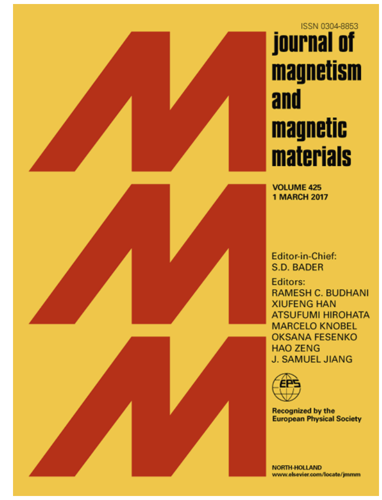
Accepted Manuscript



Analytical and numerical $K_u - B$ phase diagrams for cobalt nanostructures: stability region for a Bloch skyrmion

A. Riveros, N. Vidal-Silva, F. Tejo, J. Escrig

PII: S0304-8853(17)33669-7
DOI: https://doi.org/10.1016/j.jmmm.2018.04.018
Reference: MAGMA 63864

To appear in: *Journal of Magnetism and Magnetic Materials*

Analytical and numerical $K_u - B$ phase diagrams for cobalt nanostructures: stability region for a Bloch skyrmion

A. Riveros[1], N. Vidal-Silva[1], F. Tejo[1], and J. Escrig[1,2]
[1] *Departamento de Física, Universidad de Santiago de Chile (USACH), Av. Ecuador 3493, 9170124 Santiago, Chile*
[2] *Center for the Development of Nanoscience and Nanotechnology (CEDENNA), 9170124 Santiago, Chile*

In this paper we calculate the energies corresponding to the different magnetic phases present in a ferromagnetic cylinder by means of analytical calculations. From the comparison of these energies, it is possible to construct magnetic phase diagrams as a function of the uniaxial anisotropy of the sample and the external magnetic field applied. As proof of concept, we analyzed the magnetic phase diagrams for a cobalt dot of 240 nm in diameter and 70 nm in length, with an easy axis parallel to the dot axis, and with a magnetic field applied towards or perpendicular to this axis. From these diagrams we have obtained the stability regions for a Bloch skyrmion (Sk), a vortex core (VC) and a ferromagnetic (F) configuration, which can point in any ψ direction. Our results provide a pathway to engineer the formation and controllability of a skyrmion in a ferromagnetic dot to different anisotropy constants and magnetic fields.

I. INTRODUCTION

Skyrme was the first to describe the baryons as topological defects of continuous fields [1]. Since then, skyrmions have been found in various systems, such as ferroelectrics [2], liquid crystals [3], magnetic materials [4], among others. For example, topological magnetic skyrmions [5] have been observed in several systems [6–15], and have been proposed for potential applications in non-volatile magnetic memories [16] because the spin texture topology couples efficiently with spin transfer torques, allowing them to be moved by small current densities, opening a new paradigm for the manipulation of magnetization at the nanoscale [17]. Besides, skyrmions exhibit emergent electromagnetic phenomena, such as topological Hall effect and the skyrmion Hall effect [18, 19], and have been proposed as information carriers in novel magnetic sensors and spin logic devices [20].

Isolated skyrmions confined in cylindrical nanostructures [14, 15, 21–28] are considered to be promising for implementations in information storage and processing devices on the nanoscale [29, 30]. In these nanostructures both the Dzyaloshinskii-Moriya interaction (DMI) and the magnetic anisotropy are required to stabilize a Neel skyrmion (NS) [21–23], where the magnetic profile has a magnetic component in the radial direction, so they cannot be seen in conventional ferromagnetic materials (Co, Ni, etc.). On the other hand, the Bloch skyrmions (BS), which do not have magnetic component in the radial direction, can be stabilized in the absence of DMI, provided there is a magnetic anisotropy [24–26]. These systems show potential for room temperature control of skyrmions [31, 32].

In this paper, we are interested in obtaining analytical expressions for the energies of different magnetic configurations (ferromagnetic pointing in any direction, vortex core and Bloch skyrmion without DMI) in a cobalt nanodot that allow us to generate magnetic phase diagrams with regions of stability for each configuration as a function of the uniaxial anisotropy and the external magnetic field. In addition, we will carry out micromagnetic simulations for some particular cases, in order to be able to support the theoretical model used.

II. ANALYTICAL MODEL

We adopt a simplified description of the system, where the discrete distribution of the magnetic moments is replaced with a continuous one characterized by a slow variation of the magnetization $\vec{M}(\vec{r}) = M_0\,\hat{m}(\vec{r})$ [33], whose direction is given by the unitary vector $\hat{m}(\vec{r})$ while that M_0 corresponds to the saturation magnetization. Due to the cylindrical symmetry of the nanoparticle, it is convenient to rewrite the magnetization vector as $\hat{m}(\vec{r}) = m_r(\vec{r})\hat{r} + m_\phi(\vec{r})\hat{\phi} + m_z(\vec{r})\hat{z}$, where $\hat{r}$, $\hat{\phi}$ and $\hat{z}$ are the unitary vectors of the cylindrical coordinates.

We consider a cylindrical nanoparticle of radius R and length L which exhibits an uniaxial anisotropy whose axis of easy magnetization is parallel to the symmetry axis of the particle (chosen as the z-axis), and which is under the action of an external magnetic field $\vec{B}$ applied at an angle θ with respect to the z-axis, as shown in Fig. 1a. The total energy for this nanoparticle is given by [33]

$$E = \int_V \Bigg(- K_u m_z^2 + \frac{\mu_0}{2} M_0\,\vec{m}\cdot\vec{\nabla}U_d + A\sum_{i=x,y,z}\left(\vec{\nabla}m_i\right)^2 - M_0\,\vec{m}\cdot\vec{B}\Bigg) dV \quad , \tag{1}$$

wherein the first, second, third and fourth term corresponds to the uniaxial anisotropy, the dipolar energy, the exchange energy and the Zeeman energy, respectively. Here K_u, A and μ_0 are the anisotropy constant, exchange stiffness constant and magnetic permeability, respectively, while U_d is the well-known magnetostatic potential defined as [33] $4\pi U_d(\vec{r}) = \int G(\vec{r},\vec{r}\,')\left(\hat{n}\cdot\vec{M}(\vec{r}\,') - \vec{\nabla}\cdot\vec{M}(\vec{r}\,')\right)$, with $G(\vec{r},\vec{r}\,') = |\vec{r} -$