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Chiral skyrmions in thin magnetic films: new objects for magnetic storage technologies?

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Abstract

Axisymmetric magnetic string-like objects of nanometre sizes (chiral vortices or skyrmions) have been predicted to exist in a large group of noncentrosymmetric crystals more than two decades ago. Recently, these magnetic textures have been directly observed in nanolayers of cubic helimagnets and monolayers of magnetic metals. We develop a micromagnetic theory of chiral skyrmions in thin magnetic layers for magnetic materials with intrinsic and induced chirality. Such particle-like and stable micromagnetic objects can exist in broad ranges of applied magnetic fields including zero field. Chiral skyrmions can be used as a new type of highly mobile nanoscale data carriers.

In magnetic materials with broken chiral symmetry the structural handedness induces chiral Dzyaloshinskii–Moriya (DM) couplings [1] which stabilize two- and three-dimensional localized structures with a fixed rotation sense and nanometre sizes [2, 3]. Originally, they have been described as chiral vortex-like configurations, but they are smooth and stable, topologically non-trivial magnetization configurations and, therefore, can be identified as skyrmions in the micromagnetic limit with constant magnetization modulus, \( |M| = \text{const.} \). These skyrmions differ from other axisymmetric patterns induced by external dipole–dipole forces (bubble domains in nanolayers [4] and magnetic vortices in magnetic nanodots [5]). Importantly, chiral skyrmions can also arise in nanolayers of magnetic metals where they are stabilized by surface/interface induced DM interactions [6]. In common (centrosymmetric) magnetic crystals such solitonic states are radially unstable and collapse spontaneously under the influence of the applied field or anisotropy [2]. This singles out magnets with intrinsic and induced DM interactions into a particular class of magnetic materials where nanoscale magnetic solitons exist [3].

Recently, observations of such chiral skyrmions have been reported in nanolayers of noncentrosymmetric cubic ferromagnets (Fe,Co)Si and FeGe [7] and in monolayers of Fe with a strong surface induced DM coupling [8]. This experimental break-through is not only an impressive demonstration of a unique phenomenon: static solitons and formation of solitonic mesophases in a chiral condensed matter system [3]. These experiments also constitute a new avenue for magnetic data storage and spintronics technologies. Chiral skyrmions, as magnetic inhomogeneities localized into spots of a few nanometres, can be freely created and manipulated, e.g., in extended layers of magnetically soft materials. These countable objects allow us to fulfill a key requirement in creating versatile magnetic patterns at the nanoscale.

This work formulates the basic micromagnetic theory for thin ferromagnetic layers with chiral DM couplings and presents equilibrium solutions of isolated skyrmions applicable to a broad range of material parameters. This is the first step towards a detailed calculation of the properties and behaviour of chiral isolated skyrmions in layer systems.

As a model we consider a thin layer of a uniaxial ferromagnet with intrinsic or induced DM couplings.
micromagnetic energy density of the layer [1, 3]

\[ w = A(\text{grad} M)^2 - \mathbf{M} \cdot \mathbf{H} - K (M \cdot n)^2 + w_d + w_D \]  

(1) includes exchange energy with stiffness A, uniaxial anisotropy with constant K (n is a unity vector perpendicular to the layer surface), Zeeman, stray-field \( w_d \) and DM \( w_D \) energies [3, 9]. The chiral DM couplings are written as antisymmetric differential forms

\[ \Lambda_{ij}^{(\psi)} = M_i \frac{\partial M_j}{\partial x_k} - M_j \frac{\partial M_i}{\partial x_k} \]  

(2)

which are known as Lifshitz invariants [1].

Introducing spherical coordinates for the magnetization \( \mathbf{M} = M (\sin \theta \cos \phi, \sin \theta \sin \phi, \cos \theta) \) and cylindrical coordinates for the spatial variable \( r = (r \cos \phi, r \sin \phi, z) \) one can show that the equations minimizing functional (1) include axisymmetric localized solutions of the type \( \theta(r), \psi(\phi) \) (figure 1). The solutions \( \psi(\phi) \) depend on the magnetic symmetry [2]. In this paper, we consider stray-field free configurations \( \psi = \varphi + \pi/2 \) arising in cubic helimagnets (crystal classes 23 (T) and 432 (O)) and in uniaxial ferromagnets with \( n \) 22 (D\( _2 \)) symmetry \( (n = 3, 4, 6) \) [2, 3]. For these handed ferromagnets the part of the DM energy responsible for the stabilization of skyrmions (i.e. that includes exchange energy with stiffness \( A \) and with fixed values of z) can be written as \( \tilde{w}_D = D (\Lambda_{ij}^{(\psi)} - \Lambda_{ij}^{(\psi)}) \) where \( D \) is the Dzyaloshinskii constant [2]. The total energy of the axisymmetric string in the layer of thickness L can be written in the following reduced form \( W = 2\pi AL\tilde{w} \)

\[ \tilde{w} = \int_0^\infty \left[ \left( \frac{\theta^2}{2} + \frac{\sin^2 \theta}{2} \right) + A l \left( \frac{\pi}{2} \right) \left( \theta + \frac{\sin \theta \cos \theta}{\theta} \right) \right] + \sin^2 \theta + (H/H_a)(1 - \cos \theta) + \tilde{w}_d(\rho, l)/Q \rho^2. \]  

