicular to the disk face whose direction defines what is called vortex polarization ($p=+1$ if the centered moment points *up* or $p=-1$ if it is pointing *down*). Here, we study very thin ferromagnetic nanodisks with thickness L and radius R so that the aspect ratio $L/R \ll 1$. In this case, one can assume $\vec{\nabla}\cdot\vec{M}=0$, and hence, the only source of magnetostatic interactions is the superficial magnetic charges. To write the vortex state in these dots, it is convenient to parametrize the magnetization $\vec{M}(\vec{r})$ by two scalar fields: the polar $\theta(\vec{r})$ and azimuthal $\phi(\vec{r})$ angles, $\vec{\mu}(\vec{r})=\vec{M}(\vec{r})/M=(\sin\theta\cos\phi, \sin\theta\sin\phi, \cos\theta)$. Using $m(\vec{r})=\cos\theta(\vec{r})$, the vortex state configuration can be written as $m(\vec{r})=m_0^{\pm}(\vec{r})=\cos\theta_0^{\pm}(\vec{r})$ and $\phi(\vec{r})=\phi_0^{\pm}(\vec{r})=\arctan(y/x)\pm\pi/2$, where the magnetization unit vector deviates out of the plane at the vortex core $m_0^{\pm}(\vec{0})\to\pm 1$ and outside this region, $m_0^{\pm}(\vec{r})\to 0$. The vortex core size is approximately the exchange length l_0 (which can be taken to be of the order of the lattice spacing a in our simulations on a discrete lattice). In this notation, the values of $m_0^{\pm}(\vec{0})$ at the vortex center defines the vortex polarization. On the other hand, $\phi_0^{\pm}(\vec{r})$ defines the vortex chirality. The flux closed in-plane vortex $[\phi_0^{\pm}(\vec{r})]$ and the perpendicular component in the center $[m_0^{\pm}(\vec{0})]$ are independent of each other so that four different magnetization states of one disk are possible.

Our paper is organized as follows: In Sec. II, the model and the associated methods of numerical analysis are presented and discussed. Section III is devoted to the study of sample with a single hole. There, we emphasize the vortex core reversal process induced by its interaction with the defect and the nonordinary circumstances favoring it. The case of doubly hollowed disk is studied in Sec. IV, which is different from the former case, in the same sense that no holes configuration was observed to yield the core switching: indeed, it is always captured by one of the defects before any reversal is observed in our simulations. We finally close our work in Sec. V by pointing out our conclusions and prospects for forthcoming investigation.

II. MODEL AND METHODS

In order to describe a thin magnetic nanodisk we pursue an alternative strategy, substituting the disk by a two-dimensional film with magnetization vectors distributed in a regular square lattice inside a circumference of radius R. In addition, the magnetostatic interactions due to the presence of the magnetic charges in the lateral and top surfaces of the dot are replaced by local potentials. Since we are going to study systems with one and two holes and also with no hole, the model used is summarized by the following general Hamiltonian:

$$H = -\sum_{\{i,j\}} J_{ij}\vec{\mu}_i\cdot\vec{\mu}_j + \sum_{\alpha=1,2}\sum_k \lambda_\alpha(\vec{\mu}_k\cdot\hat{n}_{k,\alpha})^2 + \sum_{D=1,2}\sum_l \lambda_{D,l}(\vec{\mu}_l\cdot\hat{n}_{D,l})^2 - \sum_i \vec{h}\cdot\vec{\mu}_i, \qquad (1)$$

where $J_{ij}=0$ for sites inside the holes and $J_{ij}=J>0$ for the remaining sites of the film. Here, $\mu_i=\vec{M}_i(\vec{r})/M_s=\mu_i^x\hat{x}+\mu_i^y\hat{y}+\mu_i^z\hat{z}$ is the unit spin vector at position i (M_s is the saturation magnetization) and the sum $\{i,j\}$ is the over nearest-neighbor spins. The terms with positive constants $(\lambda_\alpha, \lambda_{D,l})$ mimic the magnetostatic energies (see below) in the top face of the disk, λ_1, while λ_2 accounts for the lateral edge. At the hole borders the analogous constants—taking into account the surface charges at the edges—are $\lambda_{1,l}$ and $\lambda_{2,l}$ for holes one and two, respectively. For the case without defects, $\lambda_{1,l}=\lambda_{2,l}=0$ while for the situation with a single defect $\lambda_{2,l}=0$. In turn, $\vec{h}$ is the external magnetic field. The hole defects are introduced by removing a number of neighbor spins around sites $\vec{r}_1=(0,d_1)$ and $\vec{r}_2=(0,-d_2)$ from the system ($d_1>0$ and $d_2>0$). Of course, the number of neighbor spins removed around a particular position ($\vec{r}_1$ or $\vec{r}_2$) defines the hole sizes ϱ_1 and ϱ_2. Now, the magnetostatic energy favors the spins to be parallel to the film surfaces. Therefore, the local unit vectors $\hat{n}$ defined on the points characterizing the surfaces of the material are always perpendicular to these surfaces (or boundaries): $\hat{n}_{k,1}=\hat{z}$ is perpendicular to the disk face in the xy-plane; $\hat{n}_{k,2}$ is radially perpendicular to the circumference envelop with radius R at each point; $\hat{n}_{1,l}$ and $\hat{n}_{2,l}$ are radially perpendicular to the border points of holes one (pointing to $\vec{r}_1$) and two (directed to $\vec{r}_2$), respectively.

