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Magnetic Charge Ordering of Pinwheel Artificial Spin Ice in in-Plane External Magnetic Fields and Its Application For Tunable Vortex Pinning

Timothy Draher
tjdraher96@gmail.com

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Pinwheel artificial spin ice (ASI) systems fabricated using permalloy nanobars offer tunable control of superconducting vortices in an ASI-superconductor hybrid. Vortex pinning is achieved by tuning the ordering of the ASI’s magnetic charge distribution via an external field to create an optimal potential energy landscape to which superconducting vortex motion can be impeded or pinned. Magnetic charge ordering in a pinwheel ASI is visualized using MuMax3 micromagnetic simulations to aid in characterizing the correlation of charge ordering among the spin ice system with the application of the external field. Vortex pinning is characterized in a sample of pinwheel spin ice patterned atop a 100nm thin film of MoGe. DC resistance measurements are conducted when both an out-of-plane field is applied to induce superconducting vortices in the MoGe film and an in-plane field is used to tune the ordering of the ASI’s magnetic charges. Effects of both the strength and orientation of the in-plane field on vortex dynamics are explored by measuring (i) the field amplitude dependence of the dissipation at a fixed field orientation and (ii) the angle dependence of dissipation in a fixed amplitude of the magnetic field. They are accounted for in terms of the ordering of the ASI’s magnetic charges revealed by MuMax3 simulations.
MAGNETIC CHARGE ORDERING OF PINWHEEL ARTIFICIAL SPIN ICE IN IN-PLANE EXTERNAL MAGNETIC FIELDS AND ITS APPLICATION FOR TUNABLE VORTEX PINNING

BY
TIMOTHY DRAHER
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A THESIS SUBMITTED TO THE GRADUATE SCHOOL IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE MASTER OF SCIENCE

DEPARTMENT OF PHYSICS

Thesis Director:
Zhili Xiao
ACKNOWLEDGEMENTS

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Most importantly, I want to thank my parents, Mary and Joseph, for their stalwart love and support throughout my entire life. I also want to thank my closest friends, Sawyer Echkoff and Dylan Ingersoll, for being the brothers by my side through everything. No amount of words can sufficiently show my gratitude for everything that you have all done for me. I wouldn’t be the person I am today if it were not for you.
DEDICATION

To all my loving family and friends, thank you
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CHAPTER 1
INTRODUCTION

One of the challenges in superconductor research is to find solutions to minimize/diminish the finite electrical resistance caused by the movement of vortices. Recent research reveals that a two-dimensional (2D) ferromagnetic pinwheel artificial spin ice (ASI) structure atop a superconducting film offers tunable control of vortex dynamics by altering the potential energy landscape of the vortex system [1]. Applied external in-plane fields orient the magnetic charge distribution of the ASI structure thereby manipulating the direction of vortex motion. It has been demonstrated that a particular magnetic charge arrangement can create impedance of vortex motion by pinning them in place with a particular potential energy environment. Up to now, all research on vortex dynamics of the ASI-superconductor hybrid system has been conducted after the strength of the in-plane magnetic field was reduced to zero once the desired magnetic charge distribution in the ASI is reached. This thesis work is to investigate vortex dynamics in the presence of in-plane fields of various strengths and orientations.

1.1 Superconductivity

Superconductivity is a unique state of matter containing many exotic electrical and magnetic properties of certain materials. Two are most commonly understood as the absence of electrical resistance and the expulsion of magnetic field lines (Meissner effect) from a material as the temperature is below a characteristic transition temperature, $T_c$ [2]. One reason
that type-II superconductors are of interest is because they possess a mixed state between the normal resistive and Meissner states, which is bounded by a lower and upper critical applied field value $H_{c1}$ and $H_{c2}$, respectively (Figure 1.1).

