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Reorientation phase transitions in planar arrays of dipolarly interacting ferromagnetic particles

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ABSTRACT

Reorientation phase transitions (RPT) taking place in regular arrays of rectangular submicron-size ferromagnetic particles due to the competition between the external magnetic field of arbitrary direction and internal dipolar fields are analysed in this article. Dipolar interaction between particles is taken into account via real-space calculations of magnetometric demagnetizing factors. Long stripe arrays are also under consideration. I find that the direction of the external magnetic field determines the kind of the phase transition, while the dipolar interaction between particles can significantly change the values of RPT critical field. Calculations were presented for a set of submicron particles/stripe arrays, which were under experimental investigations recently.

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1. Introduction

Patterned magnetic structures, namely stripes and dots arranged in lattices of different types and regularity, have been a hot topic of investigation during the last decade [1]. A special importance have a resent attempts to use magnetic nanodot arrays for logic operations [2], for which the realization without involving multidomain elements is preferable. The well-developed numerical methods give a possibility to analyse domain wall formation and hysteretic properties in submicron particles [3] and effective anisotropies and energies of individual nanoparticles, considered as a conglomerate of atoms ([4] and references therein). Nevertheless, the question that has arisen in almost all the experimental and theoretical works is whether each magnetic element can be considered individually or whether some kind of interaction between elements should be taken into account? It was shown recently, that strong exchange coupling exists between the fine particles in self-organized magnetic arrays [5], whilst in many physical situations the dipolar interparticle interaction should be considered.

In the first approximation the role of dipolar forces is possible to describe via calculations of the magnetometric demagnetising factor (MDF), which gives, actually, a shape anisotropy field. Changes in the MDF influence practically all measurable magnetic parameters of the object, including the dependence of blocking temperature on density in arrays of superparamagnetic spheres [6], establishing ground states in dot arrays [7], spin wave localisation in rectangular magnetic elements [8] and spin wave dynamics in long wires [9], in planar dots ([10,11] and references therein) and in nanostrips [12]. In its turn, the MDF value can be significantly changed due to the interparticle dipolar interaction.

The MDF calculation with necessary accuracy, even for isolated particle of arbitrary (non-ellipsoidal) shape, is not a standard task and usually can be performed only numerically and in definite approximations. The result of the article [13] is unique, as it gives the rigorous analytical expression for the MDF of the particles with the shape of rectangular prism. For particles/particle arrays with non-rectangular shape such an approach allows to find the optimal solution with minimal order of integrals for numerical calculations. In arrays with dipolar interaction between particles, the MDF can be also calculated by micromagnetic methods like it was presented in [14]. But in plenty of cases taking into account the particle shape more rigorously is necessary [15].

In the article [16] the application of the generalised Aharoni's approach [13] to the *array* of long interacting stripes was demonstrated by calculation of the corresponding MDF. In the present article I prolong this work, presenting the *analytical* expressions for MDF in arrays of finite rectangular dots of arbitrary aspect ratio. Results of these calculations, I use then as a basis for a special phase transition analysis; the interest in this topic has been stimulated by resent experimental and theoretical investigations. Namely, a magnetic moment reorientation, arising in different structures due to competing anisotropies of dipolar origin was investigated in systems of circular dots [17] and arrays of long nanowires [18,19]. As it was shown, the existence of this transition (reorientation phase transitions, RPT) can be predicted on the basis of the MDF calculations. It is necessary to note, that the term "phase transitions" is used here in some untraditional meaning. Historically, the term "orientation phase transition" was

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accepted for *bulk* magnets [20], where the constant of anisotropy, being a function of temperature, changes its sign. In such a case symmetry of the magnetic structure changes, and, as a result, the transition between different phases of the magnet arises. RPT takes place both with changing of temperature and due to external magnetic field. These kinds of transitions obey all the features of usual phase transition (among them, they could be also of the first and the second kind, etc.). In the case under consideration, i.e., if we consider arrays of *confined* particles (submicron or nanoparticles) the rigorous thermodynamic theory of phase transitions could not be developed in the same way, as for bulk material. But these different physical cases have the important similar feature; the anisotropy constant changes its sign. The physical background of it is different in magnetic bulk material and magnetic nanostructures under consideration. But the mathematical description and physical consequences are similar. Previously, the classical Landau thermodynamical theory is shown to be useful in different field of micromagnetics; see, for instance, the successful establishing of a catastrophe model for fine particles, embedded in a less ferromagnetic matrix [21]. Here, using the similar way of mathematical parallel, I give an analytical analysis of the RPT scenario in an external magnetic field in regular arrays of finite rectangular dots of submicron dimensions and in arrays of infinitely long stripes.

The paper is comprised of sections as follows:

In Section I calculate the effective magnetometric demagnetizing factor (MDF) of interacting rectangular prisms in regular arrays by generalizing the result for an individual rectangular prism [13] (the corresponding geometry of particle array is presented in Fig. 1a). This result is also extended for the important case of an array of interacting infinite stripes by generalizing the classical Brown's equation for individual infinite prism [13,16,22]. Here, the final expressions for MDF of particle arrays are analytic. As such, this allows one to avoid integral operations with the dipolar field that require precious processing time and give non-strict results owing to a strong inhomogeneity (singularity) of the dipolar field in particle's ages (corners). Also, in this paper, I work in real rather than usually used reciprocal space [23]. There are a number of advantages of chosen approach that include allowing changes to the number of prisms in the array under consideration, or to take into account the effects of the sample shape. Calculations by these formulae for arrays of finite rectangular particles and infinite rectangular prisms are presented in Figs. 2 and 3.

In Section 3, I use the described results of the MDF calculations for the analysis of the RPT, which takes place when the intrinsic dipolar interaction is in a competition with external magnetic field [24], while the dipolar interparticle interaction acts as an additional source of the shape anisotropy energy. The geometries of *planar* particles under consideration are presented in Fig. 1b and c, the corresponding results were presented in Fig. 4.

2. MDF of ferromagnetic particles/stripes with rectangular cross-section in regular arrays: a real-space approach.

We consider here an ordered 2-dimensional array of identical ferromagnetic homogeneous rectangular dots (prisms) with the unit cell dimension $A_x \times A_z$ (Fig. 1a). A dot with the number (n,l) has the radius-vector $\mathbf{A}_{nl}=(nA_x, lA_z, 0)$ of its centre of mass and extends over the volume $-L_x+nA_x<x<L_x+nA_x$, $-L_z+lA_z<z<L_z+lA_z$, $-L_y<y<L_y$. Note, that the size of this volume is identical for every particle, being equal to $2L_x \times 2L_z \times 2L_y=V$.

For an array of finite-size nanoparticles the general expression of MDF takes the form

$$I_{pp}=\frac{1}{(2N_x+1)(2N_z+1)V}\sum\nolimits_{n,n',l,l'}\int_V d\mathbf{r}\int_{V'} d\mathbf{r}'\frac{\partial^2}{\partial r_p \partial r'_p}\frac{1}{\sqrt{\left|\mathbf{r}-\mathbf{r}'-\mathbf{A}_{n-n',l-l'}\right|}}. \tag{1}$$

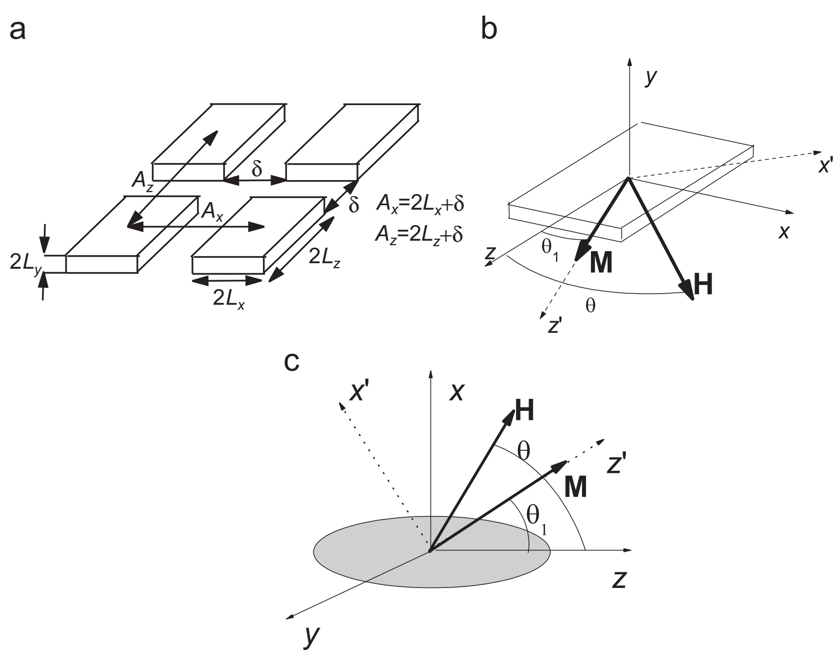

Fig. 1. Geometries of the magnetic systems considered in this article. (a) Ordered array of particles with the rectangular cross-section; all the geometrical parameters used in the text and calculations are indicated. The *z*-axis is parallel to the longest axis of the particle, the *y*-axis is perpendicular to the patterned media. (b) Rectangular elongated particle (we consider the similar geometry for a stripe with infinitely long length (in *z* direction) and a rectangular cross-section in the *xy* plane); c. Planar round dot. In both cases presented in (a) and (b) the *z*-axis coincides with the magnetization direction (vector **M**) in the absence of the external magnetic field, the z'-axis points the direction of **M** in the external field **H**. The angles between **H** and *z*-axis, **M** and *z*-axis are θ and θ_1 correspondingly. Here, as it is following from the symmetry of the system, both vectors **H** and **M** are in the same plane (choosing *x*0*z*) that is perpendicular to the plane of the particle. The difference is that in the case of a round dot, in contrast to a rectangular one elongated in the plane, it is convenient to analyse out-of plane directions of the external field; because of all in-plane directions are identical.

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