As we have already mentioned in principle, our model Hamiltonian [Eq. (1)] could describe a very thin disk with aspect ratio $L/R \ll 1$. In fact, several known experimental results with nanodisks can be qualitatively reproduced using it. For instance, the vortex core precession mode (which has a rather low eigenfrequency[8,20]) can be easily obtained—at least qualitatively—with this simple model (see below). However, it is not well known how defects can change this picture. Defects must be naturally present[21] or artificially inserted[12,17,22] in the film samples. It has been predicted theoretically[13–15,23] and also observed experimentally[12,22] that small holes incorporated into the magnetic structures can attract and capture magnetic vortices. On the other hand, we argue that another effect can occur: the vortex core switching due to an involved dynamical state of the magnet, which should include the coherent magnetization oscillations (near the defect) matched to the vortex motion. Actually, a somewhat similar effect has been observed in quite recent experiments.[19] There, the pathway developed to reverse the diagonal onion state in elongated nanorings is quite sensitive to intentionally inserted cavities, as well as their sizes and locations. Here, the picture comprises a vortexlike configuration with polarization, say, up, which after interacting with a hole of a given size at a specified position (these values clearly depend on other parameters such as the whole nanodisk size, applied field amplitude for resonantly exciting the gyrotropic mode, etc.), turns out to be down, eventually reversing the sense of its gyrotropic motion. What should be

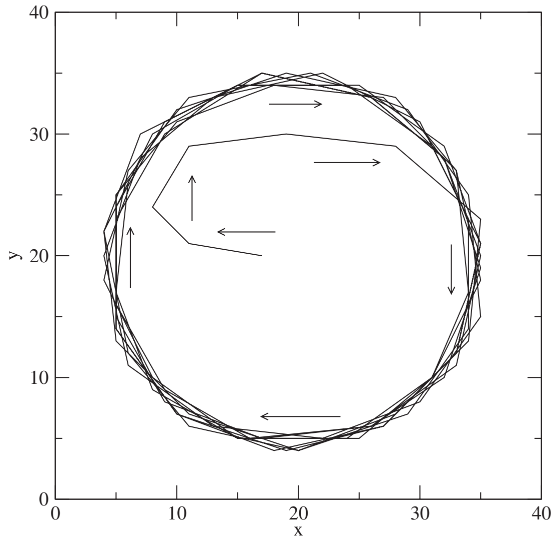

FIG. 1. Trajectory of the vortex core [beginning at the disk center $(20a,20a)$], in the xy plane after turning off the external field. Here, no hole is inserted and the arrows indicate the direction of the motion.

stressed is that such a remarkable phenomenon shows up in our simulations only for very special situations involving the physical parameters, for instance, the hole must be relatively small (around 5%–10% of the sample size). In addition, the insertion of a second similar hole in any position deeply jeopardizes the magnetization evolution, and the vortex core is always captured by one of the holes before any core reversal process.

Our results are obtained by using spin dynamics simulations for a square lattice occupying all possible points inside a circumference with radius R (in most simulations we have used $R=20a$, $25a$, $30a$). It is solved by employing the fourth-order predictor-corrector method. The calculations presented here consider only $R=20a$, $\lambda_1=0.2\ J$, and $\lambda_2=2\ J$. The choice of other values of λ_1 does not alter the essential physics if it is not large enough (in all investigations we have used the range $0<\lambda_1<0.28$). For $\lambda_1>0.28$, the vortex becomes essentially planar and does not develop the out-of-plane components at the core.[24] On the other hand, we have verified only a limited range of λ_2. Indeed, the interval $1.8<\lambda_2<2.2$ leads to the same quantitative and qualitative results. In order to excite the vortex core precession mode, an external perturbation was applied. Here, we have chosen a sinusoidal external magnetic field of the form $\vec{h}_{\text{ext}}(t)=\vec{h}_0\sin(\omega t)$, with $\vec{h}_0=0.01\ \text{J}\hat{x}$ and $\omega=0.089\ J$. These are the best conditions we have identified in our simulations favoring the core reversal. For instance, large changes in these field parameters will not produce the main phenomena we intend to describe. In all cases, the duration of the sinusoidal field was $700\ J^{-1}$ and the total time of the simulations was $10^4\ J^{-1}$ with time increment equal to $\Delta t=0.01\ J^{-1}$. First, in the absence of the defects and after turning the field off, we observe the precession mode with a circular trajectory, as expected (see, Fig. 1). For a better analysis of this mode, we have plotted the behavior of the magnetization in the x direction $\langle\mu_x\rangle$ as a function of time and its Fourier

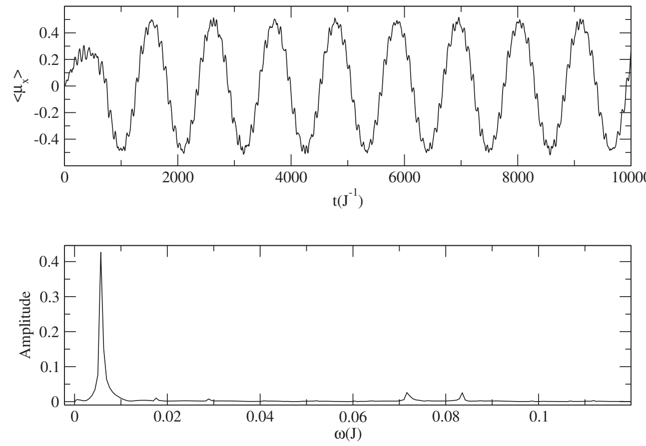

FIG. 2. Magnetization in the x direction as a function of time and its Fourier transform.

transform (see Fig. 2; the same behavior can be seen for $\langle\mu_y\rangle$). The Fourier transform presents a peak at a well defined frequency $\omega_R=0.0056\ J$, which is the frequency of the vortex core precession (the resonance frequency, see Fig. 3). Of course, it depends on the size R of the disk. More realistically, the resonance frequency depends on the aspect ratio L/R. However, since our model assumes a very thin disk, we can, in principle, obtain ω_R as a function of L/R only for $L/R\ll 1$. We also studied the behavior of ω_R as a function of $1/R$, which appears to be essentially linear, at least for $1/R\ll 1$ (see Fig. 4), in qualitatively accordance with experimental findings.[8,20] All above comparisons (and others not presented here) show that this model works very well. It gives us a perspective that Hamiltonian Eq. (1) is also able to predict facts not yet observed in experiments.

