

Clocking emergent magnetic monopoles in square artificial spin ice

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(Received 10 July 2025; accepted 25 August 2025; published 16 September 2025)

Dipolar-coupled single-domain nanomagnet lattices, known as artificial spin ice (ASI), exhibit geometric frustration, emergence, reconfigurability, and collective magnetization dynamics, making them a promising platform for magnetic logic devices, reconfigurable magnonics, and unconventional computing. One local feature that could serve as an information carrier in such systems is the emergent magnetic monopole. However, applied global magnetic fields often trigger uncontrolled avalanchelike switching of nanomagnets, leading to detrimental loss of encoded information. Microstate control and stepwise monopole motion remain a key challenge. In this work, we explore the nature of monopole motion in square ASI via so-called astroid clocking protocols and demonstrate controlled stepwise propagation. Using x-ray magnetic circular dichroism and magneto-optical Kerr microscopy imaging, we experimentally verify controlled single-step monopole motion in square ASI. We reveal a rich spectrum of emergent monopole pathways referred to as string, zigzag, and ferromagnetic domain regimes. Our finding shows that these pathways of monopole propagation are determined by the angle and strength of the clocking field. This approach offers a higher level of control of emergent magnetic monopole propagation in ASI, with potential applications in data storage and unconventional computing.

DOI: [10.1103/physrevb.112.094428](https://doi.org/10.1103/physrevb.112.094428)

I. INTRODUCTION

Artificial spin ice (ASI) systems [1–3] are lithographically patterned arrays of single-domain nanomagnets arranged in periodic or aperiodic lattices [4] that exhibit a wide range of exotic properties such as geometrical frustration [5,6], emergent magnetic monopoles [7–9], and collective magnetization dynamics [10,11]. Recently, ASI systems have moved beyond mimicking spin ice materials and have emerged as functional platforms for reconfigurable magneto-magnetics [12], magnetism [13,14], and unconventional computing [15–17].

An interesting feature of these frustrated systems is the presence of topological excitations referred to as emergent magnetic monopoles. Emergent monopole charge nucleation and movement have been examined in ASIs by application of external magnetic fields [3,8,9,18–21], temperature [10,14,22], or both [23]. Typically, global fields are found to give rise to cascadelike switching of nanomagnets [21]. Such avalanches are generally undesirable in applications such as nanomagnetic logic, reconfigurable magnonics, and computation due to less reliability and control [20,24,25]. In order to

realize a nanomagnetic device based on magnetic charge, it is important to ensure avalanche-free and controlled propagation of the monopoles.

As part of this effort, prior research has demonstrated control over nucleation and avalanche propagation of magnetic monopoles by locally modifying the shape anisotropy of nanomagnets within arrays [20] or along their edges [14]. Likewise, the creation of defect sites where the nucleation switching field is lower than the lattice switching field enables control over monopole pathways [24]. Furthermore, modifications in existing lattices [16,26,27] or the design of new lattice structures [28] have been explored to access a broader range of microstates, i.e., different configurations of the macrospins in the ASI ensemble.

Despite these efforts, controlling monopole motion and accessing a large number of microstates using a global field remains a key challenge for the advancement of ASI as a functional computation system. Recently, we demonstrated stepwise domain growth in a pinwheel ASI using global fields [25]. This method exploits the shape and orientation of the nanomagnet switching astroid and is referred to as *astroid clocking*.

In this work, we employ astroid clocking protocols to achieve controlled propagation of emergent monopoles in square ASI. We demonstrate the clocking of unbound monopole-antimonopole charges nucleating at the array edges and propagating in a stepwise manner. We examine the transition from stepwise to avalanchelike reversal of nanomagnets as a function of field strength and clocking angles. Further, we explore the inherent monopole dynamics and uncover rich

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emergent magnetic monopole pathways, which we refer to as string, zigzag, and ferromagnetic regimes. We show that by using simple astroid clocking protocols, a large number of microstates can be accessed. In contrast to previous works, we demonstrate dynamic control of monopole motion without modification of the ASI system itself.

II. METHODS

For this study, ensembles of 30×30 and 80×80 nanomagnets with lateral dimensions $l \times w = 470 \times 170$ nm were patterned using electron-beam lithography (EBL) and lift-off. The lattice spacing a , as defined in Fig. 1, is 600 nm. A permalloy ($\text{Ni}_{80}\text{Fe}_{20}$) thin film of thickness $t = 10$ nm, followed by a 2 nm Al layer to mitigate oxidation, was deposited using electron-beam evaporation. Magnetic imaging of the ASI arrays was performed using magneto-optic Kerr effect (MOKE) microscopy and x-ray magnetic circular dichroism photoemission electron microscopy (XMCD-PEEM). The XMCD-PEEM experiments were performed at the ALBA synchrotron facilities [29] and magnetic contrast was obtained from the circular dichroism measured at the Fe L_3 edge. We performed numerical simulations using FLATSPIN, a large-scale point-dipole ASI simulator [30]. The key model parameters used are $\alpha = 0.002$, $\beta = 4.8$, $\gamma = 3.0$, $b = 0.28$, $c = 1$, $h_k = 0.14$, and $k_{\text{disorder}} = 0.04$.