![Figure 1.1: Type-II superconductor phase diagram. Phase A: Meissner state with full expulsion of field lines. Phase B: $H_{c1}$ and $H_{c2}$ set the external field bounds for the mixed vortex state. Phase C: Field lines penetrate through freely in normal resistive state [3].](image)

If the external field is within the critical field range of $H_{c1}$ and $H_{c2}$, finite magnetic flux will quantize and penetrate through the superconductor [4]. These flux quanta of magnetic field generate a lattice of spiraling supercurrent loops around the penetrating flux core, often called Abrikosov vortices, as shown in Figure 1.2.
Figure 1.2: Abrikosov vortex lattice of penetrating magnetic field flux. Black arrows indicate direction of supercurrent flow. Blue indicates the magnitude of the magnetic field through the surface [5].

1.2 Abrikosov Vortices

The dynamics of the vortices can generally be described by the time-dependent Ginzburg-Landau theory of superconductivity [6]. The magnetic field distribution of a vortex has the exact solution (1.1):

\[ B(r) = \frac{\Phi_0}{2\pi\lambda^2} K_0 \left( \frac{r}{\lambda} \right) \]  \hspace{1cm} (1.1)

where \( K_0 \) is a zero-order Bessel function, \( \lambda \) the London penetration depth, and \( \Phi_0 \) the superconducting flux quantum of magnetic field with value \( \Phi_0 = 2.07 \cdot 10^{-15} \) Wb [7]. The field can be expressed in two limiting forms:

\[ B(r) \to \frac{\Phi_0}{2\pi\lambda^2} \left( \frac{\pi \lambda}{2 r} \right)^{1/2} e^{-r/\lambda} \quad r \to \infty \]  \hspace{1cm} (1.2)
\[ B(r) \approx \frac{\Phi_0}{2\pi\lambda^2} \left[ \ln \frac{\lambda}{r} + 0.12 \right] \quad \xi \ll r \ll \lambda \quad (1.3) \]

where at large distances from the core (1.2), the field decays on the order of \( \lambda \) [2]. Meanwhile, as \( r \ll \lambda \) (1.3), the flux enclosed in a circle of radius \( r \) is much less than \( \Phi_0 \).

When an applied current is sent across the material, the vortices feel an induced Lorenz force [1]. They can respond by moving perpendicular to the applied current in the superconductor and dissipate energy, resulting in resistance. The control of this response is heavily desired in a superconductor's applications. It is possible for the vortices to be pinned in place by structural defects in the material. However, a uniform pinning environment can also be constructed by patterning a pinwheel ASI array upon a 2D superconducting nanofilm as elaborated in detail below.

### 1.3 Pinwheel Artificial Spin Ice

Spin ice is a configuration of magnetic Ising spins that interact strongly with their nearest neighbors, i.e., commonly compared to the tetrahedral lattice of hydrogen ions in frozen water ice [8]. The strong interaction between local spins is correlated to the highly ordered geometry of water ice. A set of spin placement conditions called ice rules set a highly degenerate ground state where two spins point inward of the unit cell while two must point out, shown in Figure 1.3.
Excitations of the ground state configurations are characteristics of geometric frustration and have been shown to behave as deconfined magnetic monopoles with corresponding long-distance interactions [8]. Figure 1.4 depicts the emergence of these monopoles by flipping a shared spin moment between two adjacent lattice cells. Each of the cells exhibits a higher energy state with excess magnetic field concentrated at the center. The excited lattice sites now behave as magnetic monopoles and will undergo interaction on distances far beyond the order of the lattice spacing. Figure 1.5 demonstrates this interaction by illustrating the magnetic field lines conjoining two opposite magnetic charges in the lattice. The higher energy state is achievable by application of an external magnetic field.
Figure 1.4: Spin flip between adjacent lattice cells resulting in localized magnetic monopoles. (A-B) Dipole moment shared between two neighboring lattice cells initially obeys the ice rule, then flips and creates an excess of positive and negative (red/blue) field respectively at the center of each cell. (C-D) Monopole representation of spin-moment flipping, where arrow heads are positive and tails are negative charges [8].
Figure 1.5: Long-range field interaction of positive (red) and negative (blue) magnetic charges across multiple lattice sites [8].

