Three-Dimensional Magnetic Normal Modes in Mesoscopic Permalloy Prisms

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IFF-9: Electronic Properties

Static flux-closure structures in three-dimensional mesoscopic ferromagnets are known to differ quite significantly from their two-dimensional counterparts. How these differences reflect in the dynamic properties of the magnetization is, to date, an open question. Magnetic excitations in laterally confined thin-film structures have been a topic of broad interest over the past years. In particular, the special dynamic properties of magnetic vortex structures have been studied intensively by numerous groups. Using micromagnetic simulations, we have extended this field by investigating the magnetic normal modes of *three-dimensional* mesoscopic samples, thereby probing the influence of a three-dimensional spatial confinement on magnetic excitations. Fourier analysis methods were applied to extract well-defined oscillation modes. We find that the vortex dynamics in three-dimensional samples displays an interesting variety of features that were not reported previously. The simulations provide specific predictions concerning the occurence of new excitation modes and their variation with particle size. It should be possible to identify these modes experimentally.

Magnetic flux-closure structures of three-dimensional mesoscopic particles display distinct differences compared with those known from thin-film elements. In practical terms, a “thick” magnetic particle can be defined as one with significant variations of the magnetic structure along the film thickness. In contrast to this, the magnetic structure of a thin-film element only varies along the plane of the element. It has been predicted by simulations [1] and confirmed experimentally [2] that the magnetic domain structure in thick particles dislplays a pronounced asymmetry which is absent in thin-film elements of similar size. Contrary to the numerous realizations of flux-closure-patterns observed in sub-micron-sized thin-film elements [3], thicker samples of comparable size are almost exclusively magetized in one state, known as the generalized Landau pattern [2]. This flux-closure pattern can be coarsely characterized by a subdivision of the sample into four domains, as displayed on the top frame of Fig. 1.Alternatively, this domain structure can be regaded as a variant of the vortex state, with characteristic three-dimensional properties: The magnetization circulates around a “core”, either in clockwise or anti-clockwise direction. On the surfaces, the vortex is located at one of the two junctions at which two 90° domain walls meet the central 180° domain wall. The surface vortices are located at opposite sides on the the top and bottom surface. This is shown in the bottom panel of Fig. 1, where the core of the vortex is dispayed using an isosurface representation. The details of this complex structure, which contains characteristic asymmetric domain walls, has been thoroughly described in Refs. [1, 2].

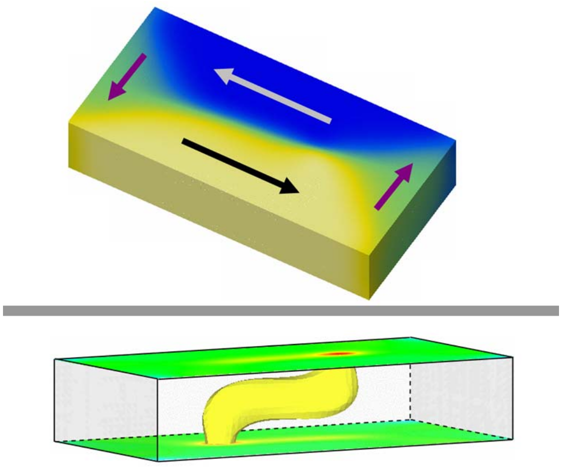

FIG. 1: Top: Simulatied static magnetization structure in a $400 \times 200 \times 80$ nm^3 Permalloy prism. The structure is divided into four domains. On the surface, the magnetization circulates around a point (vortex). Bottom: The vortex contains a core that is stretched along the sample. The yellow surface displays the core region, where the perpendicular magnetization component exceeds a value of 70%.

The dynamic properties of this structure, however, had not been investigated before. Our goal was therefore to investigate how the characteristics of the static three-dimensional magnetic structure modify the dynamic modes compared to the well-known case of thin-film elements. Using micromagnetic finite-element simulations and Fourier filtering techniques, we could identify a large number of characteristic normals modes of the magnetization oscillations occuring in this complex magnetic structure [4]. The structure was tipped away from equilibrium by applying a short and weak magnetic field pulse to the sample and recording the subsequent oscillations of the magnetization. We studied Permalloy prisms of different size in the sub-micron range. The thickness was varied between 60 and 80 nm. All prisms had the same aspect ratio.