Before studying the problem of interest, we have also plotted the behavior of the z component of the magnetization as function of time (and its Fourier transform) in the absence of a defect (see Fig. 5). In this case, the average magnetization over the whole sample oscillates around a small positive

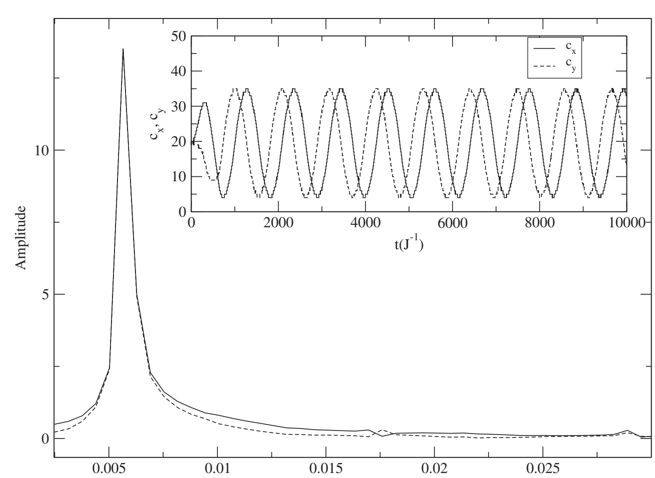

FIG. 3. Position components (c_x,c_y) of the vortex center as function of time. Note that the Fourier transform leads to a peak at the same frequency observed in Fig. 2. This is the resonance frequency of the gyrotropic motion.

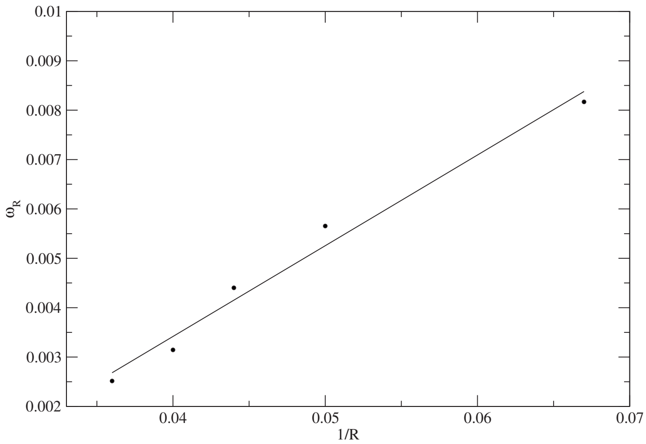

FIG. 4. The behavior of the gyrotropic frequency, ω_R, as function of the aspect ratio, R^{-1}, obtained from the present model. Points are simulational results while the line is the linear fitting.

value (because the out-of-plane spins forming the vortex core are pointing along the positive z direction) all the time without abrupt changes, indicating that there is no magnetization reversal during the vortex core precession, as expected. In addition, the main peak in the Fourier transform occurs at a frequency 0.078 J, which is different from ω_R.

This model involves several parameters and, of course, it is very hard to treat in details all aspects. Therefore we have exposed here the general behavior of the vortex core dynamics and the main particular phenomena found for specific conditions. We notice that a hole, independent of its size and position, in general, attracts the vortex core to its center, i.e., the core almost always falls into the hole (sometimes, scatteringlike events may occur). Some theoretical[13,14,23,25,26] and experimental works have already reported the capture process.[11,12,27] Hence, it would be interesting to consider other possibilities for the vortex dynamics in the presence of such type of defects. Two situations are analyzed in details. The first one, which is more remarkable, describes the vortex core switching due to the vortex defect interaction. It happens only for very special circumstances and our work indicates the most suitable configurations in order to aid possible experimental probing. The other one relies on the fate of the core to be trapped by one of the two holes (two configurations that yield this capture are presented). Such a situation also serves to illustrate how a relatively small perturbation eliminates the magnetization reversal and how the center of the vortex oscillates after a capture process.

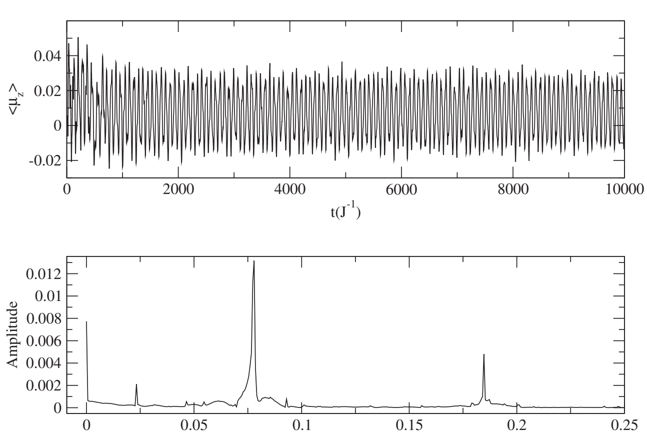

FIG. 5. $\langle \mu_z \rangle$ versus t and its Fourier transform. Note that $\langle \mu_z \rangle$ oscillates around a positive value.

III. NANODISK WITH A SINGLE HOLE AND THE VORTEX CORE SWITCHING

Now we consider some effects that a hole may induce on the vortex core dynamics. When a small hole is inserted in the circular film, the vortex core suffers influences so that the magnetization dynamics should become much richer. Indeed, holes induce an attractive effective potential for the vortex,[13,14,23,25] and therefore, such force may compete with the effects of applied fields, magnetostatic, anisotropies, etc.