These observations of geometric frustration can also be studied with magnetic dipole moments in locally interacting ferromagnetic nanobar arrays called artificial spin ice (ASI). ASI lattices can be fabricated in a multitude of configurations with various emergent phenomena and properties of interest. Each bar’s magnetic macrospin dipole moment will either align or anti-align along its longitudinal axis in the absence of an external magnetic field. Pinwheel spin ice is a particularly interesting ASI orientation due to its easily switchable four-fold degenerate ordering via an external magnetic field [1]. The pinwheel ice pattern consists of orthogonally oriented bars to each nearest neighbor, pointed at the midpoint of one another. An example is given in Figure 1.6 [10].
Figure 1.6: (Left) Pinwheel ASI lattice with unit cell defined in yellow. (Right) Dipole moment orientations (black arrows) about a unit cell. $T_1 - T_4$ label the spin configurations of each state with increasing magnetostatic energy [10].

1.4 Vortex Pinning Potential Landscape

The magnetic charges are an emergent property of the ASI system and their presence in the ASI-superconductor hybrid alters the potential energy environment felt by the Abrikosov vortices. Applying an in-plane external field can generate positive and negative charge chains throughout the pinwheel ASI system [1]. Figure 1.7 demonstrates two configurations of charge chains where an applied field is along the vertical and horizontal directions in each image, respectively. The chains form alternating peaks and valleys of potential energy barriers that confine the movement of the vortices. Varying the orientation of the applied field allows for the capability to easily tune the potential environment and thus enable a programmable switching between the normal and superconducting state [1].
Figure 1.7: Magnetic-force microscopy images of vertical (left) and horizontal (right) charge chains from a pinwheel ASI. Bright and dark spots represent positive and negative charges, respectively. White arrows represent the magnetization directions connecting them [1].

1.5 Thesis Goals

The goal for this thesis is to simulate and observe the magnetic ordering of the pinwheel ASI array in the presence of external in-plane magnetic fields and how these magnetic orderings as pinning landscapes affect the vortex dynamics in an ASI-superconductor hybrid. Quantitative analysis of micromagnetic simulations help to characterize the correlation between the magnetic charge orderings and both the strength and orientation of the in-plane magnetic field. These simulations are performed with similar physical sample size parameters to provide a sufficiently comparative analysis with experiment. A triple-axis vector magnet is used to apply external fields, both in-plane and out-of-plane, to a patterned pinwheel ASI sample atop a superconducting thin film of molybdenum germanium (MoGe). DC transport measurements are conducted to observe and characterize the vortex dynamics of the MoGe film while the magnetic charge ordering of the ASI is tuned by an in-plane magnetic field. The in-plane magnetic field sweeps are conducted at various strengths/orientations relative to the applied current.
CHAPTER 2
MUMAX3 MICROMAGNETIC SIMULATIONS

MuMax is a GPU-accelerated micromagnetic software used to simulate the pinwheel spin ice ordering under the Landau-Lifshitz micromagnetic formalism [11]. We use MuMax3 to computationally build a three-dimensional (3D) spin ice geometry, stimulate it to external in-plane fields, and observe the magnetization configurations of the system via static images of the charge ordering.

2.1 Initialization Methods

The system initialization methods can be divided into two steps. The first is defining the 3D space that the spin ice will occupy, while the second step is the geometric construction of the pinwheel spin ice configuration. The space’s dimensions are set to $X = 2000\text{nm}$, $Y = 2000\text{nm}$, and $Z = 125\ \text{nm}$ with chosen cell size of $5 \times 5 \times 5\text{nm}$. These parameters are designed such that the system size is comparable to a section of physical ASI sample while also remaining within a regime of reasonable computation time. With the system dimensions and cell size defined, there are 400 cells in both the x and y directions. This results in a total of 160,000 cells per single x-y plane. $Z = 125\text{nm}$ confines the height of the system to be 25 cells tall. With these given system parameters, there are 4 million defined cells available. The confined Z dimension is kept small to drastically reduce computation time, as we are only interested in the field close to the surface of the bar.
Next, the nanobar array is constructed using shape generation functions native to Mumax. A series of these generation steps are displayed in Figure 2.1, with the final pinwheel configuration emphasized in Figure 2.2.

