Spin dynamics of a magnetic antivortex: Micromagnetic simulations

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We report on a study of the dynamics of a magnetic antivortex in a submicrometer, asteroid-shaped, permalloy ferromagnet using micromagnetic simulations. As with vortex states in disk and square geometries, a gyrotropic mode was found in which a shifted antivortex core orbits about the center of the asteroid. Pulsed magnetic fields were used to generate azimuthal or radial spin wave modes, depending on the field orientation. The degeneracy of low-frequency azimuthal mode frequencies is lifted by gyrotropic motion of the antivortex core, and restored by inserting a hole in the center of the particle to suppress this motion. We briefly compare the dynamics of the vortex state of the asteroid to the antivortex. The size dependence of the antivortex modes is reported.

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Recently, there have been substantial efforts to understand the excitation spectrum of magnetic vortex structures.1–11,24,25 There exist two basic types of magnetic vortex structures in a quasi-two-dimensional ferromagnet—a “circular vortex,” which we simply call a vortex in the remainder of this paper, and an “antivortex”—both of which contain a nanometer-scale core area where the magnetization is perpendicular to the plane of the sample.12,13 Cartoons of an antivortex and a vortex in an asteroid-shaped particle are shown in Fig. 1. The winding number of an antivortex is −1 and +1 for a vortex. In addition to a fundamental interest in understanding the physics of these simple structures, the singular spin configurations in magnetic vortices and their dynamics suggest possible applications in spin logic operations.4,14,15 Much research has been done on vortices in a circular disk, both theoretically and experimentally.2,3,5–7,9–11 Two classes of excitations in the circular disk have been identified. One is associated with the gyrotropic motion of the core about its equilibrium position with a frequency lower than 1 GHz for micrometer-sized disks.2,3 The other type consists of spin wave modes at higher frequencies.5–7,9–11 The excitations of a vortex state in particles with a “cross” structure and in rectangular particles have also been observed; these differ from circular particles both because of the lower symmetry of the particle and because of the Landau domain structure around the vortex.1,3,4,8,24,25

We are not aware of research on the dynamics of an antivortex, but such a study may be useful in understanding the dynamical properties of a complex multivortex structure such as in cross tie walls and in long particles.13,16–21 Since an antivortex has been found experimentally in an asteroid shaped permalloy particle (see Fig. 1),13 we focus on that system in this report.

We found that there is also a metastable vortex state at all sizes studied, shown in Fig. 1(b), as well as two metastable or stable single domain states; the latter will not be discussed in this Rapid communication. Both the vortex and antivortex states are sufficiently stable to sustain the weak perturbations that we applied without evolving into another metastable state.

Considering the shape complexity of an asteroid, here we report only on micromagnetic simulations of the antivortex dynamics in this particle.22 A gyrotropic mode was observed and two kinds of spin wave modes were excited by applying pulsed fields at different angles to the sample plane. The size dependence of the dynamic excitations was also systematically studied.

Asteroids were simulated with lateral size L ranging from 200 nm to 1 μm and thickness t ranging from 10 to 30 nm. The circular edges of the particles had a radius of r = (96/200)L. Typical permalloy material parameters were used, with saturation magnetization M_s = 8 × 10^5 A/m, exchange stiffness constant A = 1.05 μerg/cm, and gyromagnetic ratio γ = 17.6 MHz/Oe. For most simulations, a damping parameter of α = 0.04 was used. Cubic cells with a size of 4 or 5 nm were used in the discretized simulations.

Because of the out-of-plane magnetization of the antivortex core, one may expect that a gyrotropic mode will appear once the core is shifted away from its equilibrium position and released.2 In our simulations, the antivortex core was shifted by applying a constant in-plane magnetic field. After the core stabilized at an off-center position, the applied field was removed. The remaining gyrotropic force on the antivortex core caused it to orbit about its equilibrium position, spiraling back to the center due to the damping. Figure 2 shows the time evolution of the two in-plane components of the average magnetization and the trace of the antivortex core for a 200 × 200 × 20 nm³ asteroid particle. The core was initially shifted by a constant field of H_z = 100 Oe. The
The relative smallness of the inter-diagonal directions of the asteroid, where a spin wave well modes are mainly localized in an X-shape region along the spatially uniform pulse. The spectral amplitude and phase images of the lowest two azimuthal modes for the \( P = -1 \) case. (d) Spectral amplitude and phase of the highest azimuthal mode at 4.0 GHz for the coreless asteroid. In (b) and (c), the phase chiralities of the two lowest azimuthal modes are shown by the superimposed broad arrows.

