Physics Letters A 380 (2016) 2013–2016

Contents lists available at ScienceDirect

Physics Letters A

www.elsevier.com/locate/pla

Thermodynamics and magnetization reversal in artificial brickwork spin ice

Y. Li [a,*], T.X. Wang [b], Z.T. Hou [a], H.Y. Liu [a], X.F. Dai [a], G.D. Liu [a]

[a] *School of Material Science and Engineering, Hebei University of Technology, Tianjin 300130, China*
[b] *College of Physics and Information Engineering, Henan Normal University, 453007 Xinxiang, China*

ARTICLE INFO

Article history:
Received 13 November 2015
Received in revised form 6 April 2016
Accepted 13 April 2016
Available online 16 April 2016
Communicated by R. Wu

Keywords:
Artificial spin ice
Frustration
Magnetization reversal

ABSTRACT

The thermodynamics and magnetization reversal behavior of three artificial frustrated brickwork systems are investigated by means of the Monte Carlo method. Three frustrated systems have different array patterns of ferromagnetic nanoislands, and consequently different geometry symmetry and magnetic properties. The simulated results show that two brickwork systems which have only 'three-spins' vertex exhibit the long-range ordered magnetic ground state, and one brickwork system that contains mixed 'two-spins' and 'four-spins' vertex as well as 'three-spins' vertex has a high degeneracy of ground state and no long-range order. In all three frustrated systems, there occurs the phase transition from the magnetic ground order to disorder. Three frustrated brickwork lattices show significant differences in the reversal mechanism in the presence of magnetic field for different lattice spacings.

1. Introduction

In 2006, the square artificial spin ice was first proposed to serve as an experimental route for studying the physics of a special class of natural spin ices, i.e., the pyrochlore ferromagnets [1–5]. Since then, a variety of two-dimensional artificial frustrated systems such as triangular [6] and honeycomb (Kagomé) lattices [7,8], were realized by an ordered array of lithographically fabricated single-domain ferromagnetic nanostructures. A great amount of experimental and theoretical studies had made much progress on the magnetic behaviors of artificial spin ices, such as the ground state [9–11], dipolar correlation [12–14], and thermodynamic and magnetization reversal [15–19], and magnetic monopole [20–22]. Currently, the artificial spin ices have been an important topic of condensed matter physics because they can offer new opportunities for exploring physical phenomena associated with disorder in spin ice or the array geometry inaccessible in any natural system [23].

Frustration in artificial spin ice originates from the intrinsic incompatibility between the fundamental magnetic interactions and the underlying lattice geometry, which leads to a high degree of degeneracy of ground states. Various geometry and topology structures give rise to complex orderings and unusual collective magnetic behaviors of frustrated systems. As studied mostly before, the square spin ice exhibits the ordered magnetic ground state [10] while the kagomé spin ice has only the long-range magnetic charge order but no the magnetic moment order at the ground state [7]. The brickwork frustrated systems, as another type of designed frustrated systems, have different geometrical arrangements from the square and kagomé lattices, and only received a little attention so far [13,17]. Especially, thermodynamics and magnetization reversal properties of the brickwork frustrated systems have been rarely reported as far as we are concerned.

In this letter we investigate thermalized dynamics and magnetization reversal behavior in three types of artificial frustrated brickwork lattices by the Monte Carlo simulation. In section 2, the lattice models considered and the Monte Carlo simulation process are given. The simulated results are presented in section 3. The ground magnetic configurations and magnetic charge ordering are first discussed, then the specific heat and the phase transition temperature of three systems with different lattice spacings are presented, and finally the magnetization reversal of three frustrated systems is studied in the presence of the magnetic field. Section 4 gives the conclusions.

