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Computer Simulation of Magnetic Skyrmions

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Abstract: We present results of numerical simulation of thermodynamics for array of Classical Heisenberg spins placed on 2D square lattice, which effectively represents the behaviour of single layer. Using Metropolis algorithm, we show the temperature behaviour of system with competing Heisenberg and Dzyaloshinskii-Moriya interaction (DMI) in contrast with classical Heisenberg system. We show the process of nucleating of skyrmion depending on the value of external magnetic field. We proposed the controlling method for movement of skyrmions.

Keywords: Monte Carlo method; magnetic Skyrmion; Heisenberg model; Dzyaloshinskii-Moriya interaction

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1. Introduction

Spintronics or magnetic electronics is continually evolving and new promising materials for new storage and processing data devices are emerging. Racetrack memory (RM) is considered one of the most attractive non-volatile data storages in future advanced computer architectures. The existing RM samples are based on the motion of the domain wall (DW), which, however, has some internal limitations, such as scalability, density and energy consumption due to the physical properties inherent in the DW. Recently, magnetic skyrmions have been proposed as an alternative to DW in racetrack memory. Skyrmion characteristics, such as nanoscale size, topological stability, and an ultra-low current depinning current make it a promising element of the data storages in future electronics with extremely low power consumption, with high-speed read-write and ultra-high recording density. A magnetic skyrmion is a topological object consisting of a skyrmion core, an outer domain, and a wall that separates the skyrmion core from the outer domain. The skyrmion size and wall width are two fundamental quantities of a skyrmion that depend sensitively on material parameters such as exchange energy, magnetic anisotropy, Dzyaloshinskii-Moriya interaction, and magnetic field [1–5]. At the moment, theoretical and numerical studies are primarily carried out, and experimental approaches to the construction of magnetic running memory based on skyrmions are being developed. The superiority of such technology over racetrack memory based on the motion of the domain wall has already been demonstrated [6,7].

2. Models and Methods

The Heisenberg model is one of the models used in statistical physics to model ferromagnetism. It is used in the study of critical points and phase transitions of different magnetic systems. We used the lattice Hamiltonian, consisting of Heisenberg exchange H_J and DMI interaction H_D terms for the microscopic description of a chiral helimagnet [8,9], see formulas (1)–(3).

$$H = H_J + H_D, \tag{1}$$

$$H_J = -J \sum_r \vec{S}_r \cdot (\vec{S}_{r+\hat{x}} + \vec{S}_{r+\hat{y}}), \tag{2}$$

$$H_D = -D \sum_r \vec{S}_r \times \vec{S}_{r+\hat{x}} \cdot \hat{x} + \vec{S}_r \times \vec{S}_{r+\hat{y}} \cdot \hat{y}, \tag{3}$$

where $\vec{S}_r$ is the atomic spin, J is the ferromagnetic short-range exchange interaction, the DMI interaction $D = 0.6J$ [8,9].

The formulas (2) and (3) used for calculating interaction between $\vec{S}_r$ and its neighbours along the X axis and Y axis for 2D lattice. When calculating the total energy of the system, only unique neighbours standing "above" along the Y axis and "right" along the X axis are taken into account for pairs interaction.

A spin $\vec{S} = \{S^x; S^y; S^z\}$ is introduced as a three-dimensional unit-length vector in accordance with formulas:

$$S^x = sin(\varphi)cos(\vartheta), \tag{4}$$

$$S^y = sin(\varphi)sin(\vartheta), \tag{5}$$

$$S^z = cos(\varphi), \tag{6}$$

where $\varphi = [0; \pi]$, $\vartheta = [0; 2\pi]$.

In the frame of our computer model, the magnetic film has a size of $N = L \times L$. Magnetic film representing the system of Heisenberg spins is placed in the nodes of a 2D square lattice, where a spin has four nearest neighbours in film (with periodic boundary conditional).

For computer simulation, we used parallel modification of Metropolis algorithm [10,11].