In this section we consider the presence of a single hole of radius $\varrho_1=\varrho$. For the external field, we use the parameters of the previous section. In a nanodisk with a cavity, one expects that magnetic charges are also induced in the cavity walls analogously as they appear in the usual surfaces of the disk. Therefore, taking into account only the presence of defect one at position $\vec{r}_1$, in principle, we should use $\lambda_{1,l}\neq 0$, which corresponds to the influences of the magnetostatic energy coming from the edge of the hole cavity. Here we will show only influences of very small defects as compared to the disk size and consequently, $\lambda_{1,l}$ could be neglected in first approximation since the hole wall can support only a tiny amount of magnetic charges. More realistic analysis should then take this parameter to be small, for example, as compared to λ_2. However, it is illustrative to study the system for a large range of $\lambda_{1,l}$ values, say, $0\leq\lambda_{1,l}\leq\lambda_2$, for elucidating its effects on the whole properties of the magnetization. Generally, for the smallest hole considered (four neighbor spins removed, $\varrho_1=\varrho=a$), the vortex core is almost always captured (or sometimes scattered) by the defect for $\lambda_{1,l}>2.3\times 10^{-4}$. Hence, large enough contributions of magnetostatic energy coming from the cavity wall (i.e., large $\lambda_{1,l}$) leads to the common phenomena of capture, or even the more seldom scatteringlike effect, observed for larger holes. Indeed, larger holes always capture the vortex core, independently of $\lambda_{1,l}$ (recall that besides magnetostatic, exchange gets lower as the hole size increases), which agrees with experimental[11,12,27] and theoretical[25,28] results, which consider defects occupying an appreciable fraction of the disk. Therefore, if one wishes to look for different possibilities, perhaps the small defects should be the focus. With this strategy, we will first analyze several parameter possibilities and later we will consider $\varrho=a$ and use $\lambda_{1,l}=\lambda_2/10^4$ (or, for simplicity, $\lambda_{1,l}=0$) for all subsequent calculations. Indeed, the most important phenomenon we would like to describe here happens only for $0\leq\lambda_{1,l}\leq 2.3\times 10^{-4}$ J. Physically, it is reasonable to think that a small cavity wall has only a tiny contribution to the magnetostatic energy.

The size and position of the hole can be controlled, and so we have studied several cases. For example, for a central hole with size a, the resonance frequency of the gyrotropic mode is given by 0.0034 J, which is smaller than the one we have observed for the usual nanodisk $\omega_R=0.0056\ J$ (a fact qualitatively predicted by analytical treatment[28]). The problem with this configuration is that the ground state is a vortex pinned to the hole (of course, without an out-of-plane core), and therefore, the vortex needs to be previously released from the cavity to exhibit the gyrotropic mode. Changes in the defect size and position lead to the following general situations: Depending on the initial conditions (external sinusoidal fields, essentially), then, as the vortex core moves sufficiently close the defect border, it can be either transmitted or captured by the cavity. These are interesting effects due to core hole interaction but, for very special features of the film, a much more rare dynamical event may be triggered. Actually, choosing the coordinate system in which the disk center is put at $(20a,20a)$ and if and only if we use $\vec{r}_1=(0,33a)$ [or $(0,7a)$] for the center position (along the y axis at $d_1=\pm 13a$) of a hole with size $\varrho=1a$ (four neighbor spins removed), then a fabulous phenomenon occurs: the magnetic vortex core is reversed. For all disk sizes studied, only one configuration was found to reverse the core magnetization. Always, the hole must be relatively small and is placed near enough the disk border, perpendicularly to the field. Particularly, for $R=20a$ and $\rho=a$, the asymmetric conditions with $d_1=13a$ seems to be a unique defect position possible to trigger the switching process. It should be emphasized that the switching of magnetic domains generally depends on a myriad of detailed features of the magnetic particles, and topological effects ultimately limit this possibility. Therefore, the occurrence of such a delicate dynamical effect should not be expected for any ordinary configuration of the magnet with a hole. Usually, what is observed is the capture of the core when the defect is large enough; conversely, only small changes in its dynamics are observed for very small defects. The main lesson is: the core reversal seems to demand relatively small hole (in our case around 5%–10% of the nanodisk dimension) combined with other favorable events, such as its location and suitable applied oscillating field. Another important point is that, assuming $\lambda_{1,l}/\lambda_2 \ll 1$ and for special conditions and parameters (such as d_1 and ϱ used here), the reversal of the magnetization of the vortex core (along the z direction) can always be reproduced. In Fig. 6 we show the trajectory of the vortex core. Note that this mode starts with the same frequency of the case without a hole (Fig. 1) in a trajectory outer the hole. However, after some revolutions, when the vortex core moves again very near the hole border (in a region in between the hole and disk walls), it quickly changes the direction of the motion simultaneously with the magnetization reversal along the z direction (see video of the vortex core motion and the switching phenomenon as auxiliary material[29]). Really, a change in the sense of gyration unambiguously indicates a change in the vortex core polarization. Then the vortex core again develops a precession mode with a smaller frequency $\omega_R^{(2)}=0.0025\ J$ as shown in Fig. 7 (an orbit with radius smaller than d_y). An appreciable part of the kinetic energy of the vortex was transformed in spin waves. To see more clearly the switching behavior, the z component of the average magnetization $\langle \mu_z \rangle$ is plotted in Fig. 8, which can be compared with Fig. 5. Let us note the rapid change in the mean value of $\langle \mu_z \rangle$ from positive (when the core direction was up) to negative (when the core is down). In the Fourier transform, the main peak happens in almost the same frequency for the case without a hole.

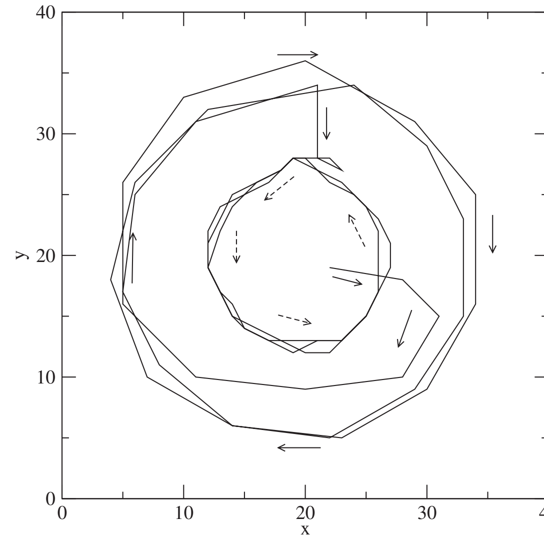

FIG. 6. Typical trajectory of the vortex core in a disk containing a hole [at position $(0,33a)$]. The vortex core motion starts in the disk center $(20a,20a)$ and the precession mode is excited by a field pulse. The comparison of this motion with that shown in Fig. 1 clearly shows the effect of the hole on vortex core dynamics.

