**Precise probing spin wave dynamics in circular magnetic dots: influence of dots aspect ratio, magnetic field and direction of microwave field pumping**

*A.A. Awad*[1], *J. F. Sierra*[1], *G. N. Kakazei*[2], *D.-S Han*[3], *S.-K. Kim*[3], *V. Metlushko*[4], *K.Y. Guslienko*[5], *and F.G. Aliev*[1]

[1] *Dpto. Física de la Materia Condensada, CIII, Universidad Autónoma de Madrid, 28049 Madrid, Spain*

[2] *Depto. Fisica da Faculdade de Ciencias, Universidade do Porto, 4169-007 Porto, Portugal*

[3] *Research Center for Spin Dynamics and Spin-Wave Devices, Seoul National University, Seoul, 1510744 South Korea*[3] [4] *Dept. of Electrical and Computer Engineering, University of Illinois at Chicago, Chicago, Illinois, 60607 USA*

[5] Dpto. Fisica de Materiales, Universidad del Pais Vasco, 20018 Donostia-San Sebastian, Spain

*ahmad.awad@uam.es*

Vortices are encountered many natural systems ranging from galaxies to superconductors and superfluids. Knowledge of vortex dynamics in stratified conditions is of special importance. Spin wave dynamics in Permalloy dots with magnetic vortex and situated in the applied external in-plain magnetic field could be considered as a simple toy model to investigate dynamics of single vortex state in the confined stratified media.

First we discuss dependence of spin wave modes (Fig.1a) excited by in-plane magnetic field on dots aspect ratio [1]. The frequency splitting of two lowest azimuthal modes was observed (Fig. 1b) and described by dynamic splitting model accounting the spin waves and vortex gyrotropic mode interaction [2].

Secondly, we describe precise measurements of spin dynamics in the vortex state of the circular magnetic dots by exciting spins in different in-plane directions (Fig. 2b,c) with respect to applied in-plane bias magnetic field [3]. Spin wave dynamics was measured using FMR-VNA technique [4,5]. We unambiguously demonstrate experimentally and by micromagnetic simulations the existence of two distinct dynamic vortex (stable and metastable) regimes. Dynamic response in the metastable state strongly depends on relative orientation of the external rf pumping and bias magnetic fields. Parallel rf pumping (Fig. 2c) is shown to be unique tool to observe spin excitation modes localized near the strongly shifted vortex core for the bias field between the vortex nucleation and annihilation fields. Meanwhile, the perpendicular rf pumping(Fig. 2b) which excites the spin waves throughout the entire dot, reveals crossover between two dynamic vortex regimes near the nucleation field. Our findings open new possibilities for development of magnetic devices with precise control over the magnetization switching process. They also underscore importance of understanding of dynamic response in different nanostructured materials with vortices in confined and stratified conditions.

This work was supported by Spanish MICINN (MAT2009-10139), Consolider (CSD2007-00010) and CAM (P2009/MAT-1726).

**References:**

[1] A. Awad, et al., Appl. Phys. Lett., 96, 012503 (2010).
[2] K.Guslienko, et al., Phys. Rev. Lett., 101, 247203 (2008).
[3] F.G. Aliev, et al., Phys. Rev. B 79, 174433 (2009).
[4] J. F. Sierra, et al., Appl. Phys. Lett., 93, 172510, (2008).
[5] J. F. Sierra, et al., Appl. Phys. Lett., 94, 012506 (2009).