Square ASI consists of single-domain nanomagnets arranged on two sublattices rotated $+45^\circ$ and -45° with respect to the x axis, as shown in Fig. 1(a). In square ASI, four nanomagnets meet at a vertex. It is useful to describe the vertices in terms of their net magnetization or emergent magnetic charge. The magnetization of a vertex is the sum of the magnetic moments of its neighboring nanomagnets. Similarly, a vertex holds an emergent magnetic charge if there is an imbalance of nanomagnets magnetized into or out from the vertex, as illustrated in Fig. 1(a) by red and green dots. Such charges are referred to as magnetic monopoles [7,10].

Controlled switching of nanomagnets within the ensemble enables the creation and propagation of monopole charges in the ASI. The switching characteristics of the single-domain nanomagnets can be represented by a critical astroid switching curve, shown in Fig. 1(b), similar to the Stoner-Wohlfarth astroid. This switching astroid curve represents the switching threshold as a function of angle.

The stadium-shaped nanomagnets used in this study have a switching curve with twofold rotational symmetry, which can be exploited to selectively address the two sublattices that are rotated 90° with respect to each other in the square ASI. Figure 1(b) shows the switching curve for the stadium-shaped nanomagnets oriented along $\pm 45^\circ$, as well as the clocking fields H_A and H_B which will be used in this study. These are applied along $+\theta$ and $-\theta$, respectively, and will, for convenience, be referred to as the A and B fields.

As dipolar interactions are also present in the ASI, it is possible to go beyond sublattice control even when using global fields. Dipolar interactions from neighboring magnets will promote the switching of certain magnets within one sublattice depending on the local configuration of macrospins. Thus, by carefully selecting the clocking field angle and the field strength, only a subset of nanomagnets within one sublattice will switch.

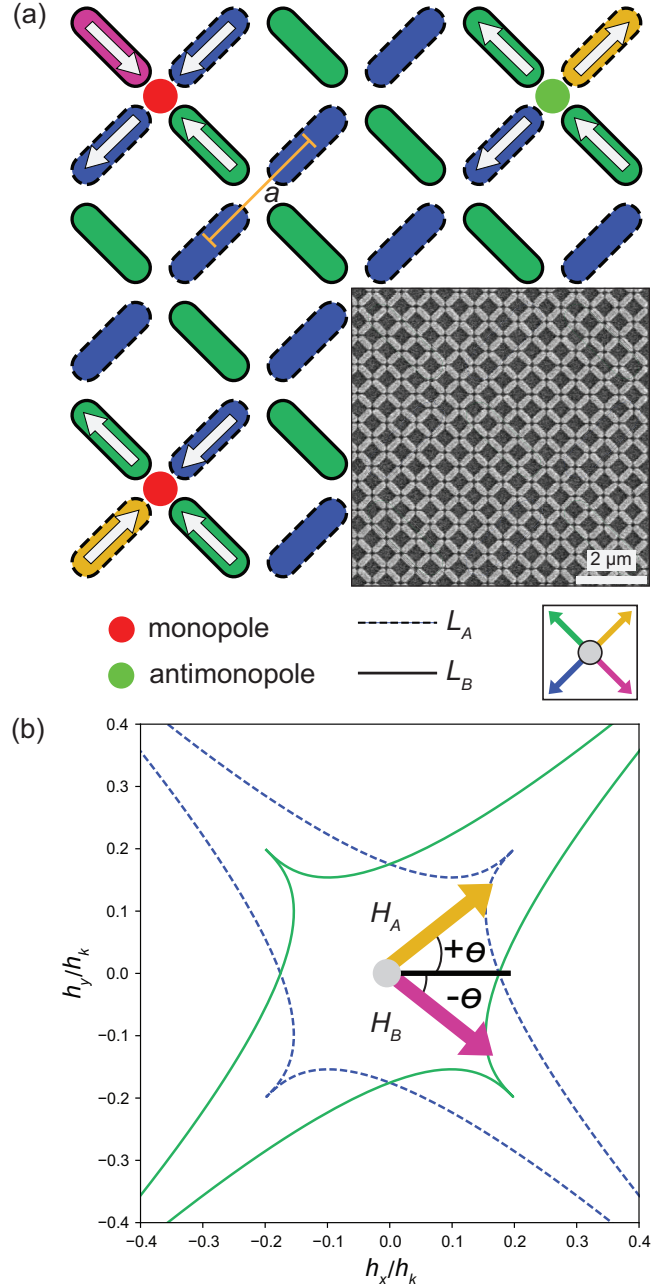


FIG. 1. Astroid clocking in square ASI. (a) Schematic of square ASI with two sublattices, L_A (dashed outline) and L_B (solid outline), of single-domain nanomagnets oriented at $\pm 45^\circ$. Colors correspond to the magnetization direction as indicated by the white arrows. Red and green dots represent emergent magnetic monopole and antimonopole charges, respectively. The distance a indicates the lattice spacing. The inset shows a scanning electron microscopy (SEM) image of a patterned square ASI. (b) Switching astroids of stadium-shaped nanomagnets oriented along the two sublattices, L_A (dashed line) and L_B (solid line). Astroid axes are normalized with respect to the hard-axis switching threshold h_k , where h_x and h_y are the horizontal and the vertical components of the external magnetic field. H_A and H_B are the clocking fields making an angle $\pm\theta$ with respect to the horizontal direction.