(3)

Here, we use a new spatial variable \( \rho = r/x_0 \) and characteristic parameters

\[ x_0 = \sqrt{\frac{A}{K}}, \quad H_a = \frac{K}{M}, \quad Q = \frac{K}{2\pi M^2}, \quad \kappa = \frac{4\sqrt{\lambda K}}{\pi D}, \quad l = \frac{L}{x_0}, \]  

(4)

where \( x_0 \) is the Bloch wall thickness, \( H_a \) is the anisotropy field, \( Q \) is the quality factor [9] and the parameter \( \kappa \) describes

\( n \)

Figure 1. (a) Axisymmetric isolated skyrmion with the core diameter \( 2R_S \) in a thin magnetic layer of thickness \( L \). (b) The magnetization profile along the diameter cross-section \( \theta(r) \) and the perpendicular magnetization \( m_z(r) \) indicate a strong localization of the skyrmion core; \( a(\theta_0, \theta_0) \) is the inflection point and the core radius \( R_0 \) is derived from equation (6)).

The relative contribution of the DM energy. For \( \kappa > 1 \) chiral modulations in the form of helices or skyrmion lattices become equilibrium states in bulk magnets [2]). The stray-field energy of the axisymmetric string \( \tilde{w}_d \) is derived by solving the corresponding magnetostatic problem [12]: \( \tilde{w}_d(\rho, l) = \cos \theta (1 - \Omega(\rho, l))^{-1} \). The solutions in figure 2 demonstrate a variation of the relative contribution of the DM energy. For \( \kappa < 1 \) chiral modulations in the form of helices or skyrmion lattices become equilibrium states in bulk magnets [2]). The stray-field energy of the axisymmetric string \( \tilde{w}_d \) is derived by solving the corresponding magnetostatic problem [12]: \( \tilde{w}_d(\rho, l) = \cos \theta (1 - \Omega(\rho, l))^{-1} \). The equations minimizing the functional W (3) with boundary conditions \( \theta(0) = \pi, \theta(\infty) = 0 \) yield the magnetization profiles for skyrmions \( \theta(r) \) (figure 1) in the phase space of the four control parameters, \( \kappa, H/H_a, Q, l \).

Typical solutions \( \theta(r) \) derived by numerical minimization of energy functional (3) are presented in figure 2. In a broad range of the control parameters the skyrmion profiles \( \theta(r) \) consist of strongly localized arrow-like cores with linear variation of the angle \( \pi(\theta - \pi) \times x \) and exponential ‘tails’ with \( \theta \propto \kappa \exp(-r/x_0) \). A skyrmion core radius can be defined as

\[ R_0 = r_0 - \theta_0 (d\theta/dr)_0^{-1}. \]  

(6)

where \( (r_0, \theta_0) \) are the coordinates of the inflection point a and \( (d\theta/dr)_0 \) is the derivative in this point (figure 1) [10].

The results in figure 2 demonstrate a variation of the skyrmion structure under the influence of magneto-dipole forces (parameters \( Q \) and \( l \)). This allows us to adjust the skyrmion structure and size by the variation of the layer thickness \( L \) or the value of the quality factor \( Q \).

In the phase diagram in reduced parameters \( \kappa, H/H_a \) and with fixed values of \( Q \) and \( l \) (figure 3) we indicate the existence area of isolated skyrmions. Obviously skyrmions exist even in very high fields without collapse. At low fields the existence region of skyrmions is bound by several critical lines (figure 3). Skyrmions remain stable in zero and negative field for \( \kappa < 1 \). At a critical field \( H_a \) a ‘bursting’ of skyrmions occurs, where their cores expand into a homogeneous state with magnetization parallel to the applied field. For \( \kappa > 1 \)
skyrmions either condense into lattices on the transition line $H^*$ or strip out into a helical structure at a lower field $H_a$. All these exceptional features of chiral skyrmions rely on the topological and energetic stabilization of their core structure by chiral DM couplings. Therefore, chiral skyrmions are fundamentally different from cylindrical bubble domains [9], which are intrinsically unstable and only arise by the surface depolarization and the tension of ordinary domain walls as an effect of the shape of a magnetized body.

In figure 4 we demonstrate how axisymmetric solutions for model (3) with $D = 0$ (thin (blue) lines) transform into solutions with DM interactions (thick (red) lines). For $D = 0$ only solutions for cylindrical domains (bubbles) exist as metastable states in a certain range of parameters $H/H_a, Q, l$ [12]. Usually bubble profiles $\theta(r)$ consist of an extended core with $\theta = \pi$ separated by a thin domain wall from the surrounding homogeneously magnetized area with $\theta = 0$ (figure 4(b)) [9, 11, 12]. In figure 4(a) energy (3) plotted as a function of the bubble core size $E(r)$ (blue line) indicates a metastable solution for $r = R_1$. Under the influence of DM interactions the profile of the energy density is modified and includes solutions for skyrmions with fixed rotation sense and finite radius $r = R_a$, and solutions for isolated bubbles, which may have different rotation sense of the magnetization ($r = R_2$ and $r = R_3$) (red lines). The coexistence of skyrmion and bubble solutions occurs in a rather narrow range of the material parameters. Outside this area bubbles are unstable and only skyrmions can arise in the film.