**Figures:**

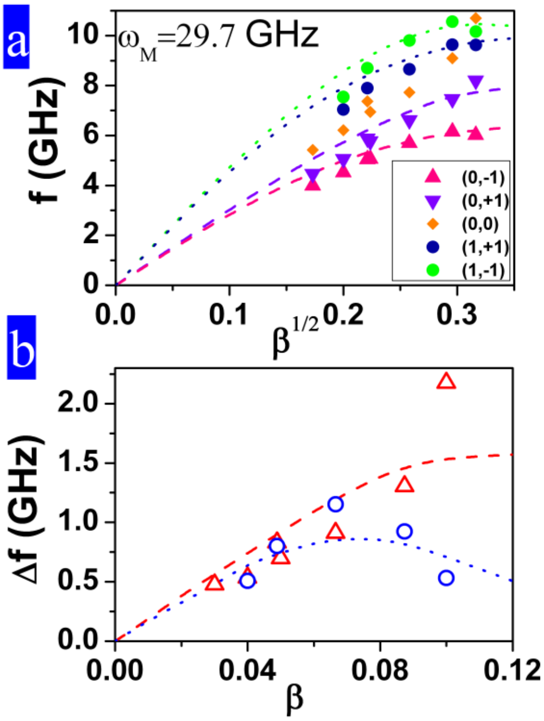


Fig. 1. (a) Measured spin wave mode frequencies vs. square root of the dot aspect ratio β. The dashed line and the dotted lines represents theoretical values for first azimuthal mode and second azimuthal mode respectively.(b) splitting open triangles of the first azimuthal mode, open circles second azimuthal mode both as function of the dot aspect ratio β. The dashed line and dotted lines represents theoretical values [2] for the first and second azimuthal modes splitting respectively.

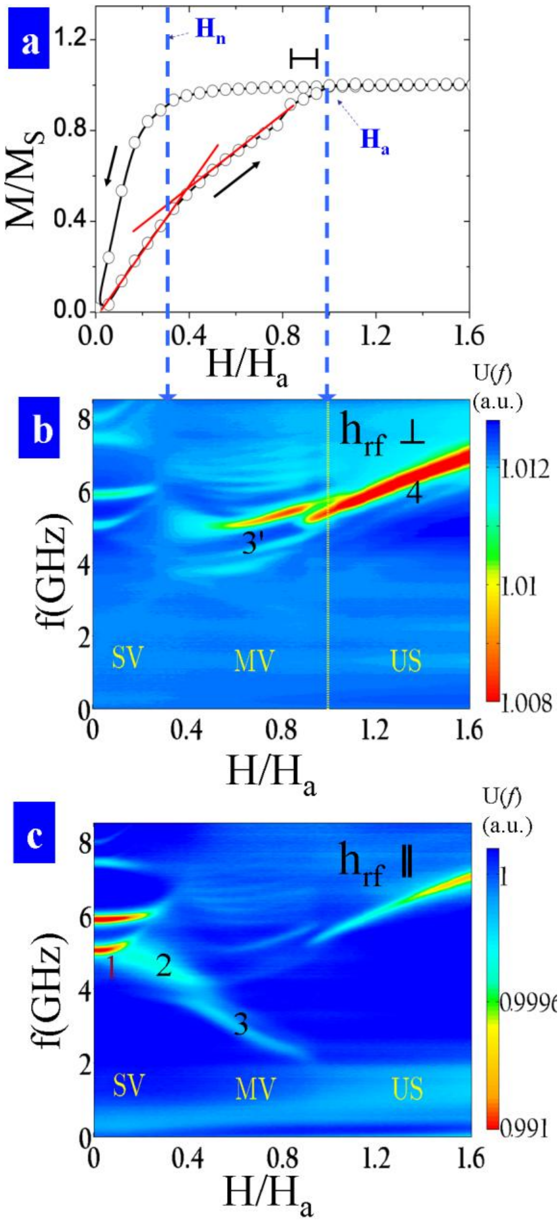


Fig. 2. (a) Magnetization vs. magnetic field normalized by the vortex annihilation field. Vertical dashed lines indicate the vortex nucleation and annihilations fields, while the error bar evaluates uncertainty in vortex annihilation field. Red lines indicate change in the slope in M(H) near $H_n$.(b,c) Intensity (U) plots of the measured spectra for the Py dot arrays with thickness 25 nm and 1035 nm diameter for rf field perpendicular (b) and parallel (c) to the increasing bias magnetic field. Numbers 1, 2, 3, 3´ and 4 label the spin wave modes.