Thus, the lack of experimental observation of core switching induced by vortex hole interaction may be credited to the large holes generally inserted into the samples, around 15%–25% of its size. In these cases the common phenomenon is the capture of the core by the defect.[12,22,27] Basic physics concepts may help us to understand this even better. As it is known, the effective potential (exchange +magnetostatic) experienced by the vortex is globally minimized inside the hole.[13,14,25,28] Conversely, if the hole is very small, it only slightly affects the vortex dynamics and no appreciable effects are expected to occur. Actually, the phenomenon of core reversal predicted here takes place for a hole of intermediary size, a situation in which the minima provided by the exchange and magnetostatic contributions are comparable. In summary, our simulations as a whole

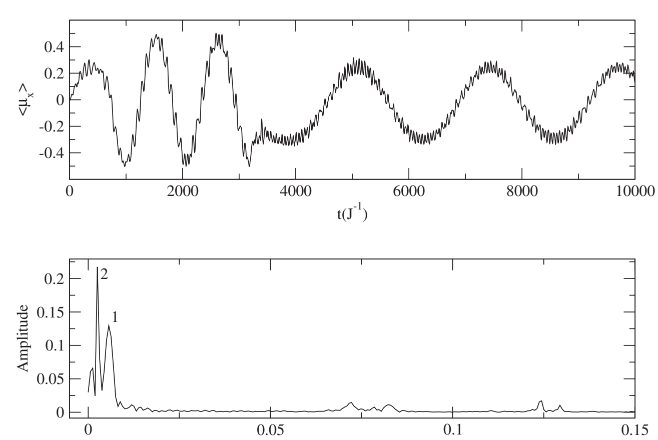

FIG. 7. $\langle \mu_x \rangle$ versus t and its Fourier transform for a film with a hole.

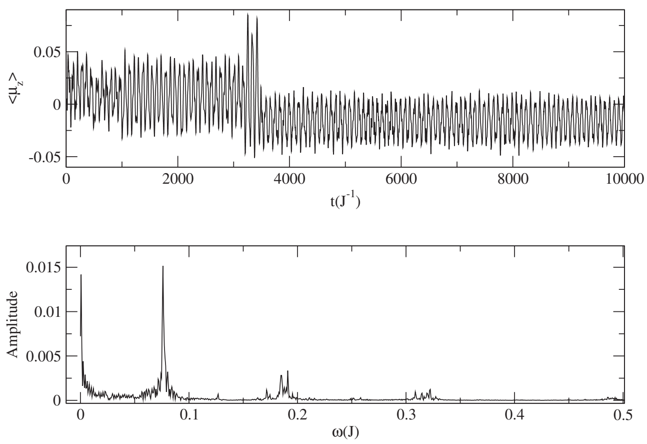

FIG. 8. Magnetization in the z direction and its Fourier transform. The vortex hole interaction causes the switching.

agree with experimental observations upon vortex core dynamics in the presence of intentionally inserted cavities. Generally, the core is captured by one of the defects, mainly when they are sufficiently large, such as in the experiments of Refs. 12, 22, and 27. Only for special circumstances the core reversal is expected to occur, demanding among other a noncentered relatively small hole. Another peculiarity of core reversal induced by vortex hole interaction is the fact that the polarization switching occur only from internal dynamical events: the vortex must be only under motion (the gyrotropic is more appropriate for it is easily reproducible) and pass suitably close to the defect so that the attraction from the hole ultimately dominates its inertia, reversing its motion sense. This in turn, demands the switching of its polarization so that the sign of the gyrotropic factor in the Landau-Lifshitz-Gilbert equation $\vec{G}\times\vec{v}$ is kept unaltered. Another dynamical explanation for this phenomenon is: first, the vortex motion excites spin-wave modes. Differently from the case without defects, the presence of the hole makes these modes with larger amplitudes due to the reflections in its border, mainly when the vortex core moves near it. Second, for a magnet of finite size, one expects that for the radiation of spin-waves, the reflection of the disk (and hole) boundaries and their effect back on the vortex core will result in the establishment of a dynamical state of the magnet, which includes both the confined moving vortex and the coherent magnetization oscillations matched to the vortex motion. Then, under this special situation, strong out-of-plane spin fluctuations arise near the hole border, changing coherently the direction of the vortex core magnetization when it passes close to the defect. Figure 9 shows an instant of the core motion immediately before the magnetization reversal.

IV. NANODISK WITH TWO HOLES

Our aim in this section is to consider the effect of two holes on the vortex core dynamics in circular thin films. Also, this study will be useful for showing that the reversal magnetization phenomenon is completely suppressed if a second defect, even small and distant from the first, is introduced into the system. In addition, the pinned vortex dynamical behavior is detailed. Similar to the former case, the disk radius is selected to be $R=20a$.

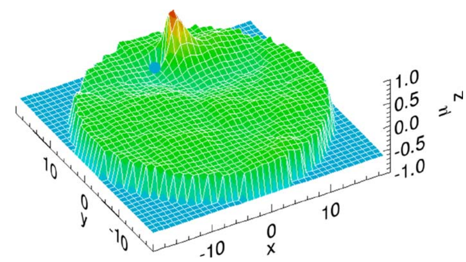

FIG. 9. (Color online) The instant immediately before the switching process. The out-of-plane magnetization fluctuations can be perceived in the irregularities present around the green surface. Note the deep protuberance with negative values of μ_z near and below the hole and the core. Such a protuberance will pull the vortex core, leading to the inversion of its polarity.

The results are obtained by choosing an external sinusoidal field to excite the gyrotropic mode. Again, the field is applied for a short time ($\sim 700\ J^{-1}$) and its parameters are $\vec{h}_0=0.01\ J\hat{x}$ and $\omega=0.0093\ J$. Of course, the vortex motion will depend on the holes size and position, as well as the external field. In all observed cases, the vortex finishes, trapped in one of the antidots, as it finds the defect in its way, even for smaller holes. Since this is the common phenomenon for all possible positions of the defects, we intend to know the dynamical process after the trapping. To illustrate this, we choose the following geometry: hole 1 at position $\vec{r}_1=(0,13a)$ and hole 2 at $\vec{r}_2=(0,-8a)$, as shown in Figs. 10 and 11. Larger defects will capture the core even faster. What should be stressed is that the presence of the second defect, even if smaller and distant of the first, will change the vortex dynamics drastically so that no core switching has been ob-

