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Topological Defects from Doping and Quenched Disorder in Artificial Ice Systems

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Abstract — **We examine the ice-rule obeying and ice-rule breaking vertices in an artificial spin ice system created using magnetic vortices in type-II superconductors with nanostructured pinning arrays. We show that this system can be doped by changing the external field to move the number of vortices away from commensurability and create sites that contain two or zero vortices. For a square ice, the doping leads to the formation of a grain boundary of vertices that do not obey the ice rules. In commensurate systems where the ice rules are obeyed, we can introduce random disorder at the individual pinning sites to create regions where vortices may not be able to flip from one side of the trap to another. For weak disorder, all of the vertices still obey the ice rules, while at intermediate levels of disorder we find grain boundaries of vertices which do not obey the ice rules. For strong disorder it is possible to create isolated paired vertices that do not obey the ice rules.**

1 INTRODUCTION

Spin ice has been an extensively studied condensed matter system since it offers one of the simplest examples of geometrical frustration. Instead of a unique ground state that satisfies the spin-spin interactions, in spin ice there can be large number of ground states with the same energy leading to an excess entropy at $T = 0$ [1]. These systems can exhibit interesting types of topological defects such as monopoles and states that obey the "ice-rules" which specify the number of spins that must point toward and away from each vertex [1, 2, 3]. The spin ice systems have a strong relation to the degenerate proton ordering in water ice [4] which lead to the name of spin ice. Although the states which obey the spin ice rules have many different orientations, it is possible to apply a bias to the system that causes a unique long range ordered state to appear. One method of applying this bias is via an external magnetic field. [2, 5].

Due to the size scale of real spin systems it is not possible to directly observe the spin ordering or defects in the spin ice states. Recently there has been extensive work on creating large scale systems that have the same properties as spin ice [5, 6, 7, 8, 9, 10, 11], such as by fabricating nanomagnetic arrays that can form an artificial spin ice. The direction of the magnetic moment of a single nanomagnet represents the spin direction, and the nanomagnets are placed in a square or honeycomb array to realize artificial square ice or artificial kagome spin ice. In these systems, it has been shown that a significant portion of the resulting vertices obey the ice rules [6, 7, 10]. For the square ice, if the interactions between the nanomagnets is small, many of the vertices do not obey the ice rules, and even in the strong interaction limit, there is still a fraction of vertices that do not obey the ice rules, suggesting that there must be some form of quenched disorder in the nanomagnets [6, 7]. In general the defect structure and defect dynamics in ice-rule obeying systems is an open problem. In very recent experiments on an artificial kagome ice system, an external field was applied to bias the system in different directions [5, 12]. For a strong biasing field, all the vertices obey the ice rules for one particular direction; however, when the field is reversed, various types of defects appear including monopoles. Once the strength of the reversed field is large enough, an oppositely polarized state appears which obeys the ice rules. This suggests that non ice-rule obeying states can be created by applying an external field. Other recent experiments have also found that an external field applied at certain angles to the artificial ice lattice symmetry directions produce a proliferation of non-ice rule obeying vertices.

Besides nanomagnetic systems, there is also a recent proposal for creating artificial spin ice systems using vortices in type-II superconductors with patterned pinning arrays [13]. In this system, each pinning site is fabricated with a double well shape so that there are two energetically favored places for the vortex to sit that are separated by a potential barrier. Another artificial spin ice proposal involves using charged colloids in optical trap arrays where again each trap is composed of a double well potential [14]. In these systems, it was demonstrated that ice rule-obeying states can be created readily for both square and kagome artificial ices. These systems have several advantages over the nanomagnetic systems. The disorder can be much more carefully tuned by altering the height of the potential

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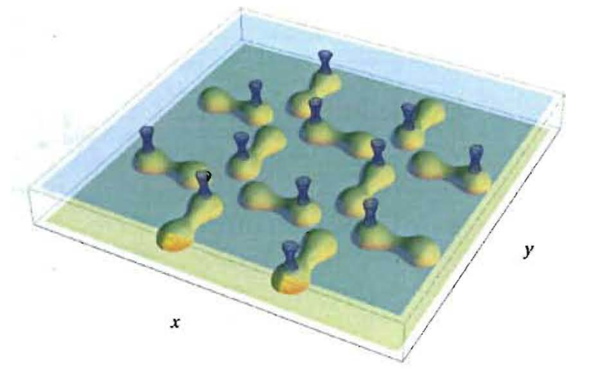

Figure 1: A schematic of the artificial square ice system constructed from pinning sites with a double well potential. The constriction in the center of each pin acts as a center barrier. Each site captures one vortex (black circles) which can sit on either end of the site. The pinning sites are placed in a square lattice. The end of the pinning site where the vortex sits defines the direction of the effective magnetic moment. For the configuration shown, each vertex has two close vortices and two far vortices. This corresponds to the ice rule of two spins in and two out.

barrier separating the two halves of each well. It is also straightforward to effectively dope these systems. In the vortex system, the density of vortices is proportional to the applied magnetic field. At commensurate fields where there is one vortex per double well trap, the ice rules are obeyed; however, by changing the magnetic field some of the pinning sites can be made to capture either more than one vortex or no vortices at all. These doped sites could than affect the ordering of the surrounding undoped vertices. If the disorder in the barriers at the centers of the traps is varied, it would be useful to understand what types of defect structures could form.