Due to fabrication defects in the nanomagnets, there will be a distribution of switching thresholds, which we will refer to

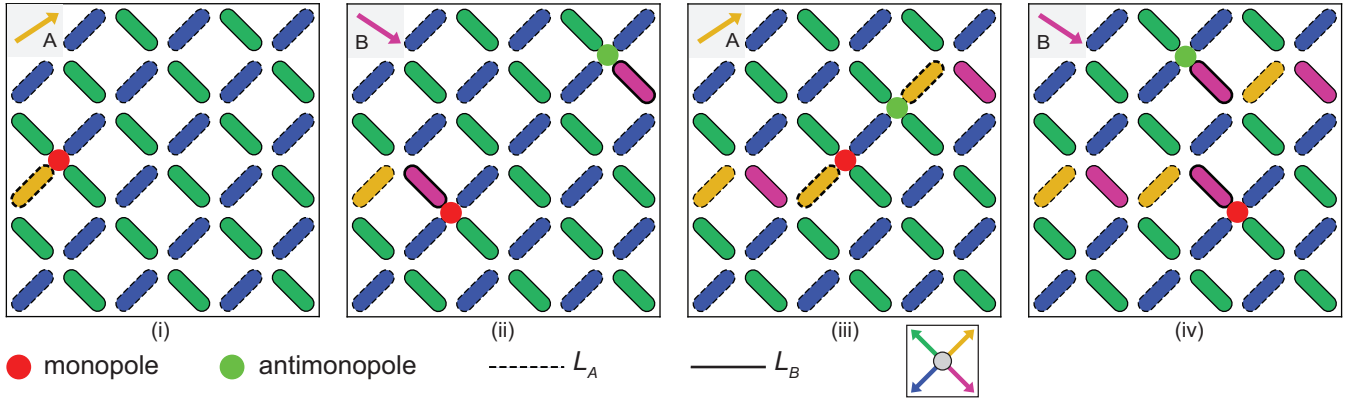


FIG. 2. Astroid clocking of emergent magnetic monopoles. Schematic illustration of astroid clocking in square ASI for four AB clocking steps, where A and B are clocking fields applied to switch magnets within sublattice L_A and L_B , respectively. Clocking field A (B) switches blue (green) magnets to yellow (pink) magnets, creating and propagating monopole (antimonopole) charges. Here, red and green dots represent emergent magnetic monopole and antimonopole charges, respectively. The color wheel shows the magnetization directions of nanomagnets.

as *disorder*. In our physically fabricated samples, we find the variation in switching thresholds to be of the order of 4%. This is modeled through the simulation parameter $k_{\text{disorder}} = 0.04$.

III. ASTROID CLOCKING OF EMERGENT MAGNETIC MONOPOLES

The results obtained for astroid clocking of magnetic monopoles resemble the example shown in Fig. 2. This figure schematically shows how a sequence of A and B clocking fields can be applied to propagate an emergent monopole charge in a polarized square ASI. The initial A field addresses the L_A sublattice and may switch blue magnets into yellow. In the illustrated example, the combination of disorder and dipolar interactions causes one blue magnet to switch first under the external field A, which creates a monopole charge close to the left edge; see Fig. 2(i). Next, we apply the B field, which addresses the L_B sublattice and can switch the next easy-to-switch green magnets to pink. In the example, two easy-to-switch green magnets are flipped: one at the right edge and one neighboring the left monopole. In Fig. 2(ii), we indicate an antimonopole charge in green on the right edge and also the propagating left monopole charge in red, which has moved one step to the right. Subsequent application of A and B fields, or AB clocking for short, will continue to propagate the two monopole charges.

IV. EXPERIMENTAL STEPWISE CONTROL OF MAGNETIC MONOPOLES

In this section, we explore how different regimes of monopole motion can be realized using astroid clocking. First, we demonstrate different pathways through which the magnetization of a polarized square ASI can be reversed using astroid clocking. We then explore how stepwise and controlled monopole motion can be achieved. In subsequent sections, a more detailed investigation of the impact of field strength and clocking angle on the observed regimes is performed. We image array microstates during clocking directly using MOKE microscopy and XMCD-PEEM. The experimental data are corroborated by numerical simulations.

A. Reversal pathways and microstate control

In the following, we investigate the magnetization reversal of an initially polarized square ASI using astroid clocking. During clocking, quenched disorder, e.g., hard-to-switch magnets, will tend to halt magnetization reversal for a fixed clocking field H . In order to continue monopole propagation, we increase H in steps of 0.2 mT after a certain number n of AB clocking steps. For each clocking angle, we chose n such that we typically see magnetization switching for each AB step.

Figure 3(a) shows the magnetization reversal of a square ASI for the clocking angle of $\theta = 10^\circ$. Here, the clocking field strength is increased after every $n = 25$ AB clocking steps and starts at 11 mT and ends at 12.8 mT. We see that switching tends to start from the edges of the array and propagates as horizontal strings, at $t = n$. At the end of these strings, there are emergent monopole charges (as illustrated in Fig. 2). The clocking field strength H is gradually increased and, close to $t = 4n$ clocking steps, we see monopole and antimonopole charges meeting each other. As these annihilate, full strings of flipped magnets extending from one edge to the other are formed.

