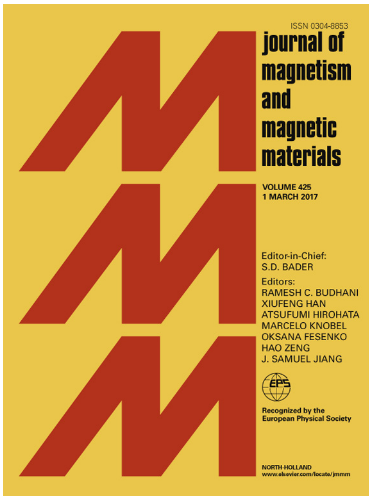

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Geometry induced phase transitions in magnetic spherical shell

Mykola I. Sloika[a,*], Denis D. Sheka[a], Volodymyr P. Kravchuk[b], Oleksandr V. Pylypovskyi[a], Yuri Gaididei[b]

[a] *Taras Shevchenko National University of Kyiv, 01601 Kyiv, Ukraine*
[b] *Bogolyubov Institute for Theoretical Physics of National Academy of Sciences of Ukraine, 03680 Kyiv, Ukraine*

Abstract

Equilibrium magnetization states in spherical shells of a magnetically soft ferromagnet form two out-of-surface vortices with codirectionally magnetized vortex cores at the sphere poles: (i) a whirligig state with the in-surface magnetization oriented along parallels is typical for thick shells; (ii) a three dimensional onion state with the in-surface meridional direction of the magnetization is realized in thin shells. The geometry of spherical shell prohibits an existence of spatially homogeneous magnetization distribution, even in the case of small sample radii. By varying geometrical parameters a continuous phase transition between the whirligig and onion states takes place. The detailed analytical description of the phase diagram is well confirmed by micromagnetic simulations.

Keywords: Ground state, phase transition, magnetic vortex, spherical shell, micromagnetic simulation

1. Introduction

Topological magnetization structures provide new properties to hosting nanomaterials, attracting intensive fundamental research as well as numerous applications to processing [1–4] and information-storage devices [2, 5–10]. Examples include domain walls [11], vortices [11, 12], skyrmions [13, 14].

The modern tendency is to extend flat structures into three dimensional (3D) space: the mutual cooperation between topology and curved geometry results in rich physics as well as in novel functionalities, forming a new topic of a magnetism in curved geometries, for a review see Ref. [15]. A thin spherical shell can be considered as one of the simplest 3D object, a bridgehead for studying the interplay of topological structures with a curvature of the underlying surface. In order to elucidate the problem, we recall some topological issues for magnetization distribution in narrow magnetic rings as a 2D counterpart of this 3D object. The magnetization structure of nanorings is well–known [12, 16–18] to form vortex and onion equilibrium states. The stability of non-trivial magnetization configuration can be explained by means of topological reasons. In the case of a ring, the topological properties of a planar magnetization distribution, $m_x+im_y = \exp(i\phi)$, on a closed loop γ can be described by the π_1–topological charge, a vorticity (or a winding number), $q = 1/(2\pi)\int_\gamma \mathrm{d}\phi \in \mathbb{Z}$. This results in $q = 1$ for the vortex state and $q = 0$ for the onion state, see Fig. 1(a). Therefore these magnetization states belong to the different homotopy classes. As a result the vortex state cannot be continuously transformed into the onion state and vice versa *if the magnetization remains in the plane of the ring.* In narrow rings the transformation from the onion to the vortex state occurs via an intermediate saturated state as the first order phase transition [18].

The situation is different in spherical shells. However strong an easy surface anisotropy might be, in accordance with the Poincaré–Hopf theorem the magnetization of a spherical shell cannot be everywhere tangential to the shell surface. Therefore the equilibrium states of magnetic spheres always include two out-of-surface vortices with diametrically opposite vortex cores [19, 20]. The topological properties of a 3D vector field $\boldsymbol{m}$ on a closed surface S are determined by the π_2–topological charge $Q = 1/(4\pi)\int_S \mathcal{J}\mathrm{d}S \in \mathbb{Z}$ (a skyrmion number) with $\mathcal{J}$ being a mapping Jacobian [21]. The skyrmion number depends on mutual polarities of the vortex cores [22]: $Q = \pm 1$ for the same polarities (both cores are magnetized inward or outward the sphere) and $Q = 0$ for the opposite polarities. Being interested in properties of magnetically soft spherical shells where the state with $Q = 0$ is always energetically preferable [20], in what follows we restrict our consideration to double-vortex states with opposite cores polarities, one core is magnetized inward and another one is magnetized outward the sphere (see Fig. 1(b)).

In addition to fundamental reasons, the interest to magnetic spherical shells is stimulated by experimental advances in production of spherical hollow nanoparticles (spherical shells) as artificial materials with unusual characteristics and numerous applications [23–31]. A variety of equilibrium magnetization configurations for spherical shells were identified in micromagnetic simulations [20, 27, 28, 32] and interpreted based on experiments [25, 27–31, 33]. Different theoretical models predicted dissimilar equilibrium states [19, 20, 32, 34–36]. In particu-

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[*] Corresponding author
Email address: `sloika.m@gmail.com` (Mykola I. Sloika)

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