One would expect the two lowest azimuthal modes to be degenerate if the antivortex core stays at the center, which is also suggested by the similarity of their spectral images. However, this degeneracy is lifted by the coupling between the azimuthal spin wave modes and the gyrotropic motion of the core, as was found in the vortex case. To further explore the relationship between this splitting and the core’s gyrotropic motion, we chose two 500 x 500 x 20 nm\(^3\) asteroids with opposite antivortex core polarities, labeled by \( P \). The bottom spectrum is for an asteroid with a 20 nm hole at the center (coreless). The power spectrum resulting from an in-plane pulsed field applied to a 500 x 500 x 20 nm\(^3\) sample along \( \hat{x} \) direction is shown in Fig. 3(a) for several cases. The low-frequency resonance peak in the power spectra of \( P = \pm 1 \) cases corresponds to the core gyrotropic mode, while the resonances in the higher-frequency region are spin wave modes that couple to the spatially uniform pulse. The spectral details for each of the spin wave modes are shown in Fig. 3(b) for the \( P = +1 \) case. The two lowest azimuthal spin wave modes are mainly localized in an X-shape region along the diagonal directions of the asteroid, where a spin wave well structure is formed due to the relative smallness of the inter-dimensional complex spectrum, with information about both the spectral amplitude and the spectral phase. The resonances in the power spectrum indicate eigenmode frequencies.
The difference between the spectrum of the long arm direction and the diagonal direction of the asteroid can be ascribed to the different angles between the wave vector and the static equilibrium internal magnetic field. For radial modes, the wave vector is perpendicular to the internal field in the diagonal direction, thus having the characteristics of a Damon-Eshbach mode (DEM). However, along the long arm directions, the wave vector of radial modes is (anti)parallel to the internal field, which has magnetostatic backward volume mode (BVM) character. Thus, as a result of the unique spin configuration of a magnetic antivortex, both the azimuthal and the radial spin wave modes in the asteroid sample are hybrids of the DEM and BVM modes.

We also studied the size dependence of the frequencies of the various modes. The frequency of the gyrotropic mode was found to increase with the thickness of the asteroid but decrease with its area. A similar size dependence of the gyrotropic mode for a vortex in a circular disk has been found analytically. Here, if we treat the asteroid sample topologically as a deformed circular disk, qualitatively we can understand the size dependence of the gyrotropic mode in an antivortex structure. The frequency of both azimuthal and radial spin wave modes decreases when either the thickness or the in-plane size of the asteroid increases. The drop of the frequency of spin wave modes can be explained by different mechanisms. On the one hand, an increase of just the thickness results in a lower static internal field while the in-plane wave vector remains the same. This lower static magnetic field will shift the dispersion curve to a lower frequency. Thus, for the same in-plane wave vector, i.e., the same mode, the frequency will decrease. On the other hand, an increase of just the in-plane size will effectively reduce the in-plane wave vector. For azimuthal modes, the BVM zone (diagonal direction) has lower internal field than the DEM zone (long arm direction). This causes the wave vector in the BVM zone to fall in a region of the BVM dispersion curve with positive group velocity. The DEM dispersion curve always has positive group velocity. For the lowest radial mode, it is mostly distributed in the DEM zone (diagonal direction). For higher-frequency radial modes, the wave vector in the BVM zone (long arm direction) corresponds to a positive group velocity. Therefore, a larger in-plane size results in a lower frequency for both azimuthal and radial spin wave modes.

Finally, we compare some of the antivortex results to the vortex states in the asteroid. We found that the gyrotropic frequency for the vortex state is approximately twice that of the antivortex state for the 200 nm asteroid, and four times as large for the 1 μm case. An important qualitative difference is that the chirality of the path of the antivortex core in gyrotropic motion is opposite to that of a vortex with the same core polarity. This will be significant for the low-frequency dynamics of vortex or antivortex arrays. This feature is simply understood in terms of the Thiele equation for the gyrotropic motion of the vortex core, in which the gyrotropic vector is determined by a product of the core’s polarity and its winding number.

A comparison of the spin waves in these different systems is problematic. Here we note several features underlying this. First, the symmetry group of the antivortex state of an asteroid is $C_{2v}$, while it is $C_4$ in the vortex asteroid, as it is in the
vortex on a square. Thus the underlying symmetry classification of the spin wave states is significantly different. Second, the trade-off between exchange energy and dipolar energy is much more favorable to the formation of Landau domains in both the asteroid and square particle vortex states than in antivortex states. We find that the vortex state in the larger-area asteroids contains well-defined triangular Landau domains with domain walls along the long axes of the asteroid, just as in the vortex state in square particles. Thus there should be well-defined intradomain Landau domains with domain walls along the long axes of the asteroid, just as in the vortex state in square particles. 

In summary, we have studied dynamic excitations of a magnetic antivortex structure in asteroid samples and identified several eigenmodes of the system using micromagnetic simulations. The modes were generated by magnetic pulses similar to those likely to be used experimentally. The generation of lower-symmetry modes would require field pulses of different spatial symmetry which are not included here. The size dependence of the modes and the interaction between two different kind of modes have also been discussed. A brief comparison of these results to the dynamics of a vortex in asteroid and square particles is presented.

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