2. Model and method

In general, the elongated nanomagnetic island can be effectively treated as a single macroscopic spin due to its single domain character, and each giant spin points along the island's long axis because of the shape anisotropy of the islands. We con-

---

[*] Corresponding author.
E-mail address: liyingphy@126.com (Y. Li).

http://dx.doi.org/10.1016/j.physleta.2016.04.019

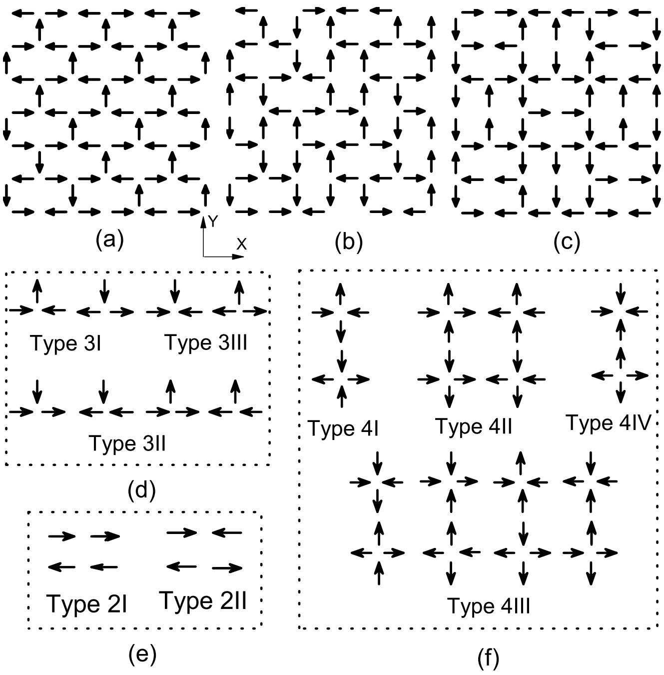

Fig. 1. (a)–(c) Schematics of a portion of three brickwork frustrated systems. (d) Three types of 'three-spins' vertices, (e) two types of 'two-spins' vertices, and (f) four types of 'four-spins' vertices.

sider three different brickwork frustrated lattices, as sketched in Figs. 1(a)–1(c), here named as brick-A, brick-B, and brick-C for convenience. Brick-A and brick-C have been realized experimentally by Li et al. [13] and Gilbert et al. [17], respectively, but no experimental report for brick-B is given to date. Three frustrated lattices can actually be generated from the square frustrated lattices by regularly removing certain islands, and thus in some sense they can be regarded as different defect structures of the square frustrated lattice. In brick-A, half of islands in the vertical direction are removed from the square lattices, while in brick-B and brick-C three quarters of islands in both directions are respectively removed from the square frustrated lattice. Obviously, three types of brickwork frustrated lattices have different geometry structures and symmetries. Comparing with four islands meeting at each vertex in the square frustrated lattice, three spins meet at the vertex for brick-A and brick-B while two, three or four islands meet at the vertex for brick-C, see Figs. 1(d)–1(f).

At the 'three-spins' vertex in brick-A and brick-B, there are a total of $2^3 = 8$ possible magnetic configurations, as in Fig. 1(d). According to the magnetostatic energies, eight magnetic configurations can be divided into three types of vertices, i.e., type 3I, type 3II and type 3III, where $E_{3\text{I}} < E_{3\text{II}} < E_{3\text{III}}$. Types 3I and 3II obey the 1-in/2-out or 2-in/1-out spin ice rule. In brick-C the vertex types have 'two-spins' and 'four-spins' vertex as well as 'three-spins' vertex, as shown by type 2I and type 2II in Fig. 1(e) and type 4I, type 4II, type 4III and type 4IV in Fig. 1(f), where $E_{2\text{I}} < E_{2\text{II}}$ and $E_{4\text{I}} < E_{4\text{II}} < E_{4\text{III}} < E_{4\text{IV}}$. There exist 28 possible magnetic configurations at the vertex of brick-C.