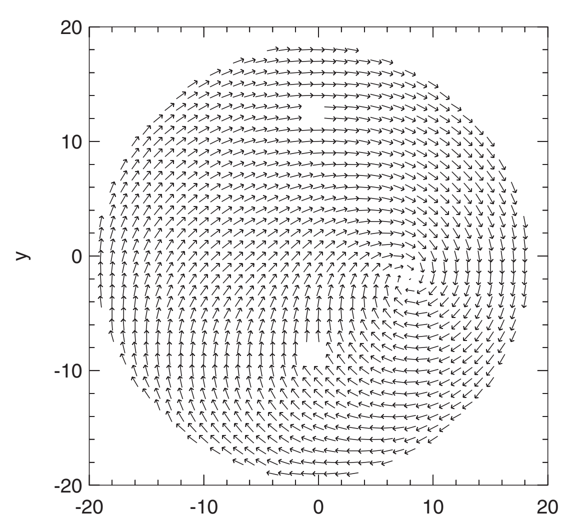

FIG. 10. An instantaneous position of the vortex core in a circular magnetic thin film with two holes centered at $(0,13a)$ and $(0,-8a)$. The holes sizes are of the order of the lattice spacing a (in each defect, there are four spins removed). The length of the arrows is proportional to the spin projection into the XY plane. Note the small arrows around the vortex center at $(8a,-2a)$ forming the vortex core.

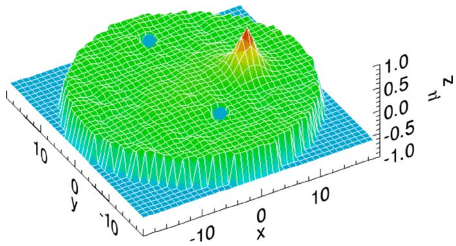

FIG. 11. (Color online) Three-dimensional view of Fig. 10. The vortex polarization is up (yellow red peak). Note the out-of-plane fluctuations generated by the core motion. These spin waves propagate through the system and are reflected in the disk and holes borders.

served before it is captured by one of the holes. Figure 12 shows the mean magnetization $\langle \mu^x \rangle$ along the x direction as a function of time. As the vortex core moves, this mean magnetization oscillates almost harmonically from -0.5 to 0.5, indicating that the motion is approximately circular (or elliptical) around the disk center. However, at about $t \sim 5000\ J^{-1}$, the core decreases considerably its velocity near hole 1, moving slowly in spiral (outer the antidot 2 and inner antidot 1) until hitting antidot 2 again, where it is captured at about $t=8000\ A^{-1}$. Now, the sense of gyration is not changed and consequently, there is no switching process. The $\langle \mu^x \rangle$ magnetization oscillations stop abruptly, becoming almost constant around 0.4 (actually, $\langle \mu^x \rangle$ oscillates very rapidly with a very small amplitude around 0.4). We also have calculated the Fourier transform of $\langle \mu^x \rangle$ (see Fig. 12). It has two main peaks: the first one refers to the oscillating external field (along the x direction) and the second is related to the resonance frequency. In our unit system, such resonance frequency is given by $\omega_{\text{res-d}} \sim 0.0057\ J$, which can be compared with the analogous problem of a film without defects $\omega_R \sim 0.0056\ J$. Similar graphics are obtained for $\langle \mu^y \rangle$ as shown in Fig. 13. The difference is that, after being pinned, the mean y magnetization oscillates around zero (with a relatively large amplitude as compared to its counterpart in x) and not around a finite value as what happened to $\langle \mu^x \rangle$. In

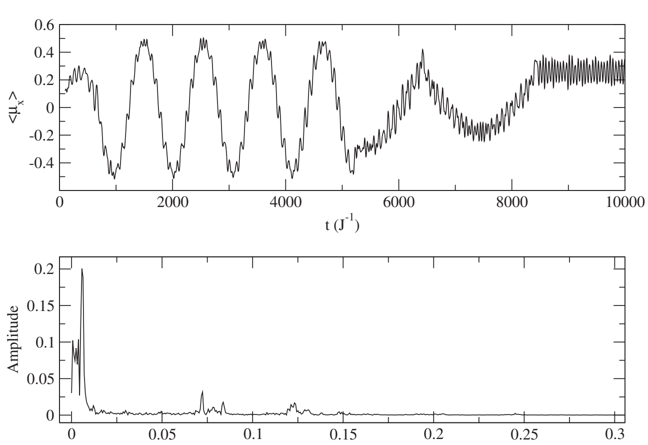

FIG. 12. Mean magnetization $\langle \mu^x \rangle$ as a function of time and its Fourier transform. The resonance frequency is approximately $0.0057\ J$. This figure shows clearly that the vortex core is captured by one hole at $t \sim 8000\ J^{-1}$.

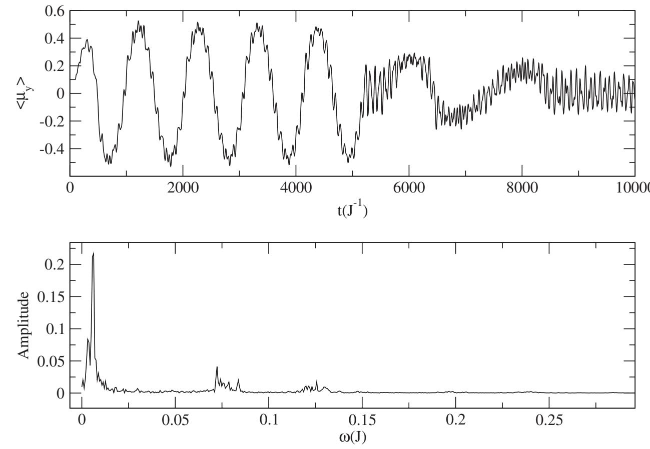

FIG. 13. Mean magnetization $\langle \mu^y \rangle$ as a function of time and its Fourier transform.

addition, there is no first large peak exhibited in the $\langle \mu^x \rangle$. The reasons are simple: first, the holes were displayed in the y axis [at $(0,13a)$ and $(0,-8a)$] and second, the external sinusoidal field (responsible for the first peak in the Fourier transform of $\langle \mu^x \rangle$) is applied along the x direction and, hence, it cannot appear in $\langle \mu^y \rangle$. The trajectory of the vortex core is shown in Fig. 14.