In order to elucidate the physical mechanisms for the stabilization of chiral skyrmions in thin magnetic layers, a simplified semi-quantitative discussion is useful. The profiles $\theta(r)$ in the skyrmion centre are linear. The strong localization of its core allows us to use a linear ansatz $\theta = \pi(1-r/R)$, $0 \leq r \leq R$, $\theta = 0$, ($r > R$) as a suitable approximation for skyrmion solutions. With this trial function the equilibrium sizes of the skyrmion are derived by minimization of the function

$$\Phi = \tilde{A}(H, Q)v^2 - 2xv/l + v^3G(v)/Q, \ v = R/L,$$

(7)

**Figure 3.** The magnetic phase diagram in reduced variables $\kappa$ and applied magnetic field $H/H_a$ for fixed values of $Q$ and the reduced layer thickness $l$ indicate the existence region of isolated skyrmions. In the double-hatched area spatially modulated phases (helicoids and skyrmion lattices) correspond to the equilibrium state of the film.

**Figure 4.** Energy $E$ of isolated bubbles and skyrmions as a function of their sizes (a) and the corresponding magnetization profiles $\theta(\rho)$ (b) for a centrosymmetric magnet ($D = 0$) and with finite DM energy ($D \neq 0$).

Recent experiments in nanolayers of magnetic materials with intrinsic (cubic helimagnets Fe$_{0.5}$Co$_{0.5}$Si and FeGe [7]) and with induced chirality (Fe/W bilayers) [8]) report observations of bound skyrmion states (lattices) (regions with $\kappa > 1$ in figure 3). Isolated skyrmions with $R_s \approx 45$ nm have been observed in a Fe$_{0.5}$Co$_{0.5}$Si nanolayer ($L = 20$ nm) in the applied field larger than the critical field $H^* \approx 50$ mT (figure 3) [7]. Using experimental data from [7, 13] we found that for this sample $\kappa = 1.75$ and $x_0 = 16$ nm. Our theoretical model results corroborate the identification of the observed magnetization patterns as chiral skyrmions.

In conclusion, in magnetic layers with intrinsic or induced DM interactions isolated skyrmions with well-defined sizes can exist as regular solutions of micromagnetic equations in a broad range of the material parameters (figures 2 and 3). Chiral skyrmions as particle-like spots of reverse magnetization can be considered as the smallest conceivable micromagnetic configuration. Importantly and in contrast to alternative and traditional storage technologies based on highly coercive or soft magnets, chiral skyrmions can exist in magnetically soft nanolayers even at zero field, when sufficiently strong DM interactions can be induced. In such materials, chiral skyrmions can be easily created, transported and controlled, e.g., by electric currents and applied magnetic fields. Stable chiral skyrmions in extended layer systems are promising objects for novel types of magnetic data storages, but also for logical bit-wise operations in extended layer systems.

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References

[1] Dzyaloshinskii I E 1964 Sov. Phys.—JETP 19 960
[2] Bogdanov A N and Yablonsky D A 1989 Zh. Eksp. Teor. Fiz. 95 178
   Bogdanov A N and Yablonsky D A 1989 Sov. Phys.—JETP 68 101
   Bogdanov A and Hubert A 1994 J. Magn. Magn. Mater. 138 255
[3] Rößler U K et al 2006 Nature 442 797
   Rößler U K et al 2011 J. Phys.: Conf. Ser. 303 012105
[4] Kiselev N S et al 2010 Phys. Rev. B 81 054409
   Kiselev N S 2007 Appl. Phys. Lett. 91 132507
   Kiselev N S 2008 Appl. Phys. Lett. 93 162502
   Bran C et al 2009 Phys. Rev. B 79 024430
[5] Schneider M et al 2000 Appl. Phys. Lett. 77 2909
   Wachowiak A et al 2002 Science 298 577
   Butenko A B et al 2009 Phys. Rev. B 80 134410
[6] Bogdanov A N and Rößler U K 2001 Phys. Rev. Lett. 87 037203
[7] Yu X Z et al 2010 Nature 465 901
   Yu X Z et al 2011 Nature Mater. 10 106
[8] Heinze S et al 2011 Nature Phys. 7 713
[9] Hubert A and Schäfer R 1998 Magnetic Domains (Berlin: Springer)
[10] Bogdanov A and Hubert A 1999 J. Magn. Magn. Mater. 195 182
[11] Thiele A A 1970 J. Appl. Phys. 41 1139
   Thiele A A 1969 Bell System Tech. J. 48 3287
[12] Tu Y 1971 J. Appl. Phys. 42 5704
   DeBonte W J 1973 J. Appl. Phys. 44 1793
[13] Beille J et al 1981 J. Phys. F 11 2153