At this clocking angle, the continued stepwise propagation of the emergent charges results in antiferromagnetic ordering, close to $t = 7n$ clocking steps. However, disorder prevents the ensemble from having a perfectly ordered antiferromagnetic state during magnetization reversal. We refer to the propagation of observed emergent monopole charges at $\theta = 10^\circ$ as the *string regime*.

Next, Fig. 3(b) shows magnetization reversal at a wider clocking angle of $\theta = 45^\circ$. Here, H is increased every $n = 15$ AB clocking steps and ranges from 11 to 13 mT. Similar to the clocking angle $\theta = 10^\circ$, nucleations start at the edges for clocking steps $t = n$ and grow stepwise. However, here the monopole charges more frequently moves *across* different rows as the field is gradually increased; see $t = 8n$. This behavior is qualitatively different from the first case. At $\theta = 45^\circ$, only a few strings propagate at any given time. As a result, the change in ensemble state appears to develop slower than for $\theta = 10^\circ$. This behavior may be attributed to a broader

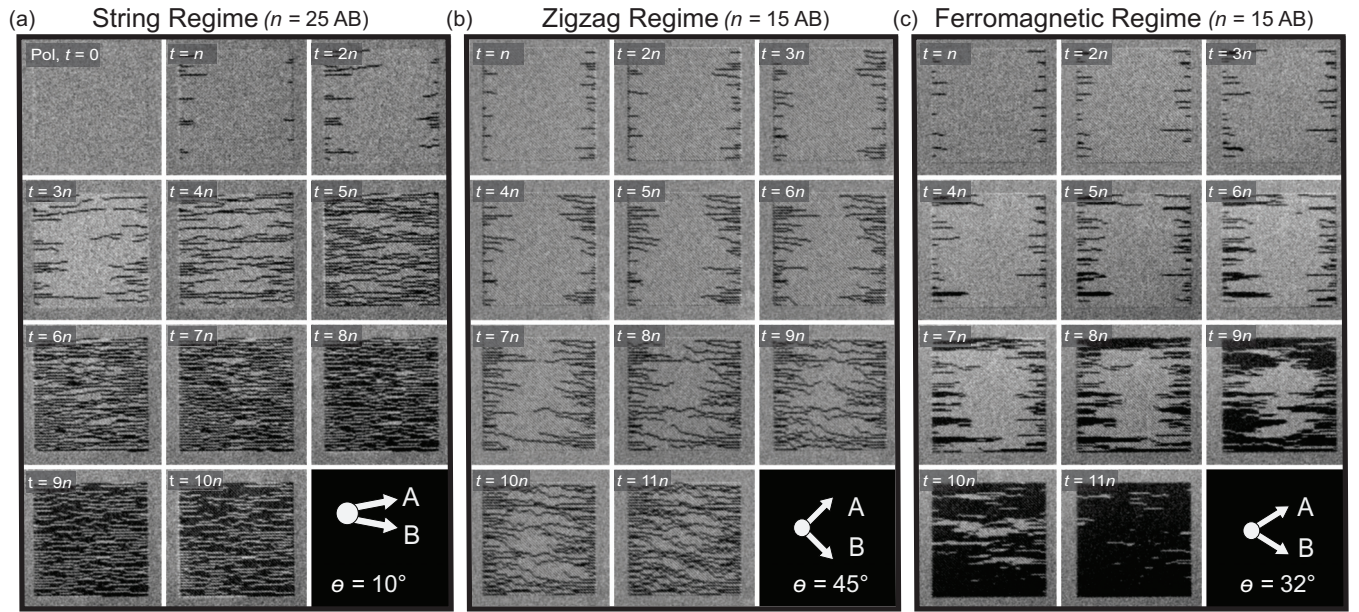


FIG. 3. Controlled magnetization reversal using AB clocking in a 80×80 square ASI ensemble. Three time series of MOKE images showing stepwise magnetization reversal of polarized square ASI. (a) String regime at clocking angle $\theta = 10^\circ$, where $n = 25$ AB clocking steps. (b) Zigzag regime at clocking angle $\theta = 45^\circ$, where $n = 15$ AB clocking steps. (c) Ferromagnetic regime at clocking angle $\theta = 32^\circ$, where $n = 15$ AB clocking steps. After each n step, the magnetic field is increased by 0.2 mT.

distribution of switching thresholds at this angle. We refer to this stepwise propagation of monopoles across different rows at this clocking angle $\theta = 45^\circ$ as the *zigzag regime*.

Finally, we investigate magnetization reversal at an intermediate clocking angle $\theta = 32^\circ$; see Fig. 3(c). The strength of the applied clocking field is increased every $n = 15$ AB clocking steps and ranges from 12 to 14 mT. Similar to the clocking angles $\theta = 10^\circ$ and $\theta = 45^\circ$, nucleations start at the edges for clocking steps $t = n$ and grow stepwise. For a gradual increase in clocking field strength, at $t = 5n$, neighboring monopole strings start intertwining and growing as an extended domain. Surprisingly, we find that continued AB clocking at this angle gives rise to monopole charges moving collectively and forming emergent two-dimensional (2D) ferromagnetic domains; see $t = 8n$. We refer to this collective stepwise monopole motion as the *ferromagnetic regime*.

