EQUILIBRIUM STATES OF PERMALLOY SPHERICAL NANOSHELL

Mykola Sloika*, Denis Sheka*, Volodymyr Kravchuk, Yuri Gaididei****
** Faculty of Radio Physics, Electronics and Computer Systems, Taras Shevchenko National University of Kyiv,64/13, Volodymyrska Str., City of Kyiv, Ukraine, 01601,*
e-mail: sloika.m@gmail.com, sheka@univ.net.ua
***Bogolyubov Institute for Theoretical Physics, Kyiv, Ukraine,*
e-mail: vkravchuk@bitp.kiev.ua, ybg@bitp.kiev.ua

***Abstract**: The equilibrium states of magnetic spherical shell has been studied both theoretically and using micromagnetic simulations. The continuous transformation from the vortex state into onion one has been demonstrated. The critical radius as a control parameter of this transformation has been obtained as a function of the spherical shell thickness.*

A competition between short-range exchange and long-range magnetostatic interactions results in nontrivial distribution of magnetization in a magnetic nanoparticle. Such magnetic distributions as vortex and onion are widely studied for the case of planar structures. Recently a significant interest to nanomagnets with curved shape appears. On the one hand it is due to modern techniques of fabrication of nanoparticles of a custom shape, and on the other hand the curvature might significantly change magnetic properties of the sample [1]. It has been shown that magnetic nanoparticle of ring shape has three possible ground states: vortex, onion and uniform one. In this work we studied possible equilibrium magnetization states for a thin spherical shell, which can be considered as a 3D extension of a narrow planar ring. It has been shown that vortex ground state of magnetic spherical shell consists of two vortices with opposite polarities [2].

In order to perform micromagnetic simulations we use MAGPAR code [3] with permalloy material parameters: exchange constant $A = 1.3\times10^{-11} J/m$, saturation magnetization $M_s = 8.6\times10^5 A/m$. We consider spherical shell (Fig. 1) with inner radius R and thickness h. Numerically to identify equilibrium magnetization state for particular combination R and h we use the energy minimization procedure starting from vortex and uniform states. After comparison energies for both states we consider the state with the lowest energy as the equilibrium one. Simulations results demonstrate a continuous transition from vortex to onion state for spherical shell. Using the spherical frame of reference, we parameterize the normalized magnetization as follow: $\mathbf{m} = (m_r, m_\theta, m_\varphi) = (\cos\Theta, \sin\Theta\cos\Phi, \sin\Theta\sin\Phi)$. We determine angle Φ at

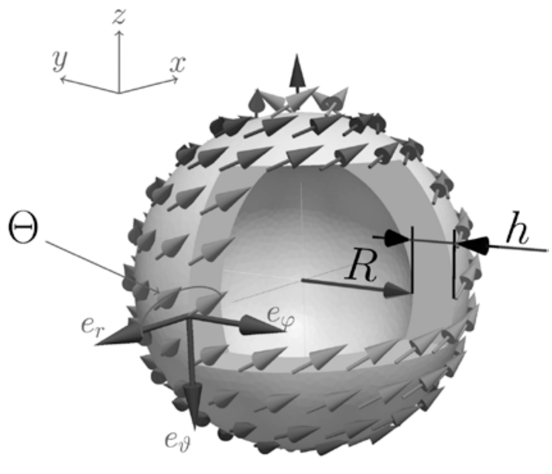

Fig. 1. Schematic of the spherical shell. Arrows correspond to the magnetic distribution.

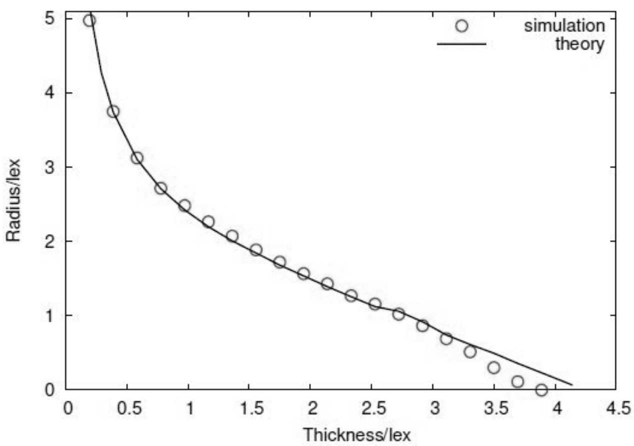

Fig 2. Normalized critical radius vs normalized thickness of spherical shell. Circles correspond to the simulation data and solid line shows theoretical values.

the equator ($\vartheta = \pi/2$). Critical radius R_c when onion state becomes ground one ($\Phi = \pi$) as function of shell thickness is displayed in Fig. 2 (circles).