Based on the above description, an interesting fact to report is that the vortex center oscillates around the hole center with small amplitude and large frequency when the vortex is pinned to the defect. This phenomenon looks similar to the one theoretically predicted in layered ferromagnetic materials.[23] Nevertheless, this effect must be very rich in nanodisks because the surface magnetostatic energy has an effective contribution, which is absent in the layered systems. Analytical estimate[28] predicts that such oscillations are related to the vortex mass and take place around 10^5 GHz, which is far beyond current possibilities of observation in

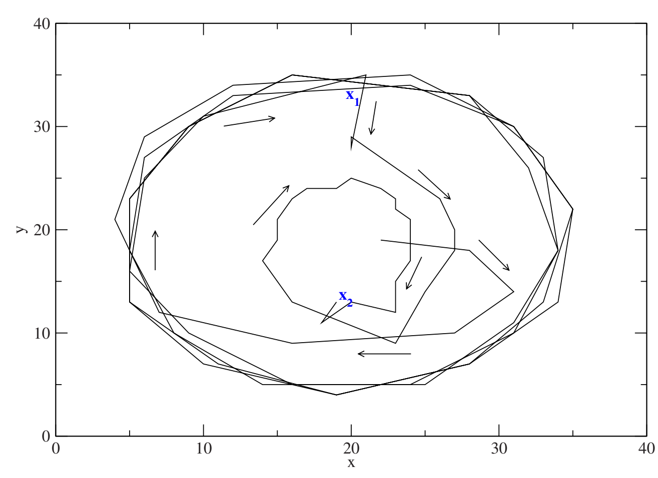

FIG. 14. (Color online) The complete orbit of the vortex core until capture by hole 2. The vortex starts its motion in the disk center at $(20a, 20a)$. The symbols X_1 and X_2 indicate the positions of antidots 1 and 2, respectively. In the studied process, the core follows an almost perfect gyrotropic mode, completing five laps around the film before feeling a strong effect of hole 1, which changes its motion direction.

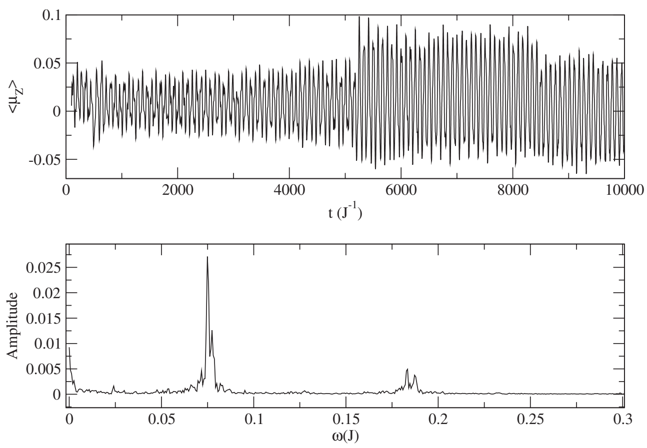

FIG. 15. Mean magnetization $\langle \mu^z \rangle$ as a function of time and its Fourier transform.

these systems,[30] ~ 10 GHz. However, a study considering all microscopic details of the pinned vortex oscillation will require further investigation.

In our present analysis, the oscillation frequency of this mode can be seen in the Fourier transform of $\langle \mu^x \rangle$ or $\langle \mu^y \rangle$ and is given by $\varpi \sim 0.123$ A. It is much higher than the resonance frequency and is much lower than masslike vibrations, as shown above. Such an intermediary frequency could be somewhat related to the *fractional gyrotropic* mode, which is predicted to occur around $10^2\ \omega_R$ and is provided by a remanent (fractional) gyrotropic vector of the vortex core, partially captured by the hole.[28] Another interesting feature can be easily seen when one compares the Fourier transforms of $\langle \mu^x \rangle$ and $\langle \mu^y \rangle$. Note that, after being captured, the magnetization amplitude oscillations are larger in the y direction than in the x direction. It means that the pinned vortex center oscillates much more along the x axis than along the y axis. Therefore, it describes an ellipse with larger semiaxis along the x direction, of the order of the hole size. For a trapped vortex, the difference in the amplitudes of oscillation of $\langle \mu^y \rangle$ and $\langle \mu^x \rangle$ increases as the hole responsible for the capture is placed nearer the circumference border of the film. Hence, this ellipse turns out to be an almost straight line if the hole is located very near the disk boundary, but it takes a circular shape if the cavity is centered in the disk. Therefore, several procedures of production and propagation of spin waves with different phases could be built only by changing the defect position, which is easily manipulated by lithographic techniques. Thus, our results indicate that the vortex hole system could also works as a mechanism to create and control spin waves in confined magnetic thin films.

We have also plotted the mean magnetization along the z direction, $\langle \mu^z \rangle$, and its Fourier transform, Fig. 15. There, we clearly realize that, before the capture process, $\langle \mu^z \rangle$ oscillates around a small positive value once the vortex is up polarized (negative if the polarity were down). After some vortex core laps, at about $t \sim 5000\ J^{-1}$, the amplitude of oscillation increases considerably. This is the only moment the vortex core motion suffers a strong disturb (near hole 1) and starts to slow down, changing the orbit until $t \sim 8000\ J^{-1}$, when the core is captured by hole 2 (Fig. 16). Therefore, the kinetic energy of the core decreases considerably and a large amount of spin waves is released during the instant of the capture process. The pinned vortex oscillations also generate more and more spin waves due to the rapid rotations of vortex center. The amplitude of $\langle \mu^z \rangle$ remains large after trapping but now its oscillations are quite small, meaning that the pinned vortex polarization practically vanishes.

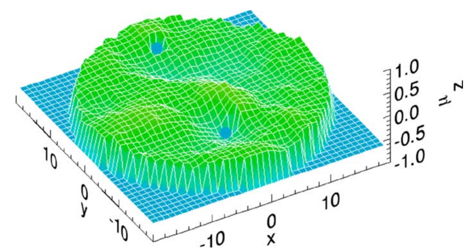

FIG. 16. (Color online) A picture of the instant that the vortex core was captured by hole 2. Note the large amount of spin waves generated in this process. Such waves can be seen by the out-of-plane fluctuations given by irregularity in the spin pattern (green surface) on the film.