Our results show that AB clocking using global fields not only enables controlled stepwise reversal of magnetization, but also provides access to numerous microstates in the array (see the Supplemental Material, Video V1 [31]). This is in contrast to the avalanche reversal typically observed for linear field sweeps [21]. Furthermore, AB clocking at various angles promotes distinct regimes of monopole motion that can be accessed at will.

B. Stepwise monopole motion

In this section, we investigate stepwise monopole motion for low clocking fields at angles $\theta = 10^\circ$ and $\theta = 45^\circ$.

Figure 4(a) presents XMCD-PEEM images showing the evolution of monopole states in a square ASI over 10 clocking field steps. The clocking field is applied at an angle of $\theta = 10^\circ$ with a strength of 11 mT, the lowest field strength for which we see switching at this field angle. The ensemble

is initially polarized towards the left (bright contrast in the XMCD images) and then subjected to AB clocking for $t = 10$ field steps starting with a B field for this experiment. Images are captured after each clocking field, i.e., A or B, to observe the dynamic evolution of monopole propagation.

Figure 4(b) provides a color-coded representation of the XMCD-PEEM images in Fig. 4(a), where distinct colors illustrate the temporal evolution of the monopole propagation at clocking angle $\theta = 10^\circ$ for 10 field steps. From Figs. 4(a) and 4(b), we see that the clocking fields nucleate magnets at the edges of the ASI ensemble, which are easy to switch due to fewer nearest neighbors. Subsequent clocking fields gradually propagate monopole charges from the edges towards the center, showing a stepwise monopole motion for this low field at a clocking angle of $\theta = 10^\circ$. It is evident that the emergent monopoles mostly move in a stepwise manner, as the global clocking fields switch single magnets in each step. However, some clocking steps show more than one magnet switching per clocking step due to disorder.

For low field strengths, we observe a behavior that is also qualitatively similar for a clocking angle of $\theta = 45^\circ$ (see the Supplemental Material, Fig. S1(a) [31]). That is high sub-lattice selectivity and stepwise motion of monopole charges along the rows in the square ASI.

To gain a better understanding of this controlled monopole motion along the row, we model the external and dipolar fields acting on the individual nanomagnets using FLATSPIN; see Fig. 4(c). Here, the red and blue arrows represent the dipolar and external magnetic fields, respectively. For visualization, the length of the dipolar field arrow is increased by a factor of 2. Depending on their relative orientation, the dipolar field either reinforces or counteracts the external magnetic field, effectively locking or unlocking certain magnets for switching.