![Figure 2.1: (Left to Right) Mumax3 pinwheel spin ice generation substeps. (I) Single horizontal bar and vertical bar overlap at center of space. (II) Pattern is repeated throughout space. (III) Pattern is generated into two sets; one is shifted and rotated while the other remains stationary. (IV) Bars in the shifted set are separated apart and placed in their final positions. (V) The unmoved set of bars are separated, counter-rotated, and translated into their final positions.](image)

First, a single vertical bar is generated along with a horizontal bar at the center of the space (2.1, I) forming a cross pattern; a half cylinder with equivalent dimensions is added on either side of the bar to better approximate a rounded fabricated sample’s edge (see Figure 3.1) in tandem with an edge-smoothing function native to Mumax. Each bar is repeated at a chosen spatial frequency to define the distance between neighboring bars (2.1, II). Next, a second set of bars is generated. This set is shifted and rotated 45 degrees offset the stationary first set (2.1, III). Then, the second set of bars is translated again to their final positions (2.1, IV). Lastly, the original first set is rotated -45 degrees and shifted into the final positions (2.1, V). This leaves the bars to be locally orthogonal to each adjacent bar, resembling the pinwheel spin ice structure, Figure 2.2.
2.2 Spin Ice Ordering Simulations

For these simulations, the pinwheel spin ice geometry is initialized and the material parameters of permalloy are set for the bars. The material parameters of permalloy and other chosen physical constants are given in Table 2.1.

Table 2.1: Material parameters where $A_{ex}$ is the exchange stiffness, $M_{sat}$ the saturation magnetization, $\gamma$ the gyromagnetic ratio, and $\alpha$ the Landau-Lifshitz damping constant [11]

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<tr>
<th>$A_{ex}$</th>
<th>$M_{sat}$</th>
<th>$\gamma$</th>
<th>$\alpha$</th>
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<td>$1.3 \cdot 10^{-11}$ J/m</td>
<td>$8.6 \cdot 10^5$ A/m</td>
<td>$22.1$ Mrad/T</td>
<td>$0.02$</td>
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The magnetization $\vec{M}$ is initially set to random and followed by a ramping in-plane field at various angles, $\varphi$, with respect to the horizontal. Once the field reaches a particular value, the magnetic charge distribution becomes uniformly ordered throughout the sample. The charge distribution is generated by measuring the out-of-plane component of the stray field of the nanobars via a simulated magnetic-force microscopy (MFM) tip set to 100nm above the bars. The magnetic force felt by the tip of the cantilever is mapped to a field value associated with its spatial cell location in the system.

The applied in-plane field $H$ is swept up from 0-2000G at a fixed in-plane angle $\varphi$. A MFM image is taken at each field step to observe the charge ordering. The ordering can be shown in three stages: initial, intermediate, and ordered, via Figures 2.3-2.5.

The field ramps up and the spins of the ferromagnetic bars begin to align more with the applied field while others interact more strongly with their nearest neighbors. Figure 2.4 illustrates an intermediate ordering state where a majority of the nanobar magnetic moments and associated magnetic charges are ordered.

Figure 2.5 shows the horizontal charge chains observed to uniformly order at $H = 420G$. The bars now all occupy the same state and generate the hill and valley potential landscape. Vertical charge chain ordering is demonstrated at $\varphi = 90^\circ$ and $H = 460G$ in Figure 2.6.

Once the state is fully ordered, further increasing the field saturates the nanobars and thus the charges begin to elongate, Figure 2.7.
Figure 2.3: Initial randomly applied magnetization of the charge distribution at $H = 0$ with the pinwheel array overlaid for reference. Red and blue field values represent positive and negative magnetic charges, measured as into-the-plane and out-of-plane, respectively. The black arrows in every cell represent the magnetic field vector direction given by the charge distribution.
Figure 2.4: Intermediate ordering of the charge distribution at $H = 380\text{G}$. Horizontal charge chains begin to form while other bars strongly interact more locally.
Figure 2.5: Uniform charge ordering of permalloy bars along horizontal direction at $H_{\text{order}} = 420G$. 
Figure 2.6: Uniform charge ordering of permalloy bars along vertical direction ($\varphi = 90^\circ$) at $H_{order} = 460G$. 
Figure 2.7: Saturated horizontal charge chains ($\varphi = 0^\circ$) with forming tails at $H = 2000G$.

