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Field induced spin chirality and chirality switching in magnetic multilayers

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ABSTRACT

The physical origin of the field-induced spin chirality experimentally observed in rare earth multilayers is determined. It is shown that the effect is possible due to the interplay between solid-state exchange interactions (the Ruderman–Kittel–Kasuya–Yosida and the Dsyaloshinsky–Moriya interactions), the external magnetic field and a special confinement of magnetic constituents. The presented model describes a certain temperature dependence of the chirality factor in agreement with experimental data and opens a new way to design nanostructured objects with predicted handedness.

Breaking chiral symmetry is a common subject of biology, chemistry and physics [1–3]. In condensed matter, magnetic materials display a special kind of chirality, which is the different handedness of spin structure. A highly topical problem, how to change chiral parameters for practical usage, is under massive investigations particularly in helical magnets, which are solid candidates for use as elements in spintronic devices [4]. A certain imbalance between the left and right handedness in magnets with broken local inversion symmetry can be caused by the antisymmetric Dsyaloshinsky–Moriya exchange interaction (DMI) [5–6]. If the DMI is forbidden, there are no other known purely solid-state interactions that could manage the lifting of the degeneracy between the left and right chiral states. Essentially different ways of inducing the imbalance between right and left screws in originally symmetric crystallographic structures are discussed in literature. One of them is breaking the symmetry on the surface [7]. In such a case the DMI arises near the surfaces or at the interfaces between constituents in multilayers. New methods of controlling of the vortex chirality in planar nanomagnets use a breaking of the symmetry due to the special mask [8] or due to the shape of magnetic nanoparticles [9–10]. The other way of inducing chirality is applying of an external action that *imitates* the DMI: the cooling of the sample in the electric field [11] or using the interaction between the spin chirality and the elastic torsion [12]. No other external action was proposed for inducing chirality. The direct interaction between spin chirality and the magnetic field breaks the time-reversal symmetry and as a result it is forbidden. The recent investigations of the phase transition in a chiral helimagnet prove this point of view: it was shown in [4], that the chiral magnetic soliton lattice appears due to the magnetic field application, but the initial left-handed spin chirality is preserved.

Magnetic structures of rare earth multilayers are well-known [13–15], but the results on polarized neutron scattering which can clarify the question of handedness in such structures were published only recently. As it was reported in [16–17], chirality in Dy/Y multiayers can be induced by the cooling in *magnetic field* (FC procedure), while the arising handedness directly depends on the final temperature of the FC procedure. The most interesting detail, that the handedness directly depends on the thickness of the magnetic (Dy) layers, as well. In the light of the above-mentioned physical meaning of the DMI and chirality, these experimental data are quite unexpected and so far this phenomenon was not explained. It is known that the undisturbed HCP structure (inherent for the heavy rare earth like Dy and Y) is inversion symmetric and the DMI interaction is forbidden. Non-zero handedness in Dy/Y multilayers should be considered as an effect taking place due to the broken symmetry at the interfaces between magnetic and nonmagnetic layers [7,18]. But in such a case magnetic layers thicknesses should not have any influence on the observed effect. So, the questions arise: (1) if the direct interaction between the magnetic field and the spin chirality is impossible, what interaction could be a true cause of the observed effect? (2) how the surface effect can be sensitive to the magnetic structure in the volume, i.e., to the thicknesses of magnetic layers? (3) is it possible

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to control a sign and a value of the chiral parameter via the changing of the experimental conditions and geometrical parameters of the multilayers?

In this article we show the manner in which the common action of the Ruderman–Kittel–Kasuya–Yosida interaction (RKKY), the DMI at the interfaces, and the Zeeman interaction can induce the enumerated above specific chiral properties in multilayers. The model, developed here, shows the way to control chirality in helical layered structures.

We consider here the experimental results for two multilayers denoted in [17] by Dy30/Y15 and Dy30/Y30 (numbers 30 and 15 are the thicknesses of the Dy or Y layers in nanometers). Both samples are grown along the *c*-axis of the *HCP* structure, while the spins are directed in the basal *ab* plane. The magnetic layers of Dy, separated by "dead" planes of nonmagnetic Y, are helically ordered below the Neel temperature (T_N). If the magnetic layers are sufficiently thick, like in the present case, the value of a pitch angle in such "pieces of a helix" is close to the correspondent parameter of bulk Dy. The value of a pitch angle, q, usually obeys the relation $|q| < \pi/2$. The phase shift $\Phi = \sum_{n=0}^{N} q = (1+N)q$ over the entire Dy layer (here and throughout the article the monolayers with numbers $n=0$ and $n=N$ are chosen at the boundaries of the Dy layers) depends on the RKKY exchange interaction constants. It was shown that absolute values $|q|$ and $|\Phi|$ are decreasing with the decreasing temperature [13–15].

The populations n_L and n_R of the left-and right-helix domains before the FC procedure are equal, i.e.: the chirality factor $\gamma \propto (n_L - n_R)/(n_L + n_R) = 0$. After the FC procedure down from $T > T_N$ to $T < T_N$ in the external magnetic field H=900 mT directed in the basal *ab* plane (i.e., perpendicularly to the axis of the helix) the field was switched off and γ was measured. It was observed: if $T > T_1$, where T_1=145 K, the correspondent chirality factor is positive in both samples; if $T \sim T_1$, $\gamma = 0$; if $T < T_1$ the chirality factor is negative. The physical meaning of the temperature T_1 can be connected with the magnetic structure of the every Dy layer in the following way [17]; if $T=T_1$, the phase shift of the undisturbed helix (i.e., without magnetic field) $\Phi = 2\pi$. At higher temperatures, $T_1 < T < T_N$, the corresponding phase shift is $\Phi > 2\pi$ and at the lower temperatures, $T < T_1$, it is $\Phi < 2\pi$. Does chirality really depends on the phase shift or it is a simple coincidence? To clarify this phenomenon it is necessary first to consider the changes of the helical structure in bulk Dy under influence of the external magnetic field during the FC procedure.