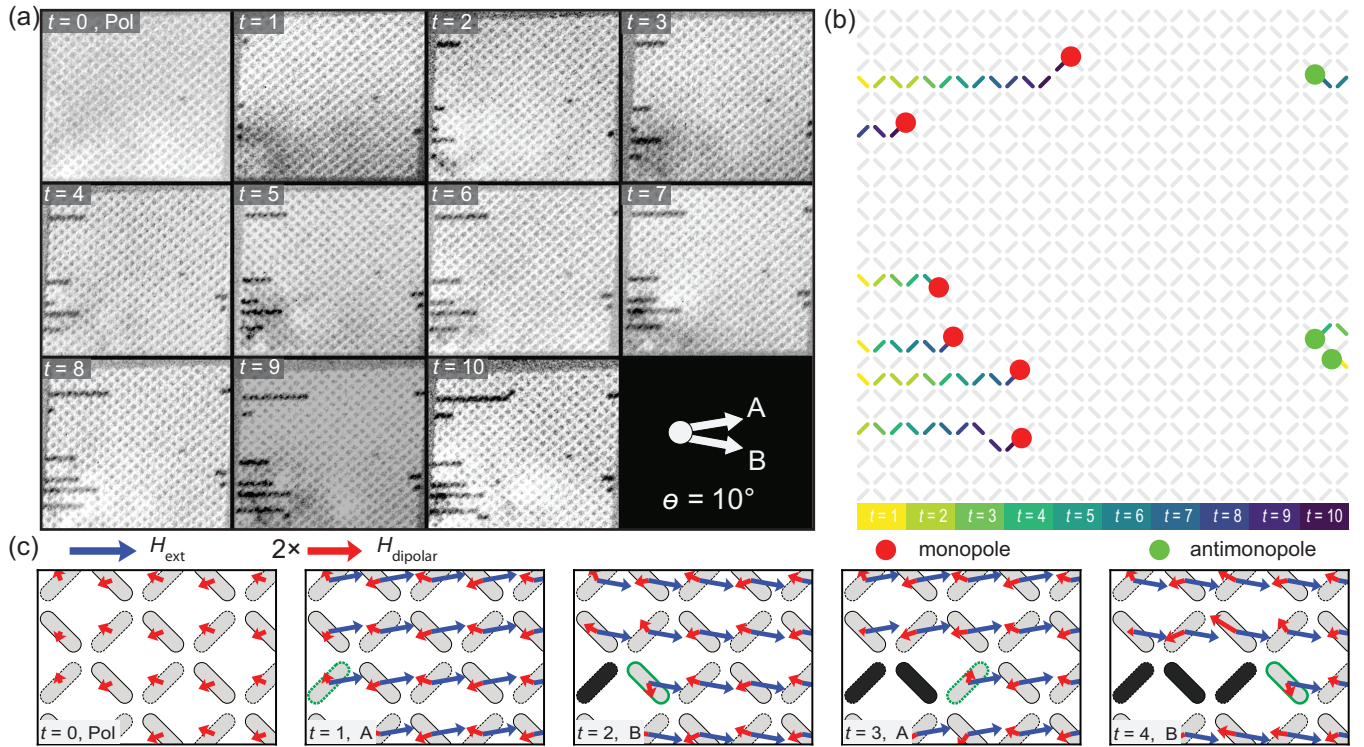


FIG. 4. Experimental realization of stepwise clocking of monopoles in a 30×30 square ASI ensemble for the low field. (a) XMCD-PEEM images of AB clocking at $\theta = 10^\circ$ for time steps $t = 0$ to $t = 10$. The bright and dark contrast in XMCD images shows nanomagnets in the ASI, with their magnetization pointing toward the left and right, respectively. (b) Color-coded image showing the time evolution of monopole motion for clocking angle $\theta = 10^\circ$. Red and green dots show emergent monopole charges. (c) Dipolar fields (red arrows) and external fields (blue arrows), as modeled using FLATSPIN. For visualization, the dipolar field arrow length is increased by a factor of 2. The green outline highlights the next magnet to switch.

In the polarized state $t = 0$, we clearly see how edge magnets are more susceptible to switching compared to interior magnets. When we apply an A field at $\theta = 10^\circ$, the edge magnet in sublattice L_A with the lowest switching field will switch, highlighted by a green outline in Fig. 4(c); see $t = 1$. As we subsequently apply a B field, the switched edge magnet plays a crucial role in modifying the dipolar landscape; see $t = 2$. It locks the closest edge magnets, i.e., the dipolar field opposing the external field in the adjacent top row, while unlocking the nearest-neighbor magnet, i.e., the dipolar field aligning with the external field, along its row highlighted by a green outline. The dipolar interactions thus favor the switching of magnets along the row.

Subsequent AB clocking continues to propagate the monopole charge along the row while simultaneously locking magnets in the adjacent rows; see $t = 3$. This locking and unlocking of nanomagnets due to dipolar interaction aligns well with our experimental results (see, e.g., the Supplemental Material, Video V2 [31]). Thus, for low clocking fields at $\theta = 10^\circ$ and $\theta = 45^\circ$, the sublattice selectivity is high and stepwise control of the monopole motion is achievable.

C. String vs zigzag monopole motion

Next, we investigate monopole motion at higher fields for clocking angles $\theta = 10^\circ$ and $\theta = 45^\circ$. Now, we select the field strengths so that the monopoles typically advance by more than one magnet for each field application.

Figure 5 shows experimental XMCD-PEEM images and their corresponding color-coded illustration for AB clocking at $\theta = 10^\circ$ with a field strength of 12 mT. The XMCD-PEEM images in Fig. 5(a) show monopole states for 10 consecutive AB clocking cycles, while Fig. 5(b) highlights the time evolution of monopole states. For higher fields at this angle, monopoles move in avalanches along horizontal rows consisting of both sublattices L_A and L_B . These horizontal, stringlike avalanches are in contrast to the single-step monopole motion observed for the low field, where we selectively switch only one sublattice at a time.

To better understand the mechanism behind this stringlike monopole motion, we model the dipolar and external fields acting on the individual magnets in FLATSPIN; see Fig. 5(c). Initially, the A field switches an easy-to-switch edge magnet; see $t = 1$ (highlighted by a green outline). The switched magnet now promotes switching along the row. Next, we apply a B field, which triggers avalanche switching of three nanomagnets for this particular simulation.

The intermediate steps shown in the dark-gray boxes show how the change in the dipolar field with each switched magnet unlocks the switching of consecutive magnets, i.e., the dipolar field aligns constructively with the external field. The high external field may also switch the misaligned sublattice, resulting in avalanche switching along the row. The avalanche stops when it encounters a hard-to-switch magnet. Further AB clocking continues to unlock switching along the same row,

