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Discrete double core skyrmions in magnetic thin films

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ABSTRACT

We study the Belavin–Polyakov double core skyrmions in two-dimensional isotropic Heisenberg ferromagnets on a discrete square lattice by means of spin dynamic simulations using periodic boundaries conditions. It is also investigated the presence of external in-plane magnetic fields and lattice defects. We have shown that these discrete skyrmions not cylindrically symmetric have a high degree of stability, similar to their continuum counterparts, even if small spatial inhomogeneities are present into the system.

1. Introduction

Except for vortices, most of the results about topological excitations and their influences on the properties of two-dimensional (2D) magnetic materials were obtained by using continuum field theories such as the nonlinear σ model. However, it would be interesting and important to adjust the existing theories concerning these structures to a realistic condition of real films with their discreteness, defects, dissipation, etc. Here, we will study such objets in a more appropriate context by considering layered ferromagnetic systems in a discrete square lattice described by the Heisenberg model $H=-J\sum_{\langle i,j\rangle}\vec{S}_i\cdot\vec{S}_j$, where $J>0$ is the ferromagnetic coupling constant, the sum is over nearest-neighbor spins and the spin field $\vec{S}(\vec{x})$ obeys the constraint $\vec{S}^2(\vec{x})=S_x^2(\vec{x})+S_y^2(\vec{x})+S_z^2(\vec{x})=S^2$ (with S being a constant). Since topology is related to continuity, then, under discretization, the topological properties are expected to be lost. Therefore, the main aim of this paper is to investigate if the stability is preserved on the discrete lattice and how the skyrmion core behaves in such situation. We have found that these spin textures are stable if they are not small enough even in finite systems; the lattice finiteness only deprives the static character of the skyrmion. Discreteness effects can be accentuated by removing spins from the lattice. Hence, another subject of our interest is the interaction between topological objects and vacancies (or nonmagnetic impurities).

Skyrmions were first found by Skyrme [1] about 50 years ago during an investigation of classical Lagrangians for possible models of nucleon–nucleon interaction. They were introduced in the context of the two-dimensional Heisenberg model by Belavin and Polyakov [2] and topologically, these objects correspond to the mapping of the spin-space sphere $\sum^2$ onto the continuum plane $\vec{x}=(x,y)$. Consequently, they are characterized by a skyrmion integer number $Q=\pm1,\pm2,\pm3,\ldots$ (see Eq. (1)) and have finite energy $E_s=4\pi JS^2|Q|$ (in an infinite system), which is independent of the skyrmions size R. The Belavin–Polyakov skyrmions can be essentially of two types, depending on the boundary conditions at $\vec{x}\to\infty$. Considering $\vec{S}(\vec{x})\to(0,0,\pm S)$ as $\vec{x}$ goes to infinity, one gets the $|Q|$ core configuration ($|Q|$ constituent point particle) while, for $\vec{S}(\vec{x})\to(\pm S,0,0)$ at infinity, one gets the $2|Q|$ core configuration (both the $|Q|$ and $2|Q|$ point particles have the same energy for the same Q). Of course, the $Q=\pm1$ skyrmions are energetically more favorable and therefore, only these structures will be investigated here.However, the last type of skyrmion is more suitable for magnetic thin film because the spins tend to become parallel to the plane of the film (for instance, along the x-direction) and therefore, hereafter we will consider only these double core structures. Indeed, in real thin film with no intrinsic anisotropy, the magnetization is forced to stay mainly in the plane of the film by dipolar interactions. Hence, topological excitations in the bulk of the film are characterized by

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an $O(2)$ winding number, $q=+1$ for vortices and $q=-1$ for antivortices. At the core of these objects, the magnetization points out of the plane (polarization $p=\pm 1$). As a result, there is the second topological invariant characterizing them (the skyrmion number commented earlier), which is defined as

$$Q = \frac{1}{8\pi}\int d^2\vec{x}\,\varepsilon_{ij}\varepsilon_{\alpha\beta\delta}n_\alpha\partial_i n_\beta\partial_j n_\gamma, \tag{1}$$

where $\hat{n}(\vec{x}) = \vec{S}/S$ is the unit vector parallel to the local magnetization $\vec{S}(\vec{x})$. A vortex with a winding number q and core polarization p has a half-integer skyrmion charge $Q = qp/2$. Therefore, a vortex–antivortex pair with parallel polarizations p have opposite skyrmion numbers adding to zero and thus belongs to the same topological sector as uniform ground states (vacuum) [3]. From the topological perspective, such a texture can be deformed continuously into a ground state. On the other hand, a vortex and an antivortex with antiparallel core polarizations have equal skyrmion numbers adding to a total of $+1$ or -1. This texture belongs to a nontrivial topological sector and thus cannot be deformed continuously into a ground state (with zero skyrmion number). Such a spin texture not cylindrically symmetric has also important consequences in quantum magnetism. For instance, for a general spin S Heisenberg 2D antiferromagnet, the merons [4] (vortices) forming the double core skyrmion are "spin-S spinons" [5,6], which are essential objects in the seek for quantum spin liquid [7] states of spin-half ($S=\frac{1}{2}$). Our aim in this letter is to investigate the stability conditions of this double core structure in a 2D ferromagnetic discrete lattice. Our motivation is threefold: firstly, a detailed knowledge of the cores movement due to the existence of spatial inhomogeneities in these materials is of great importance to understand the dynamics of multiple vortex field configurations. Secondly, it should be instructive to know how discretizations affect topological objects that are not restricted to radially symmetric configurations. Finally, our investigations may also be applied to 2D easy-plane magnets with an anisotropy able to render the out-of-plane vortices as the stable excitations [8]. To start, we take into account a pure system in square lattices of several sizes; the influence of external magnetic fields parallel to the magnetic plane is also analyzed. In addition, we study the effects of a single hole (impurity) on the skyrmion structure.