There is a relative difference in the ordering field value $H_{\text{order}}$ due to $\varphi$ dependence. Figure 2.8 shows the quasi-symmetric increase in field strength required to order the system as the angle approaches $45^\circ$ and peaks at $H = 780G$. Additional images of charge ordering at $\varphi = 30, 45, 60^\circ$ can be viewed in the appendix.
Figure 2.8: $\varphi$ dependence of in-plane field strength to sufficiently order the magnetic charge distribution.

2.3 Summary

In this study, MuMax3 micromagnetic simulations were performed on a permalloy pin-wheel artificial spin ice structure. The structure was geometrically optimized akin to a fabricated sample on top of a thin film of MoGe. The system is given an initial random magnetization. As an in-plane magnetic field is ramped, the magnetic charge distributions are observed via charge map images at each field step. These sweeps were done at several angles with respect to the horizontal to observe the angle dependence of the ordering field
value $H_{\text{order}}$. It is shown that there exists an $H_{\text{order}}$ that depends strongly on its in-plane orientation. These simulation results on the charge ordering in the ASI will help to understand the vortex dynamics in the ASI-superconductor hybrid studied in this work.
CHAPTER 3

EXPERIMENTAL METHODS

3.1 Sample Fabrication

The sample, originally fabricated by Yang-Yang Lyu, consists of molybdenum-germanium (MoGe) superconducting microbridges patterned into four sections. MoGe is chosen for its weak intrinsic vortex pinning [12]. Sections 1-3 were covered with ASIs of different configurations. Section 3 is the patterned 45° pinwheel array of interest in this study. Section 4 is without the ASI to serve as a reference.

3.1.1 MoGe Superconducting Thin Film

A microbridge film of 100 nm thick MoGe is fabricated on a silicon substrate via photolithography patterning followed by magnetron-sputtering deposition. The superconducting transition temperature $T_c$ of our MoGe film is 7.11K as seen in Figure 3.1 for both the ASI and reference sections. Experiments were conducted below $T_c$ at 6.2K.
Figure 3.1: RT curve for both pinwheel ASI and MoGe reference sections. At 1mA applied current, the critical temperature $T_c$ is 7.11K.
3.1.2 Permalloy Nanobar Array Deposition

The pinwheel ASI arrays are fabricated atop the MoGe film using electron-beam lithography followed by e-beam evaporation of permalloy [1]. Each bar has dimensions of $376 nm(l) \times 120 nm(w) \times 25 nm(h)$. Two sets of nanobars are patterned separately, such that one set is $90^\circ$ offset from the other. Figure 3.2 is a scanning electron microscopy (SEM) image of the pinwheel ASI-MoGe hybrid structure.

![Figure 3.2: Scanning electron microscopy image of patterned permalloy nanobars in pinwheel ASI configuration atop MoGe thin film.](image)

3.2 Superconducting Triple-Axis Magnet

A triple-axis vector magnet offers the ability to apply an external magnetic field in any 3D spatial orientation. It utilizes three superconducting coils placed at right angles to one another [13]. Each corresponds to the x,y, and z directions in Cartesian coordinates. The niobium-titanium (NbTi) wound coils are cooled with liquid helium. The superconducting magnets can be applied in two different operating modes, called “persistent” and “driven.”
On either side of the coil’s endpoints, a heater is installed along the wire. The heater is turned on while the power supply energizes the coil and slowly ramps the current. Once the desired field is obtained, the heaters can be turned off, along with the power supply. The attached piece of wire will cool and return to its superconducting state. This will short circuit the coil and allow a persistent supercurrent to flow for a long time within the coil. This is called the “persistent” mode of operation for the superconducting magnet. Driven mode is where the heater is kept on and the applied current in the wire is maintained at the power supply’s driving current for the desired field. Figures 3.3 and 3.4 illustrate the triple-axis magnet with installed variable-temperature insert (VTI).

Figure 3.3: Triple-axis superconducting vector magnet with installed VTI [14].
3.3 Experimental Approach

The experimental method used can be broken into two parts. The first is an out-of-plane field sweep transport measurement at fixed in-plane field strength to detect the matching fields of the ASI hybrid, while the second part is an in-plane field scan at fixed out-of-plane field strength to observe the dependence of vortex dynamics on strength and angle of the in-plane field, which tune the ASI’s charge ordering. Figure 3.5 depicts the pinweel ASI atop the superconductor thin film with reference to the applied current and external fields as they are used here.
3.3.1 **Out-of-Plane Magnetic Field Sweep Transport Measurement**

The sample is installed in the triple-axis vector magnet such that the current flows along the longitudinal direction (y). It is cooled down and maintained at 6.2K during measurements with an applied current of $I = 1mA$. A standard four-point transport method was used for the longitudinal and Hall resistance measurement of the sample. In our approach, we apply a field $H_z$ along the z direction, perpendicular to the sample’s surface. By sweeping the magnitude of $H_z$, the amount of vortices that form in the sample can be controlled. $H_z$ is swept from the negative to positive direction with each iteration, -1kG to 1kG respectively. The sweeps are performed with an additional constant in-plane field component along the transverse direction ($H_x$) to order the bar’s magnetic charge distribution for pinning. We aim to find the first matching field, $H_0$, where the density of nanobars in the ASI is equivalent to the density of vortices in the MoGe film.

As the field increases from zero, the density of vortices increases; this is observed by the increase in resistance. However, as the field approaches $H_0$, the number of vortices nearly matches that of the nanobars. If the magnetic charges are sufficiently ordered by $H_x$, the
vortices will be pinned and the resistance will decrease. Once the $z$-field reaches $H_z > H_0$, more vortices form and exist in interstitial sites between the bars, which contributes to further increasing the resistance.

### 3.3.2 In-Plane Magnetic Field Rotation

The second part of this experiment involves biasing the external $z$ magnet near the $\frac{1}{2}$, first, and second matching field values ($\frac{H_0}{2}$, $H_0$, $2H_0$) while an in-plane field $H_{xy}$ is applied and ramped. $\varphi$ dependence is explored by rotating the field via the x and y magnets, similar to the approach of the Mumax3 simulations. First, an $H_z$ value is set, which generates the vortices in the MoGe microbridge. Second, $H_{xy}$ is slowly ramped up to 5kG. Once the bar’s charge distribution becomes sufficiently ordered by $H_{xy}$, the vortices will begin to be pinned and the resistance will decrease.

A superconducting coil typically has a residual magnetic field (tens of Gauss). To sufficiently minimize it, an initial degauss procedure was performed using the x-magnet between each $\varphi$ iteration of $H_{xy}$. This involves initially applying the in-plane field to $H_{xy} = 3kG$ at $\varphi = 0^\circ$ and discretely lowering the field in a series of steps. With each field step, the field’s direction is alternated by switching the direction of the current within the coil. After several steps, the applied field is reduced to 0. Meanwhile, this procedure also leads to the demagnetized state of the ASI, i.e., random distribution of the magnetic moments in the nanobars. This process is highlighted in Figure 3.6 where the residual magnetization in the ferromagnet $B_{rm}$ decreases as the applied field gradually decays [15].
Figure 3.6: Demagnetization procedure phase diagram of residual magnetic field hysteresis $B_{rm}$ and external degaussing field $H$ in ferromagnet (blue). Alternating decay of applied $H$ with each step of procedure (black) [15].
CHAPTER 4

RESULTS AND ANALYSIS ON ASI-SUPERCONDUCTOR HYBRID

4.1 Matching Field Sweeps

Features of the first matching field are symmetrically present in Figure 4.1 at differing bias in-plane field strengths $H_x$. There is small variation in $H_0$ for the pinning with each bias field. An offset in each field scan is observed and shown to be minimized at $H_x = 600 G$, so it is chosen to be highlighted in Figure 4.2 with matching field $H_0 = 163 G$.