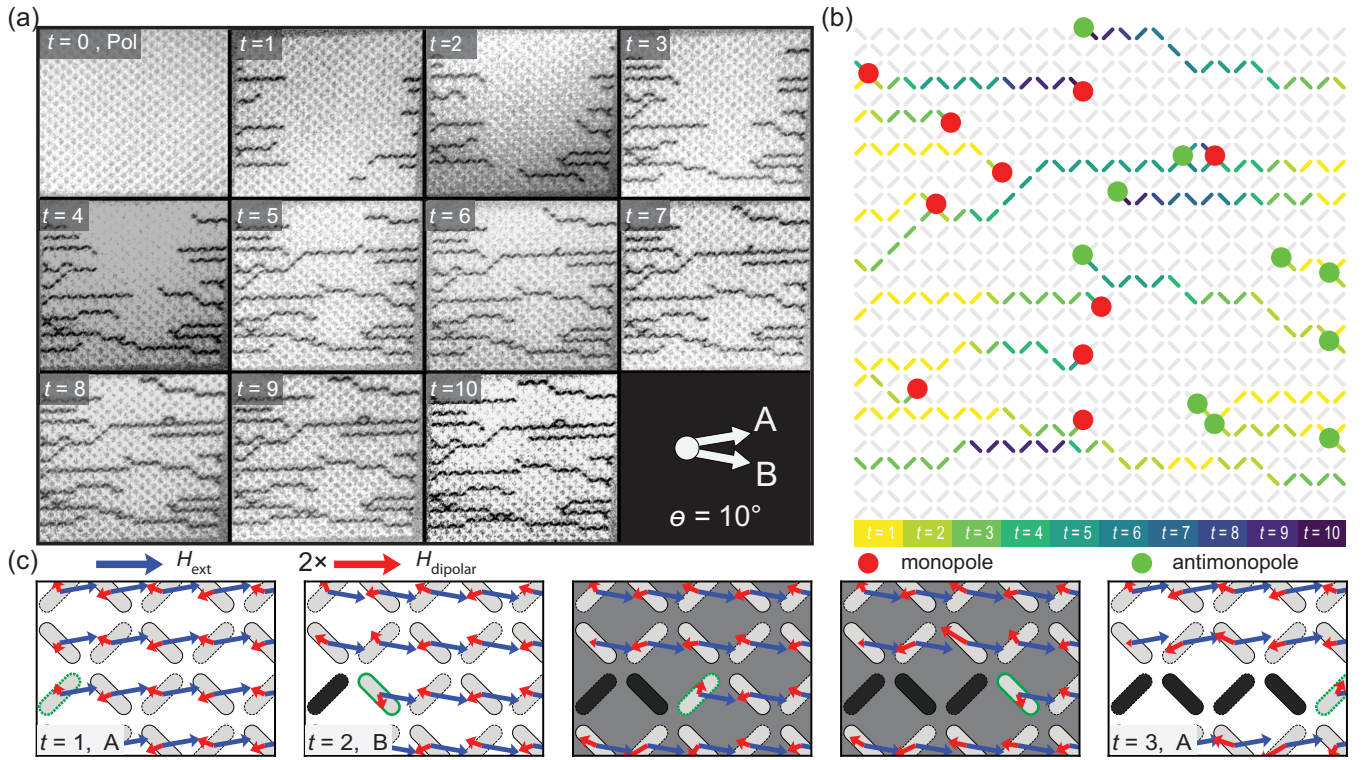


FIG. 5. String motion of monopoles in a 30×30 square ASI. (a) XMCD-PEEM images of AB clocking for the high field at $\theta = 10^\circ$. The bright and dark contrast in XMCD images shows nanomagnets in the ASI, with their magnetization pointing toward the left and right, respectively. (b) Color-coded image showing the time evolution of monopole motion for 10 clocking steps at $\theta = 10^\circ$. Red and green dots show emergent monopole charges. (c) Dipolar fields (red arrows) and external fields (blue arrows), as modeled using FLATSPIN. For visualization, the dipolar field arrow length is increased by a factor of 2. The green outline highlights the next magnet to switch. Dark-gray boxes show intermediate nanomagnet switching steps during an avalanche.

while simultaneously locking magnets in the adjacent rows for the high field at $\theta = 10^\circ$.

Figures 6(a) and 6(b) show experimental XMCD-PEEM images and their corresponding color-coded illustration for AB clocking at $\theta = 45^\circ$ with a field strength of 12.5 mT. For this higher field strength, $\theta = 45^\circ$ also gives rise to avalanchelike monopole motion. However, the direction of the monopole motion is distinctly different from the clocking at $\theta = 10^\circ$. While AB clocking at $\theta = 10^\circ$ favors monopole motion along the horizontal rows, clocking at $\theta = 45^\circ$ favors motion along diagonals containing one sublattice only, i.e., across multiple rows. The diagonal avalanches for $\theta = 45^\circ$ terminate at hard-to-switch magnets and change direction between the A and B fields, giving rise to a zigzaglike motion. This distinct monopole behavior emerges from the interplay between the clocking angle, the field strength, and the dipolar interactions within the square artificial spin ice.

Figure 6(c) shows the dipolar and external fields for clocking at $\theta = 45^\circ$. For the initial A field at $t = 1$, the switching of an edge magnet is followed by the switching of the next diagonal magnet of the same sublattice; see dark-gray box. Next, as the B field is applied, a similar avalanche is triggered along the other sublattice and terminates at a hard-to-switch magnet.

This alternating application of clocking fields A and B continues to promote switching along the respective

sublattices, while simultaneously locking magnets in another sublattice; see $t = 3$. This systematic unlocking and locking of nanomagnets along the sublattices, driven by dipolar interactions and clocking fields at $\theta = 45^\circ$, results in the characteristic zigzag monopole motion observed in experiments at higher field strengths.