For all three brickwork frustrated lattices, the long-range dipolar interactions between all spins are taken into account. In the presence of magnetic field, the magnetic interaction of nanomagnets with field is also included. Then the model Hamiltonian describing the systems can be written as

$$\mathcal{H} = D\sum_{i,j}\left[\frac{\vec{s}_i \cdot \vec{s}_j}{|\vec{r}_{ij}|^3} - \frac{3(\vec{s}_i \cdot \vec{r}_{ij})(\vec{s}_j \cdot \vec{r}_{ij})}{|\vec{r}_{ij}|^5}\right] - \vec{H}_Z \cdot \sum_i \vec{s}_i, \tag{1}$$

where $\vec{s}_i$ is a unit vector spin, i.e., $\vec{s}_i = \sigma_i \vec{e}_i$ with $\sigma_i = \pm 1$ and $\vec{e}_i$ defining the long axis of islands. The first term represents the dipolar coupling, where $D = \frac{\mu_0 \mu^2}{4\pi d^3}$ is dipolar coupling parameter with μ_0 the permeability of the vacuum, μ the magnetic moment of each spin and d the distance between two nearest spins along the vertical or horizontal direction, and the sum runs over all spin pairs i and j defining the vector $\vec{r}_{ij}$. The second term is magnetic interaction from the applied field H, and here $H_z = \mu H$. Note that the spin $\vec{s}_i$ is normalized to unity, so that the field variable H_Z as well as the dipolar coupling parameter has units of energy. In terms of the experiment [1], the size of ferromagnetic nanoscale islands is large enough to possess a large magnetic moment of approximately $\mu = 3 \times 10^7 \mu_B$ and consequently the strength of dipolar interactions at nearest-neighbor distances can reach the order of magnitude 10^4 K, depending on the lattice spacing. In our simulation, we take the values of dipolar coupling parameter D ranging from 25 meV to 20 eV.

We perform Monte Carlo simulations for three brickwork frustrated lattices. Each frustrated lattice includes 864 total spins, and free boundary conditions are used. The long-range dipolar interactions between all spin pairs were considered without introducing any cut-off energy. And a standard Metropolis algorithm with single-spin-flip dynamics is used for describing the probability of the spin reversal [24]. In the simulation, an extremely slow annealing procedure is performed for obtaining the ground state from a random initial state at high temperature to low temperature state ($T = 0.01D$) with an increment of $\Delta T = 0.01D$.

For the simulation of the magnetization reversal behavior, the magnetic field is first applied and increased to the saturated field H_s where the system reaches the saturated state. After saturating the magnetization in the positive direction, the field is subsequently reduced to zero and increased to $-H_s$ in the negative direction, and then increased to the positive saturated field in field increment of $0.01H_s$, so that a full hysteresis loop is obtained. The long enough Monte Carlo steps per spin for each hysteresis loop is used for acquiring the thermalization equilibrium. To reduce the statistical error, we have performed 10 independent sample runs for different random initial configurations to make sure that all simulated results do not depend on the initial configurations and then to collect the averaged data.

3. Results

3.1. Magnetic ground state

When the lattice spacing is very small, that is, the dipolar coupling is strong enough, the magnetic ground states of brick-A and brick-B exhibit the long-range magnetic order, and only type 3I with the lowest energy appears, as shown in Figs. 2(a) and 2(b). In this case, there exist two degenerate ground states in both brick-A and brick-B frustrated systems. In brick-A, all spins in the vertical direction align ferromagnetically while two nearest spins in the transverse direction have antiferromagnetic order. In brick-B, a spin always is antiparallel to its nearest neighbor spins in the vertical or transverse direction. For brick-C, no long-range magnetic order is observed at the ground state due to the multiple possible configurations at different vertices, but a short-range order or spin ice rule occurs, see Fig. 2(c). For a small scale system, type 2I (100%), type 3I (about 50%), type 3II (about 50%), and type 4I (100%) are found at the vertex, and there is a high degeneracy of ground state. The simulated result is consistent with the experimental one, where the ground state is experimentally achieved by thermally annealing protocol [17]. The lattice topology induces the occurrence of not only type 3I with the lowest energy but also type 3II with a higher energy so as to minimize the total energy of the system. However, for a large scale system, a small proportion of type 2II