![Figure 4.1](image)

Figure 4.1: Longitudinal resistance dependence of the perpendicular magnetic field $H_z$ at various in-plane field bias strengths. The minimum offset is indicated by the vertical dashed line matching to the $H_x = 600 G$ (red) sweep.
Figure 4.2: Longitudinal resistance dependence of $H_z$. In-plane field biased at $H_z = 600G$. The matching field value is identified by the black dashed lines (left/right) and used to find the symmetric offset of the field sweep (center). Matching field $H_0 = 163G$.

The offset, $H_{offset} = -12.9G$, is a hysteresis shift in the field scan caused by a residual magnetic field of the permalloy’s ferromagnetic magnetization. Since the sweeps are symmetric, the offset field can be calculated by identifying the local minimum resistance points at their pinning field values and taking their average (4.1):

$$H_{offset} = \frac{H_- + H_+}{2} \quad (4.1)$$

where $H_-$ and $H_+$ are the local minimums values of $H_- = -175.9G$ and $H_+ = 150.1G$ respectively.
For comparative purposes, Figure 4.3 shows no pinning present in the reference channel of only MoGe thin film.

Figure 4.3: Longitudinal resistance dependence of perpendicular field $H_z$ on reference MoGe film with no pinwheel ASI at various in-plane field bias strengths.
4.2 In-Plane Field Dependence

4.2.1 In-Plane Field Induced Vortex Ordering at 1/2 and First Matching Fields

With the offset and matching fields determined, now the external field $H_z$ is fixed near the half ($\frac{H_0}{2}$) and first matching field ($H_0$) in the negative direction at $H_z = -80G$ and $-190G$ respectively. Figure 4.4 shows the vortex pinning dip for both $H_z$ matching field curves at $H_x = 760G$. These lie within the magnetic-charge ordering regime approximated by the Mumax3 simulated spin ice systems discussed earlier (see Figures 2.6 and 2.8), but with much higher strength comparatively.

![Graph showing in-plane $H_x$ sweep at bias $H_z$ fields of -80G (red) and -190G (blue). The vortex pinning is observed via the resistance drop at $H_x = 760G$ for both sweeps. The current applied for each curve is $I = 1mA$ (red) and $I = 1.5mA$ (blue), respectively.]

Figure 4.4: In-plane $H_x$ sweep at bias $H_z$ fields of -80G (red) and -190G (blue). The vortex pinning is observed via the resistance drop at $H_x = 760G$ for both sweeps. The current applied for each curve is $I = 1mA$ (red) and $I = 1.5mA$ (blue), respectively.
For larger $H_x$ field values beyond the dip, the less dissipative state returns due to the applied field being perpendicular to the current. Such a transition reflects the different pinning effectiveness of the charge orderings in Figure 2.6 and Figure 2.7. At $H_x$ smaller than the value at which the dip occurs in Figure 4.4, the magnetic charges form straight chains in the direction of the vortex motion (see Figure 2.6), which allow vortices to move easily in the space between the chains, resulting in less effective pinning to the vortices [1]. On the other hand, the saturated charge ordering in Figure 2.7 leaves no straight paths of low pinning. Thus, vortices need to move in a zig-zag path, hindering the vortex motion and leading to less dissipation, as observed. Eventually, the field becomes strong enough to where magnetoresistance causes loss of the zero-resistive state [12].