2 Simulation Method

We consider a two-dimensional square artificial ice system for vortices in a type-II superconductor with an array of elongated pinning traps where each trap has a double well potential as illustrated in Fig. 1. When the density of vortices is one to one with the trap density, each trap captures a single vortex which can sit in either side of the double well. The well that the vortex occupies defines the direction of the effective magnetic moment of the trap. It is the repulsive vortex-vortex interactions that cause the ice rules to be obeyed in this system. The vortex dynamics are given by integrating the following equation of motion:

$$\eta \frac{d\mathbf{R}_i}{dt} = \mathbf{F}_i^{vv} + \mathbf{F}_i^s + \mathbf{F}_{ext} \qquad (1)$$

Here η is the damping constant and the vortex-vortex interaction force is of the form

$$\mathbf{F}_i^{cc} = -f_0 \sum_{i \neq j}^{N} \nabla_i V(R_{ij}) \qquad (2)$$

where the vortex-vortex interaction potential is the Bessel function $V(R_{ij}) = K_0(R_{ij})$ and R_{ij} is the distance between the vortex i and vortex j. At long range the Bessel function falls off exponentially so that a cutoff can be placed on the interaction for computational efficiency. A short range cutoff is also placed at $R_{ij} = 0.1$ to avoid a divergence in the force. The force from the substrate $\mathbf{F}_i^s$ has the following form: $\mathbf{F}_i^s = \sum_k^{N_b} (f_p/r_p) R_{ik}^{\pm} \Theta(r_p - R_{ik}^{\pm}) \Theta(R_{ik}^{\parallel} - l_k) \hat{\mathbf{R}}_{ik}^{\pm} + (f_p/r_p) R_{ik}^{\perp} \Theta(r_p - R_{ik}^{\perp}) \Theta(l_k - R_{ik}^{\parallel}) \hat{\mathbf{R}}_{ik}^{\perp} + (f_b/l)(1 - R_{ik}^{\parallel}) \Theta(l - R_{ik}^{\parallel}) \hat{\mathbf{R}}_{ik}^{\parallel}$. Here $R_{ik}^{\pm} = |\mathbf{R}_i - \mathbf{R}_k^p \pm l_k \hat{\mathbf{p}}_{\parallel}^k|$, $R_{ik}^{\perp,\parallel} = |(\mathbf{R}_i - \mathbf{R}_k^p) \cdot \hat{\mathbf{p}}_{\perp,\parallel}^k|$, $\mathbf{R}_k^p$ is the position of the center point of well k, $r_p = 0.4\lambda$ is the well radius or half width, $f_p = 15 f_0$ is the well strength, l_k is half the length of the central rectangular region of well k, and $\hat{\mathbf{p}}_{\parallel}^k$ ($\hat{\mathbf{p}}_{\perp}^k$) is a unit vector parallel (perpendicular) to the axis of well k. The force from the external field $\mathbf{F}_{ext}$ represents an applied current which can bias the vortices in different directions.

3 Defect Structures for Disordered and Doped Systems

We first consider the square ice commensurate case in which there is one vortex per trap. Disorder is added by varying the height of the barrier at the center of each well with a dispersion width δ. Vortices are initially placed on randomly chosen sides of the well and an external ac drive is applied in both the x and y-directions. We start with a high amplitude ac drive and gradually lower the amplitude to $F_{ext} = 0$. This protocol is similar to that used for the micromagnetic artificial square spin ice system where a high amplitude ac magnetic field is applied and the amplitude is slowly decreased to 0 [8]. For $\delta = 0$ when the barriers at the center of the wells are all of equal strength, each vertex obeys the square spin ice rules of two in and two out. Ordering of the system into the ice rule obeying state occurs at a very well defined threshold of the external drive. In Fig. 2(a) we show the vertex configurations in the square ice at $\delta = 0$ where all of the vertices obey the ice rules. For intermediate values of δ,

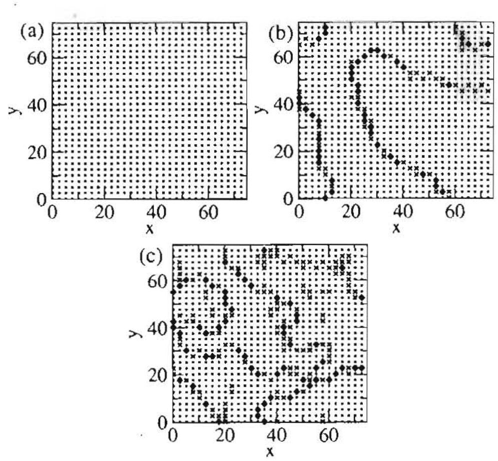

Figure 2: The vertex configurations for a system with a barrier strength of 0.25 and differing strength dispersions δ. Small circles: ice rule obeying vertices. Crosses and filled diamonds: non-ice rule obeying vertices. (a) At $\delta = 0.0$, all the vertices obey the ice rules. (b) For $\delta = 0.5$, vertices that do not obey the ice rules appear but are all located along grain boundaries. (c) At $\delta = 1.0$, there are still vertices which obey the ice rules, but the grain boundaries have proliferated and there are some non-ice rule vertices that appear away from the grain boundaries as pairs of sites.