3. Results and Discussion

Below, we show step by step, the process of nucleation of skyrmion and skyrmions lattice, using by Metropolis algorithm. It depends on the value of external out of plane magnetic field. The parameters of simulation were: $D = J = 1$, the size of the system was $N = 20 \times 20$. Visualisation was made in Paraview [12].

On Figure 1, we have stripe structure, because of competition of direct Heisenberg exchange and DM interaction. But we have more than 1 spin in one the stripe, it is the results of impact of direct interaction. The external magnetic field is zero.

When we add small external magnetic field $H_z = 0.1$, we have the beginning of process of nucleation of skyrmion. Under the influence of external magnetic field, in strips is being formed a skyrmion and in general, we can see changing in a distribution of magnetic spin configuration. And finally, when we apply $H_z = 0.5$, we have skyrmion's lattice on Figure 2.

For solving the problem with random point for nucleation of the skyrmion, we apply an in-plane magnetic field to a small area of the sample for creating the skyrmion in specific point.

Also, we can "push" the skyrmion from one side to another one using this in-plane magnetic field. This is rather precision method, see Figure 3. The main problem, it is really difficult to reproduce this in physical experiment, our colleagues are working under this experimental realisation. Now, we are working under another method, using control the anisotropy applying voltage to a sample.

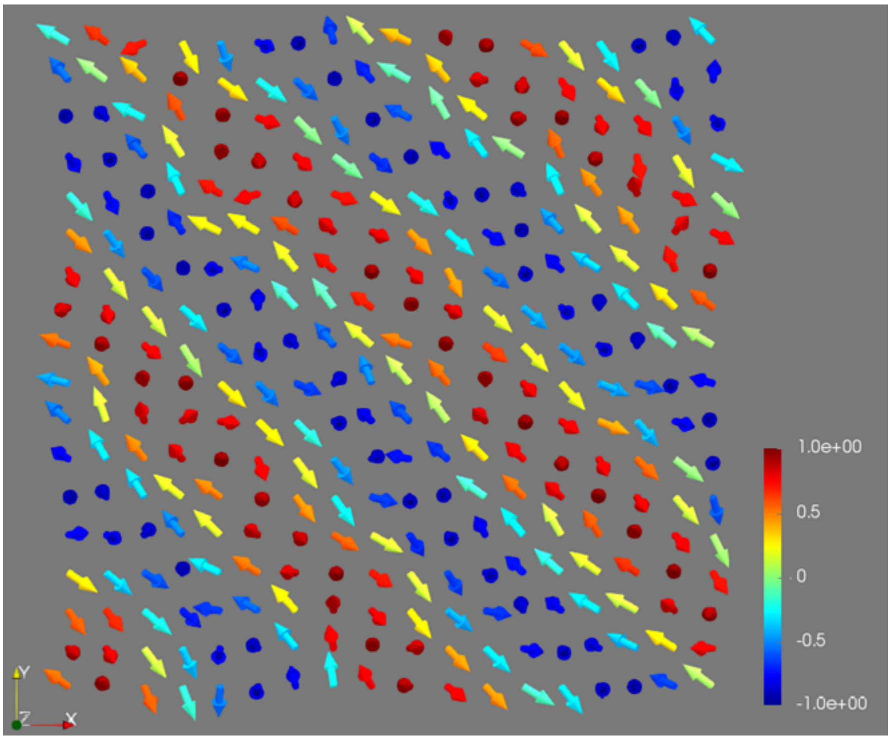

Figure 1. This is a ground state of system with DMI and Heisenberg exchange—a Spiral state.