For the sake of completeness, we now discuss a situation where the holes are not aligned along the same line crossing the disk center. Let us consider a disk with radius $20a$ centered at position $(20a, 20a)$ with two small holes $(\varrho_1 = \varrho_2 = \varrho = a)$ displayed at $(0, 33a)$ and $(12a, 8a)$. Figure 17 shows the orbit of the vortex core until it is captured by one of the holes. Even in this situation (many others, with the holes closer and apart from each other were also tested) the main facts remain the same: after being excited by the applied sinusoidal field the vortex core starts its gyrotropic motion around the disk center. Whenever passing near a hole its dynamics changes (similarly to the former case studied, say, both holes centered along y axis, as depicted in Figs. 11–13), and after some revolutions it is eventually captured by one of

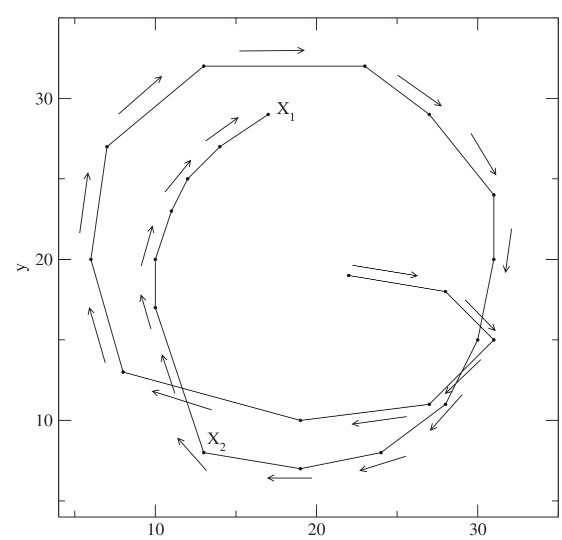

FIG. 17. The orbit of the vortex core in a nanodisk with radius $R = 20a$ centered at $(20a, 20a)$ containing two holes at positions $X_1 = (0, 33a)$ and $X_2 = (12a, 8a)$. As observed for several geometries with two defects, the fate of the core is to be captured by one of the holes.

the defects. Analogously to the previous configuration with two holes, no core reversal was observed in our simulations, neither for smaller (only one spin removed) nor larger (eight spins removed) defects. However, we cannot strictly state that no other sizes could trigger core reversal (with two or more holes), once their sizes in our simulations can be only largely varied (keeping its circular shape), say, while the smallest hole is obtained by removing a unique spin, the next possible size demands that we take four spin away, and so forth. The main point must be recalled: if core reversal could somewhat occur with two or more holes, the simplest system where this phenomenon would certainly be easily and clearly observed is that comprising of a nanodisk with a single non-centered relatively small hole.

V. CONCLUSIONS AND PROSPECTS

In this paper we have considered an alternative model for circular magnetic thin films containing artificial defects and we have also predicted an interesting way of reversing the magnetization of the vortex core, which is completely dependent on its dynamics and interaction with a relatively small hole inserted in the sample. Therefore, it should be stressed that the present switching process is not stimulated by external agents, similar to what usually occur by means of the application of magnetic or spin polarized dc current fields. The conditions necessary are summarized by the following properties: first, only one hole must be present and localized at a position near the lateral border of the disk. We suggest that the center of the hole must be placed at a distance on the order of the vortex core size away from the disk border. Second, the hole must be small, and third, the field required to excite the gyrotropic mode should be applied perpendicularly to the line joining the disk and hole centers. [Although the field is an external agent, we emphasize once more that its role is restricted for resonantly exciting the gyrotropic mode, putting the vortex core in motion. Such a field has no direct influence on the reversal mechanism, which is completely triggered by vortex hole interaction.] Clearly, the suitable parameters of the applied magnetic field, relative hole size, etc, should be probed in actual experiments.

As we observed in our simulations, those special conditions force the core to move in a circular trajectory passing exactly in between the hole and disk borders generating a large amount of spin waves, which will also develop important role in the switching process (for example, see Fig. 9). Nowadays, such defects were already intentionally introduced in nanostructures,[12,17] but they occupy a relatively large fraction of the material (about 15%–25%). Hence, the switching mechanism occurring during the vortex motion can be met only by further miniaturization of defects in nanostructures. Also in this line, we should mention the very recent experiment[19] where hole defects induce magnetization reversal in elongated Co rings. The results are aimed at the same direction of our work and are an experimental indication that our proposal may have further and broad relevance. An important difference between our prediction and the phenomenon experimentally observed in Ref. 19 is that the last needs a permanent presence of an external magnetic field (while in our case the mechanism of the vortex switching is based only on internal interactions during the vortex motion). In this aspect, the dynamical characteristic of the phenomenon predicted here is another differential in relation to the usual core reversals induced by external potentials.

To achieve more details about the vortex hole interactions, we have also considered a system with two holes. In this case no switching process was observed for several configurations analyzed. Since one of the holes will trap the vortex, we have then addressed our attention to the magnetization dynamics after the capture. When the vortex center falls into a hole, some of its energy is radiated away in the form of spin waves. The vortex center oscillates inside the hole with a frequency much larger than the resonance frequency. The bound-state vortex hole releases a large quantity of spin waves forming coherent magnetization oscillations matched to the vortex structure (part of the kinetic energy of the core lost in the capture is transformed in spin waves). These results demonstrate a significant coupling between the vortex (with the core or even captured without the core) and spin waves in a disk.

To conclude we would like to suggest that the switching mechanism reported here can be used in technological applications. Actually, this phenomenon naturally lends itself to applications in binary data storage. Therefore, it seems that our investigations may provide fundamentally ways of using magnetic nanostructures in technology.

ACKNOWLEDGMENTS

The authors thank CNPq, FAPEMIG, and CAPES (Brazilian agencies) for financial support.

*ricardodasilva@ufv.br
†apereira@ufv.br
‡winder@ufv.br

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