As was shown in [19–20], if the value of the external magnetic field, H, satisfies the relation $H < H_{crit}$, where H_{crit} directs all the spin vectors along the field, the so-called sin-structure takes place due to the competition between the indirect exchange RKKY and the Zeeman interactions. For our purposes it is important to note, that in contrast to a simple helix (presented in Fig. 1(a)), the sin-structure demonstrates the *spatially changing sense of chirality* (Fig. 1(b) and (c)). As soon as this property of the sin-structure is noted, we receive a key to the understanding of the physical origin of field-induced chirality.

If the value H fulfils the approximate relation $H \geq H_{crit}/2$, the sin-structure can be described by the formula [20]:

$$\sin\frac{q_n}{2} = 2x\sin(nq + j_0) \qquad (1)$$

here θ_n are the angles between the spins of the nth spin plane (monolayer) and the magnetic field, ξ is a dimensionless constant, $0 < 2\xi < 1$, which depends on the relation between the values of the external field and the RKKY exchange constants (see formula (3.6) in [20]), the value of φ_0 fulfils the relation $\sin\theta_0/2 = 2\xi\sin(\varphi_0)$, where θ_0 is the angle between the spins in the chosen initial monolayer and the applied field.

The model (1) can be directly applied to the explanation of the

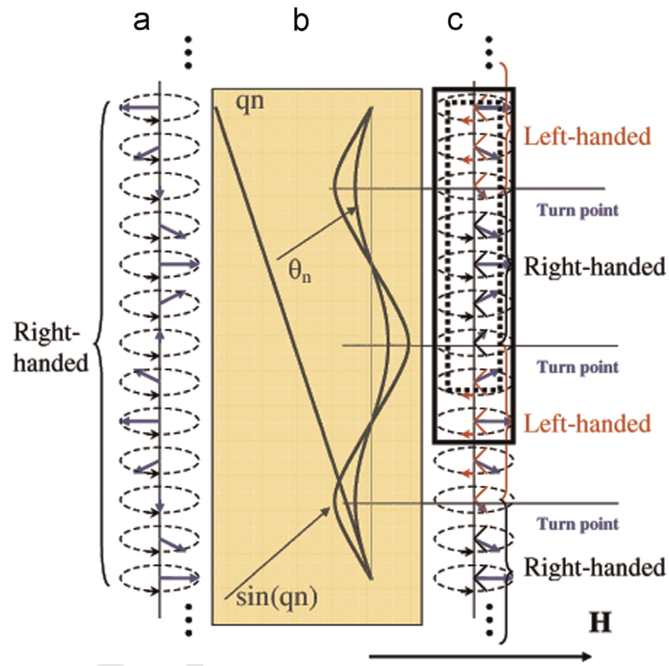

Fig. 1. The sin-structure in comparison with a simple helix with the correspondent pitch angle q (the angle between spins of adjacent monolayers). The helical axis is parallel to the *c*-axis of the *HCP* structure. The solid arrows indicate the direction of the spins in every plane of helical Dy. The dashed circular arrows help one to visualize the helix. (a) Simple helix with spins in basal *ab* plane. The handedness of the helix in the picture is chosen just for an example, as without the DMI the mirrored structure has the same properties. (b) The illustration of formula (1) gives the evidence, that the period of the sin-structure (which determines the position of neighboring fragments with opposite spin chirality) is directly connected with the period of the helix. (c) The typical sin-structure is obtained from the helix (a) via application of the magnetic field H in the basal plane (its direction is indicated by long solid arrow below). Magnetic structures of Dy layers in a multilayer are illustrated as "cut out fragments" of a bulk sin-structure: the solid-line and the dotted-line rectangles for the cases (A) and (B), correspondingly.

experimental data [17], by virtue of the fact that the external magnetic field which was applied in the experiments H=900 mT is strong enough to fulfill the demands of the model (1) validity in multilayers [14,15,19,20]. The RKKY interaction within every Dy layer is much larger than the RKKY interaction between Dy layers via non-magnetic Y [13–15]; we can neglect the last one in the given analysis.

The "turn points" at which the handedness changes, are coinciding with the extremums of the function $\sin(nq + \varphi_0)$, Fig. 1b. Every domain of the sin-structure with the right or left handedness corresponds to the fragment of the original helix in which spins are rotated by π. As a result, the right-handed and left-handed domains alternate along the *c*-axis. This behavior of the sin-structure is shown in Fig. 1c. In the bulk sin-structure the number of domains with the left and right handedness is equal, hence chirality factor γ=0. In the subsequent we show that the Dy layers in magnetic field represent the appropriately "cut out" fragments of the sin-structure, and this allows one to choose the handedness.

Using (1), one can express the Zeeman energy per one Dy layer in the following way:

$$E_Z(\varphi_0) = -g\mu_B SH\sum_{n=0}^{N}\cos(\theta_n) = -g\mu_B SH\left\{(1-4\xi^2)\frac{\Phi}{q} + 4\xi^2\frac{\sin\Phi}{\sin q}\cos(Nq + 2\varphi_0)\right\} \qquad (2)$$

The energy $E_Z(\varphi_0)$ reaches its minimums at: