Journal of Magnetism and Magnetic Materials 386 (2015) 117–124

Contents lists available at ScienceDirect

Journal of Magnetism and Magnetic Materials

journal homepage: www.elsevier.com/locate/jmmm

Pinning of thermal excitations at defects in artificial dipolar arrays: A theoretical investigation

D. Thonig [a,*], J. Henk [b]

[a] Department of Physics and Astronomy, Uppsala University, Box 516, SE-751 21 Uppsala, Sweden
[b] Institut für Physik, Martin-Luther-Universität Halle-Wittenberg, D-06120 Halle (Saale), Germany

ARTICLE INFO

Article history:
Received 11 September 2014
Received in revised form
6 March 2015
Accepted 13 March 2015
Available online 16 March 2015

Keywords:
Classical macrospin models
Dipolar arrays
Dipole–dipole interaction
Magnetic charges
Defects

ABSTRACT

In this theoretical investigation we address the effect of defects on thermal excitations in square-lattice dipolar arrays. The samples consist of nanomagnets, whose geometry is adopted from recent experiments [A. Farhan et al., Nat. Phys. 9 (2013) 375] [13] and allows for thermal activation at room temperature. Various types of defects, all of which may be produced by microstructuring techniques, are introduced into the systems. It turns out that excitations can efficiently be pinned at defects. Furthermore, it is possible to produce ferromagnetic strings of nanomagnets that connect a pair of defects; their lengths are closely related to the distance of the defects and the topology of the magnetic ground-state configuration.

1. Introduction

Topologically frustrated systems offer unexpected properties which have been studied recently in magnetic materials. A particular exciting system is artificial spin ice with its 'exotic' magnetic ground states [1–4]. Artificial spin ice is a two-dimensional (2D) array of magnetic nanoislands fabricated with desired geometries. The nanoislands are typically elongated to show a single-domain state; their magnetic moments then point in one of the two directions. Being isolated from each other, e.g. separated by a distance in the order of several hundred nanometers, they are coupled by the long-range dipole–dipole interaction.

The systems sketched above are known for low-temperature fractionalization: they exhibit collective excitations that carry only a fraction of the elementary constituent's properties. These appear due to the absence of a unique ground state and due to the violation of the 'two-in-two-out' ice rule, the latter proposed by Pauling for the proton ordering in water ice [5]. Collective excitations appear as ferromagnetically aligned nanoislands ('strings') with end points ('nodes' or 'vortices') that behave like magnetic charges [6–10]. The oppositely charged end nodes of the strings interact with each other with a distance dependence of a Coulomb potential [8]. The properties of these artificial magnetic monopoles are studied theoretically as well as experimentally with great effort.

In experiments, effective thermal excitations in artificial square-lattice dipolar arrays may be provided by field protocols of vibro-fluidized granular matter [11,12], allowing investigations of the short-range magnetic order. Long-range ordered ground states in square-lattice spin ice were obtained by thermal annealing during the fabrication [9], which is recommended for magnetic monopoles of charges ± 2. Charges of ± 4 were not observed, which has been attributed to the nanoislands' geometry. Recent investigations on artificial spin ice with reduced nanoislands' dimension [13] proved thermal excitations at room temperature, which provide observing and in particular controlling of excitations with large magnetic charges.

Improvements in nanolithography allow to design artificial spin ice in 2D structures like honeycomb (kagome ice) [10,14–16], brickwork [17,18], triangular [19], pentagonal [20], and shakti lattices [21]. A three-dimensional artificial spin ice can be realized by e.g. layer-by-layer synthesis [20]. Local modifications in the otherwise perfect array are introduced by local nanolithography [22,23]. These perturbations, considered as defects, modify significantly the properties of the system [24,25]. This leads to a question on the role of defects in dipolar arrays concerning thermal excitations. For three-dimensional spin ice and pyrochlore lattices defects have already been studied [26–29]. Investigations of defects in 2D artificial spin ice have been performed e.g. by Silva et al. [30] who addressed the interaction between magnetic string excitations caused by defects and string excitations. Other studies consider disorder as random displacements, as random island

* Corresponding author.
E-mail address: danny.thonig@physics.uu.se (D. Thonig).

http://dx.doi.org/10.1016/j.jmmm.2015.03.048
0304-8853/

orientation, as random switching field or as random exchange strengths in square [31] or honeycomb [32,33] dipolar arrays. More precisely, Mengotti et al. [34], Hügli et al. [35] and Ladak et al. [36] apply disorder as random switching field to reproduce the avalanches of mobile magnetic charge defects for high magnetic fields in kagome artificial spin ice. There, the hysteresis reveals the importance of disorder. Schumann et al. [37] studied defects in kagome spin ice and conclude that patterns with some local defects are still representative of the statistics of more perfect patterns. For square-lattice spin ice Budrikis et al. [38] concluded that the strength of disorder is more important than its origin: small perturbations do not vary the essential properties of the system. Since defects can also serve as pinning centers in conventional magnetic materials [39,40], it is conceivable to influence and control magnetic monopoles and the associated string excitations by tailoring the defects' properties. To show this for artificial dipolar arrays is the aim of the present paper.

In this work we study various defect types in square-lattice dipolar arrays—randomly distributed or inserted in a controlled manner—, with a focus on high magnetic excitations (charges of ± 4). We consider modifications of nanoislands of a vortex as a defect: (i) removal of islands from the vortex, (ii) vertical displacement of two islands, (iii) a modification of the islands' thickness or (iv) of their magnetization density. Furthermore, two defects with predefined positions and properties have been introduced into the arrays. The resulting string excitations that link these defects are analyzed with respect to defect position and string length. Magnetic ground states have been achieved by Monte Carlo simulations for given temperatures [41,42].

The paper is organized as follows. Theoretical aspects are presented in Section 2. In the discussion of the results, given in Section 3, we address randomly distributed vacancies (Section 3.1) before analyzing one or two defects with prescribed properties (Section 3.2). We conclude with Section 4. Appendices comprise information on the dipolar energies (Appendix A) and the Monte Carlo simulations (Appendix B).

2. Theoretical aspects

We build up the dipolar arrays by nanomagnets whose dimension has been taken from Ref. [13] (length 470 nm, width 170 nm, and height 3 nm). The lattice constant a of the square lattice [43] is 793.8 nm (the lattice spacing is 601 nm in Ref. [44]). The fundamental properties of the systems, e.g. interaction energies and formation probabilities of magnetic charges, scale with the lattice constant, as demonstrated in Ref. [46]. The magnetic single-domain state of each elongated nanoisland is described by a magnetization vector $\pm\boldsymbol{M}$ ('spin') aligned along the large island axis. For islands made of permalloy, $|\boldsymbol{M}| \approx 200 \cdot 10^3$ A m^{-1}.

Four islands that form a cross introduce a node ('vortex'; cf. Fig. 1a). The number of spins pointing toward the node's center $\boldsymbol{C}$ defines the charge Q of that node: $Q \in \{-4, -2, 0, +2, +4\}$; for example, $Q=0$ in Fig. 1a. To quantify thermal activation, we introduce the fraction of nodes with charge Q in the sample, $\eta_Q \equiv N_Q/N$, in which N is the number of nodes with four adjacent islands in the sample; N_Q is the number of such nodes with charge Q. On average $\langle \eta_Q \rangle = \langle \eta_{-Q} \rangle$. A path of ferromagnetically aligned nanoislands that connects a pair of nodes with opposite non-zero charges is called a 'string excitation' (Fig. 2).

Instead of approximating the nanomagnets as points [7,8,45] or dipolar needles [10,45], we compute the dipole–dipole interaction energies E_{ij} for realistic shapes by integrating over island i and island j,

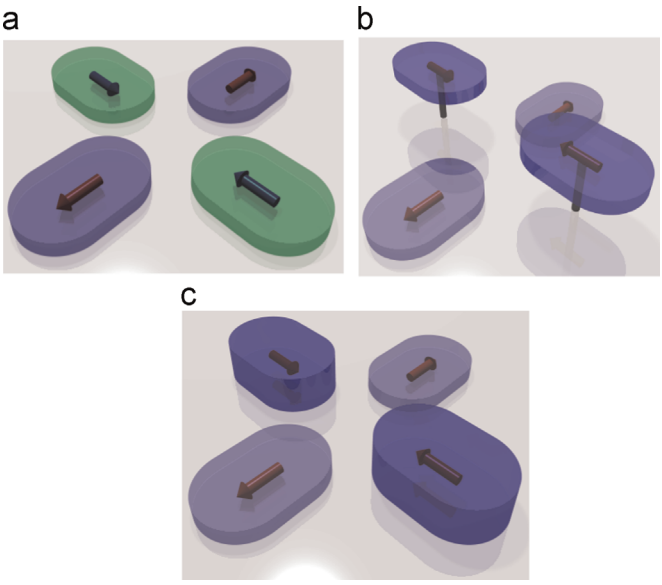

Fig. 1. Defects in a square-lattice dipolar array. At a selected node, opposite islands are modified by (a) a variation of their magnetization density, (b) a vertical displacement, and (c) a variation of their thickness. The modified islands are distinguished by color: green in (a), dark blue in (b) and (c). The arrows in each island indicate their magnetization $\boldsymbol{M}$. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this article.)

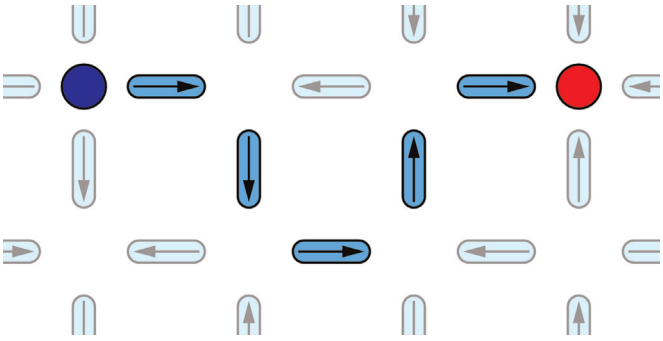

Fig. 2. String in a square-lattice dipolar array (schematic). The end points, carrying magnetic charges of -4 (dark blue dot, left-hand side) and $+4$ (red dot, right-hand side), are linked by a ferromagnetic path of islands (blue). The spin ice 'host' is visualized by faint colors. The arrows in each island indicate their magnetization $\boldsymbol{M}$. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this article.)

$$E_{ij} = \frac{\mu_0}{8\pi} \int_{\Omega_i} \int_{\Omega_j} \frac{3\boldsymbol{m}_i \cdot \boldsymbol{r}_{ij}\, \boldsymbol{m}_j \cdot \boldsymbol{r}_{ij} - \boldsymbol{m}_i \cdot \boldsymbol{m}_j\, r_{ij}^2}{r_{ij}^5} \, \mathrm{d}\boldsymbol{u}_j \, \mathrm{d}\boldsymbol{u}_i . \tag{1}$$

μ_0 is the vacuum permeability and $\boldsymbol{r}_{ij} \equiv \boldsymbol{u}_i + \boldsymbol{R}_i - \boldsymbol{u}_j - \boldsymbol{R}_j$. The position $\boldsymbol{r}$ is expressed within the i-th nanomagnet by $\boldsymbol{r} \equiv \boldsymbol{R}_i + \boldsymbol{u}_i$, where $\boldsymbol{R}_i$ is the center coordinate of the i-th nanomagnet and $\boldsymbol{u}_i$ is a position in the island relative to the center $\boldsymbol{R}_i$. Here, $\boldsymbol{u}_i$ runs over its volume Ω_i. The magnetization density $\boldsymbol{m}_i = \boldsymbol{M}_i/\Omega_i$ is assumed homogeneous. The integration is done numerically, allowing in principle for arbitrarily shaped nanoislands, e.g. rectangles, rounded rectangles or dots. In this study we focus on rounded rectangles (details in Appendix A). As pointed out elsewhere [46] the dipolar interaction [47,48] is relevant only for first- (1NN) and for second-nearest (2NN) neighbors [49], with energies $E_{1\mathrm{NN}}$ and $E_{2\mathrm{NN}}$, respectively. For a discussion of the actual $E_{1\mathrm{NN}}$ and $E_{2\mathrm{NN}}$ we refer to Ref. [46].

The interaction energies $E_{1\mathrm{NN}}$ and $E_{2\mathrm{NN}}$ of a selected node can be modified in various ways (Fig. 1): by (i) introducing vacancies (i.e. removal of islands from a node), (ii) modifying an island's magnetization density, (iii) varying the vertical displacement δz, and