4.2.2 Rotational Dependence at Second Matching Field

It follows to observe the angle dependence of the vortex pinning by rotating the in-plane field $H_{xy}$. The sample is installed in the triple-axis magnet such that $\varphi = 0^\circ$ is parallel to the applied current of $I = 1mA$ along the y-direction. The $H_z$ is biased near the second matching field at $H_z = -348G$ such that there will be approximately twice as many vortices in the MoGe film as nanobars in the ASI. Figures 4.5 and 4.6 show a series of $H_{xy}$ ramps where the resistance drops at a lesser field than the previously measured field of 760G (see Figure 4.4).
Figure 4.5: Resistance dependence of $H_{xy}$ at various in-plane angles $\varphi$. Change in vortex pinning is observed on average at $H_{xy} = 0.62kG$. Note I: $\varphi = 10^\circ$ experienced temperature fluctuation yielding a noisier curve. Note II: Sweeps were performed using the magnet’s persistent mode.

The phi-dependent measurements were taken using both magnet modes of the triple-axis vector magnet. The $40^\circ, 70^\circ$, and $80^\circ$ curves in Figure 4.6 were taken using the driven mode while the rest, including the $H_z$ fields previously in part 4.1, were measured in persistent mode. Note that the driven mode curves show lower resistances than those from the persistent mode sweeps. When compared to the persistent mode scans, with the exception of $\varphi = 30^\circ$, the driving mode resistance step is far less pronounced. Regardless of mode chosen, resistance steps are still detected near a small range $0.62 - 0.64kG$.

With this observation, the $\varphi$ dependence of $R \sim H_{xy}$ appears to be very small at the second matching field. The resistance steps vary little with the applied in-plane field and are much less than at $H_z = -80G$ and $H_z = -190G$ (see Figure 4.4). The bias $H_z$ field being
Figure 4.6: Resistance dependence of $H_{xy}$ at various in-plane angles $\varphi$. Vortex pinning observed on average at $H_{xy} = 0.64kG$. Note I: Sweeps were performed using the magnet's driven mode.
set to the second matching value greatly increases the number of vortices. The unpinned interstitial vortices have less interaction with the magnetic charges in the ASI, thus the charge ordering has much less effect on the vortex motion. Further in-plane scans could be performed at the lower $H_z$ field strength such as the first and half matching fields to test the effects of charge ordering on the $\varphi$ dependence of $R \sim H_{xy}$. 
CHAPTER 5
CONCLUSIONS AND FUTURE WORK

Charge ordering of a pinwheel artificial spin ice and its effects on vortex dynamics of a coupled superconducting film were analyzed under a tunable applied in-plane magnetic field. MuMax3 simulations demonstrate the ferromagnetic ordering of the magnetic charge distributions developed by the orientation and magnitude of an in-plane external field. They show there exists a particular field value such that the magnetic charge chains across the sample become uniform before ferromagnetic saturation is reached. Simulations also reveal a quasi-symmetric in-plane angle dependence about $\varphi = 45^\circ$ on the ordering field value. Resistance measurements find the matching fields for a 100nm MoGe superconducting thin film underneath a pinwheel ASI. At fields near the 1/2 and first matching, $H_z = -80G$ and $H_z = -190G$, vortex pinning resistance drops in the $R \sim H_x$ curves are detected with in-plane fields $H_x \approx 760G$. The measurements of $R \sim H_x$ curves at various in-plane field orientations do not show strong changes in the vortex dynamics when the $H_z$ is set near the second matching field, $-348G$. Future work could be performed by scanning the in-plane field at the half and first matching fields. In addition, continued Mumax3 simulations could be performed to modify how the lattice spacing affects the ordering and angle dependence of the field.
REFERENCES


APPENDIX

ADDITIONAL MUMAX3 IMAGES
Additional MuMax3 magnetic charge distribution images not within the body of the thesis are included in this appendix. Images include in-plane field angles of $\varphi = 30, 45, 60^\circ$ respectively.

Figure A.1: Uniform charge ordering of bars at $H_{\text{order}} = 680G$ and $\varphi = 30^\circ$. 
Figure A.2: Uniform charge ordering of bars at $H_{\text{order}} = 780\, G$ and $\varphi = 45^\circ$. Note the higher energy configurations localized in the center of the image (box).
Figure A.3: Uniform charge ordering of bars at $H_{\text{order}} = 660G$ and $\varphi = 60^\circ$. 