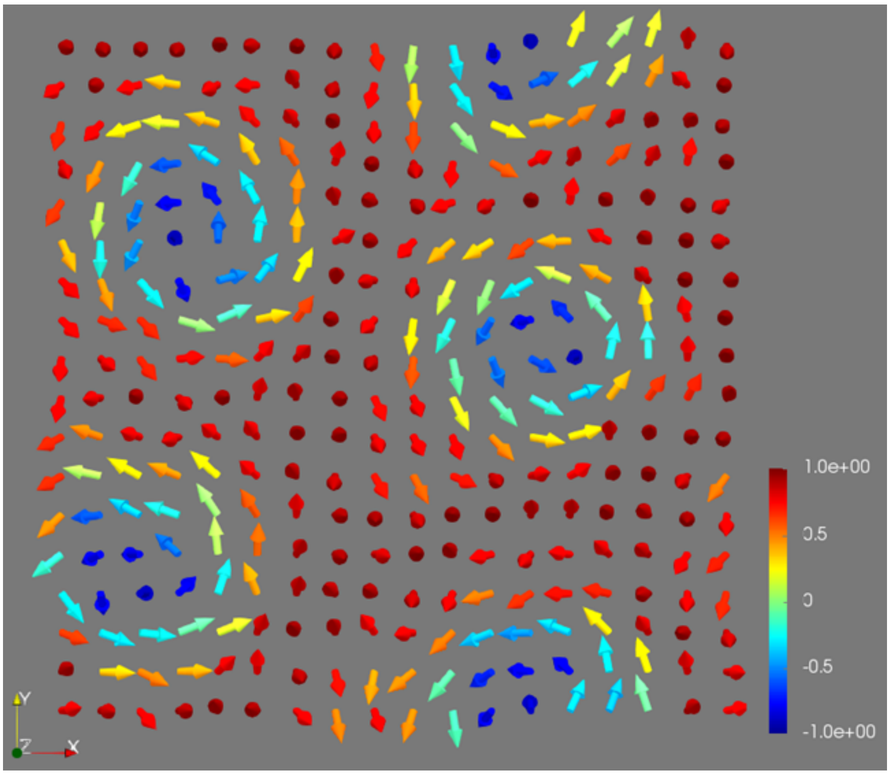

Figure 2. Skyrmion’s lattice.

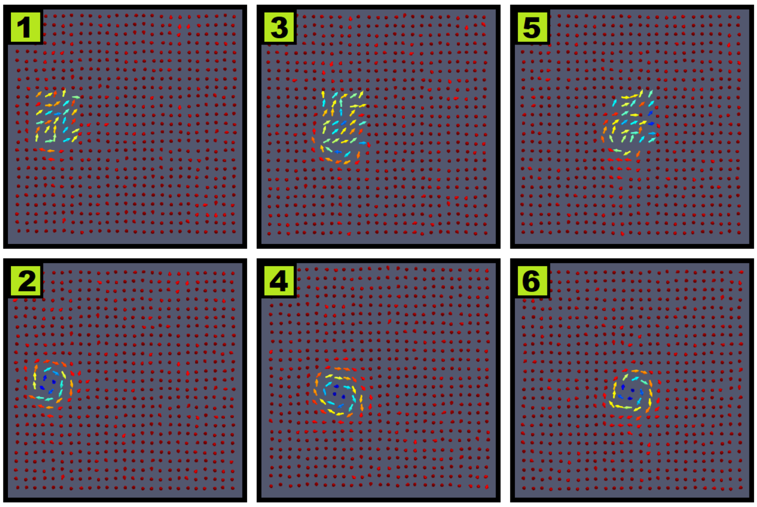

Figure 3. Movement of the skyrmion.

4. Conclusions

In the frame of the classical Heisenberg model, lattice spin systems with direct short- and Dzyaloshinskii-Moriya interactions were investigated by Monte Carlo methods.

The energy of direct interaction, which contributes to the collinear alignment of neighbouring spins and controls the ordering in the system, is given by the Heisenberg exchange integral. A much weaker interaction, favouring the perpendicular orientation of neighbouring spins, exists in some Heisenberg magnets in which electrons have a strong spin-orbit coupling. The energy of this interaction is described by the DMI interaction and leads to the fact that the spins deviate from the parallel orientation. As a result, there is a competition between collinear and non-collinear alignments of spins.

We proposed a method for manipulation of a position of a skyrmion using in-plane magnetic field.

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