2. The model and results

The continuum limit of the isotropic ferromagnet described by Hamiltonian H is the nonlinear σ model given by $(J/2)\int d^2\vec{x}(\partial_v\vec{S})^2$, $v=1,2$ and the constraint $S^2 = constant$. For simplicity we assume $S^2=1$. The explicit static configuration of a double core skyrmion can be obtained by using boundary conditions $\vec{S}\to(1,0,0)$ at $\vec{x}\to\infty$. Then, parametrizing the spin vector $\vec{S}(\vec{x})$ by two scalar fields, the polar and azimuthal angles θ and ϕ, $\vec{S} = (\cos\theta\cos\phi, \sin\theta\sin\phi, \cos\theta)$, one can write these static solutions with finite energy and centers placed at $(0\ \ ,-\ R/2)$ and $(0, R/2)$ as follows:

$$\theta_{2c} = \arccos\left[\frac{Ry}{x^2+y^2+R^2/4}\right], \tag{2a}$$

$$\phi_{2c} = \arctan\left[\frac{y-R/2}{x}\right] - \arctan\left[\frac{y+R/2}{x}\right]. \tag{2b}$$

Now, we would like to know how the above structure (see Fig. 1 for the visualization of the two cores skyrmion configuration), obtained from the continuum field theory in the thermodynamic limit, behaves in a discrete and finite lattice. To do this, we have studied systems with several sizes L (from $60a$ to $100a$, where a is the lattice spacing) by using periodic boundary conditions and spin dynamics simulations. The Heisenberg equation of motion $d\vec{S}_i/dt = i[\vec{S}_i, H]$ is solved for each spin $\vec{S}_i$ interacting with its nearest neighbors. We have employed the fourth-order predictor-corrector method. Our main aim is to obtain the behavior of the skyrmion cores. We placed the initial skyrmion at origin and the two centers as shown in Fig. 1 (i.e., displayed along the y-axis as written in Eq. (2)). If the distance between the cores (or skyrmion size) R is not small enough (compared to L), the excitation tends to be stable but it loses its static character for finite lattices. Indeed, the two cores gyrate around each other always in the clockwise sense with a defined frequency for given L and R. However, this frequency decreases as L increases. We have calculated the energy of this configuration for several sizes of the square lattices L and different skyrmion sizes $R\geq 4a$. For $R<4a$ the discreteness effects make the cores of the vortices approach each other on spiralling orbits and meet in

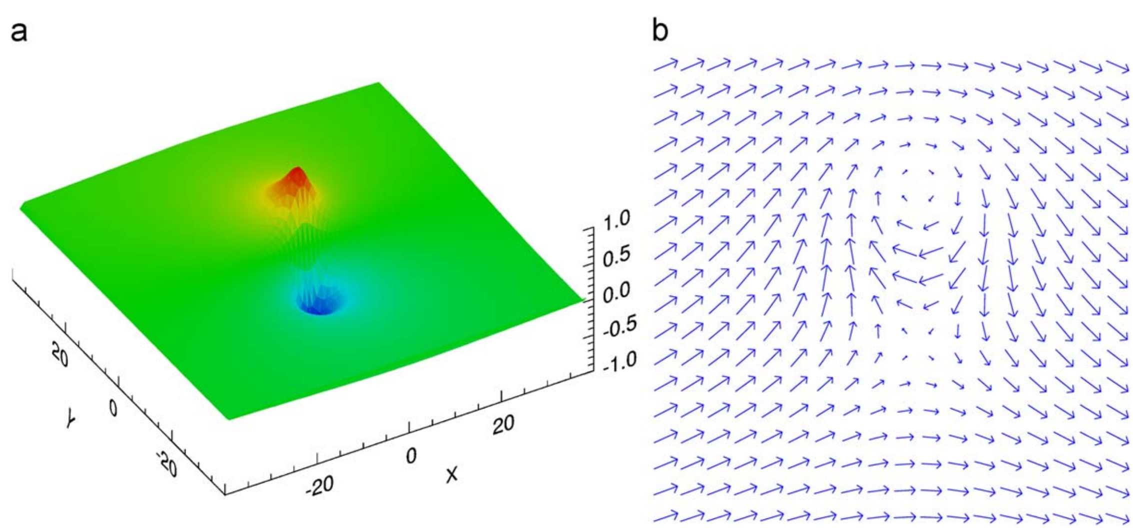

Fig. 1. Left: three-dimensional view of the skyrmion with its two centers. Up polarization is red while down polarization is blue. The green color indicates that the spins are pointing in directions almost parallel to the plane of the film. Right: top view of the skyrmion showing the chirality (winding number q) of the cores. The size of the arrows is proportional to their projection into the xy-plane.