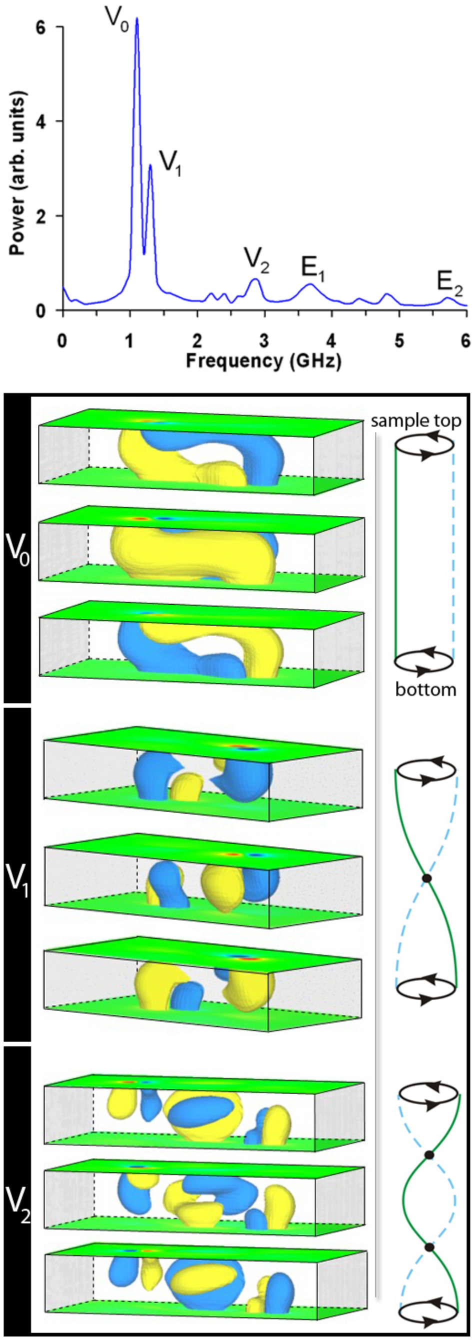

FIG. 2: Top: Typical Fourier spectrum of the oscillations occuring in a thick, mesoscopic Permalloy element following the excitation by a weak, short field pulse (simulated). Bottom: Three modes of the vortex oscillation. The V_0 mode is the three-dimensional variant of the gyrotropic vortex mode. The other modes represent higher-order variants of it. The figures display snapshots of the magnetic fluctuations δm at three different instants of a half-period of the oscillation. The yellow surfaces denote areas of positive variations, while the blue areas show the regions with negative variation.

A typical Fourier spectrum of the oscillations obtained from the simulations is shown on the top of Fig. 2. We identified various modes connected with the oscillations of the vortex (V), the edges (E) and the corners. A detailed analysis of these modes and their size dependence is given in Ref. [4]. Some of these modes are variants of the previously known modes in thin-film elements, while others are identified as genuinely three-dimensional modes connected with the special properties of the generlaized Landau structure. In particular, we found a previously unreported splitting of the rotational vortex mode frequency. In thin-fim elements, the gyrotropic excitation is a well-known magnetic mode with one specific frequency, which describes the in-plane rotation of the vortex core around its equilibrium position. In contrast this, we find that various gyrotropic modes (denoted as V_0, V_1 and V_2 in Fig. 2) can appear in the case of *thick* elements. On the sample surface, these modes appear as gyrations of the core. However, internally, the profile of the oscillations is very different. A simple "string" model as sketched on the right side of Fig. 2 explains the qualitative difference between these modes. Due to the additional degree of freedom along the film thickness, the vortex core as shown in Fig. 1 can not only exhibit a lateral displacement, but also an oscillation with varying profile along the thickness. Therefore, higher-order oscillations of the vortex core can occur, which contain one or more "nodes" inside the sample, where the magnetization does not fluctuate. Our simulations predict that these new modes should appear as clear peaks (V_1, V_2) in the Fourier spectrum of the oscillations, which should be observable in an experiment. Moreover, we make specific preditions concerning the variation of the frequencies of these new modes with increasing particle size [4].

In conclusion, our micromagnetic simulations with Fourier filtering analysis clearly predict the occurrence of new magnetic normal modes in mesoscopic ferromagnets of elevated thickness. The transition from two-dimensional to three-dimensional sample is therefore connected with a significant qualitative modification of the magnetic modes known from thin-film elements. Experimental evidence for these findings is expected to be feasible.

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