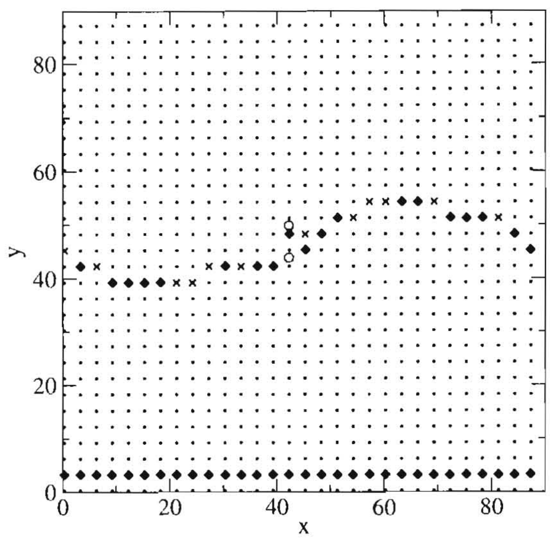

Figure 3: The vertex configuration for a system with two doubly occupied doping sites in the center (large open circles). Small circles: ice rule obeying vertices. Crosses and filled diamonds: non-ice rule obeying vertices. A single grain boundary emanates from the doping sites and crosses the entire sample while the rest of the system obeys the ice rules.

most of the vertices still obey the ice rules; however, grain boundaries appear in which the vertices do not obey the ice rules, as illustrated in Fig. 2(b) for $\delta = 0.5$. For stronger disorder, such as $\delta = 1$ shown in Fig. 2(c), the length of the grain boundaries within the system has increased, and we also observe isolated pairs of non-ice rule obeying vertices that form away from the grain boundaries. In the nanomagnet arrays, the vertex configurations were significantly disordered and no gain boundaries were observed; however, there were regions containing pairs of vertices not obeying the ice rules [6]. This suggests that the nanomagnetic square ice systems are in a strongly disordered limit. Our results also suggest that there may be different types of disordered phases and that a distinction can be drawn between disordered phases that contain only grain boundaries and those that also contain isolated paired defects. We have tested a similar protocol for a kagome ice geometry and find that in a system without disorder, all of the vertices obey the ice rules of one in and two out or two out and one in. For disordered systems, monopole defects begin to appear which have either three in or three out. In contrast to the square ice geometry, the kagome ice geometry does not exhibit grain boundaries at any value of the disorder.

The second type of disorder we consider is to dope the system by moving away from commensurability and using a magnetic field that produces a vortex density which is slightly higher than one-to-one with the pinning density. This creates sites that contain two vortices which occupy both wells. We will consider the simplest case with $\delta = 0$ so that the disorder comes only from the occupation of the wells and not from the barrier strength, and we add only two doubly-occupied wells. After conducting a rotating external drive annealing protocol as described above for the commensurate case, we find that a single domain wall forms composed of non-ice rule obeying vertices. As shown in Fig. 3, this domain wall emanates from the doping sites and spans the entire system. n the future we will consider more complicated cases case such as well-separated doping sites to see if the grain boundaries can minimize their perimeter by passing through both sites. We can also study a system with zero net doping that contains one doubly occupied site and one empty site to see whether grain boundaries form which incorporate both doping sites. The ability to control the density of grain boundaries through doping may also be a promising way to create new types of patterns; for example, large scale periodic arrays of doped sites could result in the formation of intricate periodic networks of grain boundaries. For nanomagnetic systems, it is possible to remove an individual nanomagnet in order to produce an unoccupied doping site; however, doping the nanomagnets with doubly occupied sites would not be feasible.

4 Summary

In summary, we have shown that an artificial square ice can be created using vortices in a type-II superconductor interacting with a periodic array of pinning sites where each site has a double well potential. By defining the direction of the effective spin according to the side of the double well occupied by the vortex, we find that this system obeys the ice rules for square ice. We add disorder to the system in the form of randomness of the height of the potential barrier at the center of the well, and obtain vertex configurations using a rotating drive protocol which is similar to the shaking ac magnetic field used in nanomagnetic systems. For weak disorder the entire system still obeys the square ice rules. For intermediate disorder, ice-rule breaking vertices appear and form grain boundaries, while for strong disorder there are both gain boundaries and isolated paired defects. In a system with uniform potential barrier heights, we introduce disorder by moving away from commensurability and creating some pinning sites that contain two or zero vortices. In this case we find grain boundaries that emanate from the defect site and span the sample.

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