To gain some insight to the transition mechanism we consider a model of a soft ferromagnet, where only exchange and manetostatic interactions are taken into account, and the anisotropy is neglected. The total energy normalized by $4\pi M_s^2 V$ with $V = 4/3\pi R^3$ reads: $E = E_{ms} + E_{ex}$ with E_{ms} being the magnetostatic energy and E_{ex} being the exchange energy. One can calculate magnetostatic energy using $E_{ms} = -(3/8\pi)\int_V d\mathbf{r}(\mathbf{m}\cdot\mathbf{h}^{ms})$ where $\mathbf{h}^{ms} = \mathbf{H}^{ms}/4\pi M_s$ being reduced magnetostatic field. Exchange energy can be obtained from the functional: $E_{ex} = -(3/8\pi)\ell^2\varepsilon\int_V d\mathbf{r}(\mathbf{m}\cdot\nabla^2\mathbf{m})$, where $\ell = \lambda_{ex}/R$ being the reduced exchange length, $\lambda_{ex} = \sqrt{A/4\pi M_s^2}$ being the exchange length and $\varepsilon = h/R$ being aspect ratio.

To describe the continuous transition between vortex and onion states, we use the following Ansatz:

$$\Theta = \frac{\pi}{2}\left(1 - \frac{\exp(-\vartheta/\vartheta_c) - \exp((\vartheta-\pi)/\vartheta_c)}{1-\exp(-\pi/\vartheta_c)}\right),\ \Phi = const, \tag{1}$$

where $\vartheta_c = (\sqrt{2}+\beta)\lambda_{ex}/R$ determines the vortex core size, β is the variation parameter.

Recently the exchange energy for thin curvilinear shell of an arbitrary shape has been calculated in Ref. [4]. Using that result and Ansatz (1) one can obtain an expression for exchange energy in the following form: $E_{ex} = G_1^{ex}(\beta)\cos\Phi + G_0^{ex}(\beta)$. Reduced magnetostatic field in magnetostatic energy functional can be obtained from equation $\mathbf{h}^{ms} = -\nabla\psi(\mathbf{r})$, where $\psi(\mathbf{r})$ is magnetostatic potential. Using that and Ansatz (1), the magnetostatic energy reads: $E_{ms} = G_2^{ms}(\beta)\cos^2\Phi + G_1^{ms}(\beta)\cos\Phi + G_0^{ms}(\beta)$.

Finally total energy reads: $E = G_2(\beta)\cos^2\Phi + G_1(\beta)\cos\Phi + G_0(\beta)$, where $G_2 = G_2^{ms}$, $G_1 = G_1^{ms} + G_1^{ex}$ and $G_0 = G_0^{ms} + G_0^{ex}$. One can see that equilibrium value for Φ can be found from equation: $\cos\Phi = -G_1/2G_2$. Analysis of this equation shows that for large radii $\Phi_0 \to \pi/2$ so that vortex is ground state, and for small radii $\Phi_0 \to 0$, what means that vortex state is transformed into onion one. Critical radius R_c can be found from equation: $G_1(R_c,\varepsilon) = 2G_2(R_c,\varepsilon)$. Theoretically calculated values for R_c are shown in Fig. 2 (solid line).

In conclusion, the ground states of spherical shells have been studied both theoretically and by means of micromagnetic simulations. A continuous transformation of the vortex state into onion one with the shell radius decreasing is demonstrated. The critical radius of transition is obtained as a function of the shell thickness.

References

[1] M.I. Sloika, V.P. Kravchuk, D.D. Sheka, Y.B. Gaididei, App. Phys. Letters 104, 252403 (2014).
[2] V.P. Kravchuk, D.D. Sheka, R. Streubel, D. Makarov, at all, Phys. Rev.B, 85, 144433 (2012).
[3] W. Scholz, J. Fidler, T. Schre, D. Suess, R. Dittrich, at all, Comp. Mat. Science 28, 366 (2003)
[4] Gaididei, Y., Kravchuk, V. P. Sheka, D. D. Phys. Rev. Lett., 112, 257203 (2014).