D. Ferromagnetic monopole motion

For clocking angles close to $\theta = 32^\circ$, we find the nature of the emergent monopole motion to be a combination of that found in the zigzag and string regimes. For low field strengths at 12.5 mT, the monopole motion is qualitatively similar to that found for $\theta = 10^\circ$ and $\theta = 45^\circ$, i.e., stepwise motion along the rows (see the Supplemental Material, Fig. S1(b) [31]).

As the strength of the clocking field is increased to 13 mT, however, we find that the monopole strings tend to form in pairs. This is in contrast to the 1D-like motion found for $\theta = 10^\circ$ and $\theta = 45^\circ$.

Figure 7(a) shows the color-coded representation of the experimental data obtained at $\theta = 32^\circ$. The observed behavior can be explained by investigating the dipolar fields illustrated in Fig. 7(b). In the first step $t = 1$, the A field switches multiple magnets in sublattice L_A . These switched magnets now act as a branch for subsequent switching. The combination of the subsequent B field and dipolar fields gives rise to the

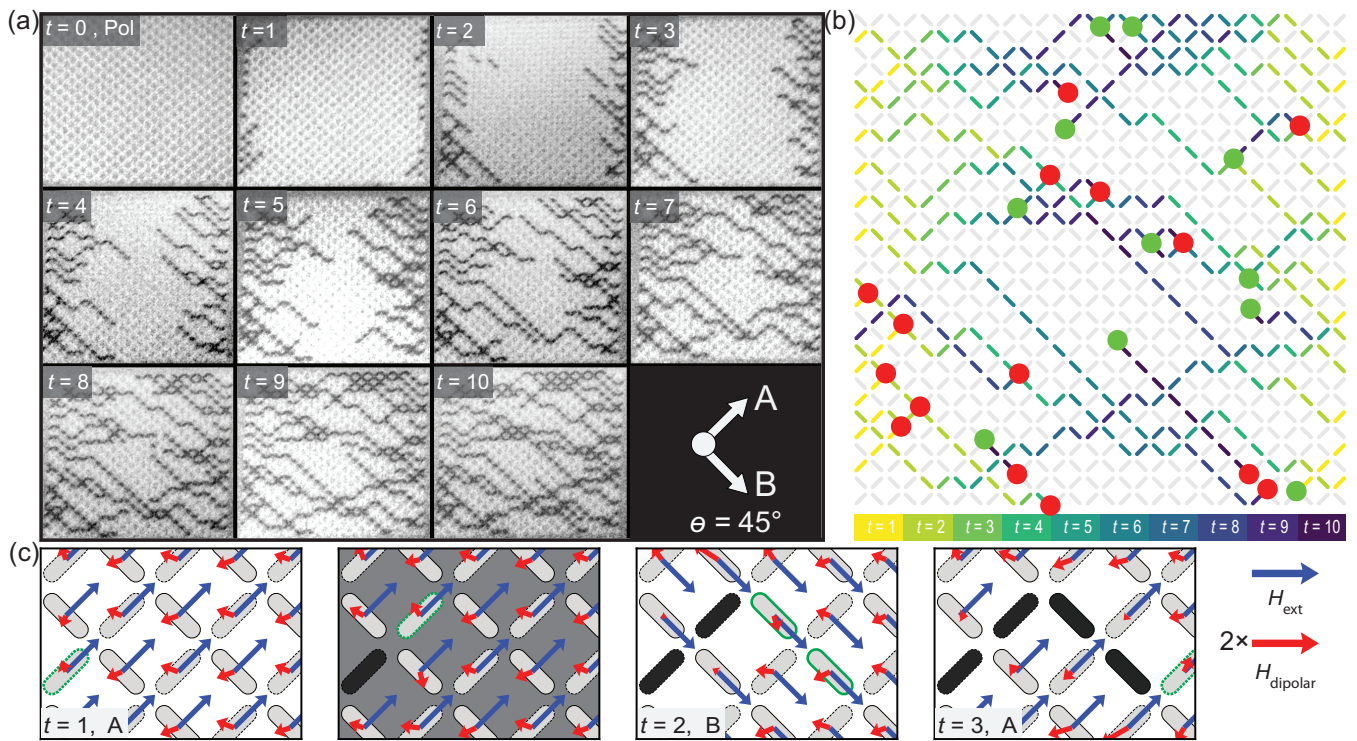


FIG. 6. Zigzag motion of monopoles in a 30×30 square ASI. (a) XMCD-PEEM images of AB clocking for a field strength of 12.5 mT applied at $\theta = 45^\circ$. The bright and dark contrast in the XMCD images shows nanomagnets in the ASI, with their magnetization pointing toward the left and right, respectively. (b) Color-coded image showing the time evolution of monopole motion for 10 clocking steps at $\theta = 45^\circ$. Red and green dots show emergent magnetic charges. (c) Dipolar fields (red arrows) and external fields (blue arrows), as modeled using FLATSPIN, for a clocking angle $\theta = 45^\circ$. For visualization, the dipolar field arrow length is increased by a factor of 2. The green outline highlights the next magnet(s) to switch. The dark-gray box shows an intermediate nanomagnet switching step during a diagonal avalanche.

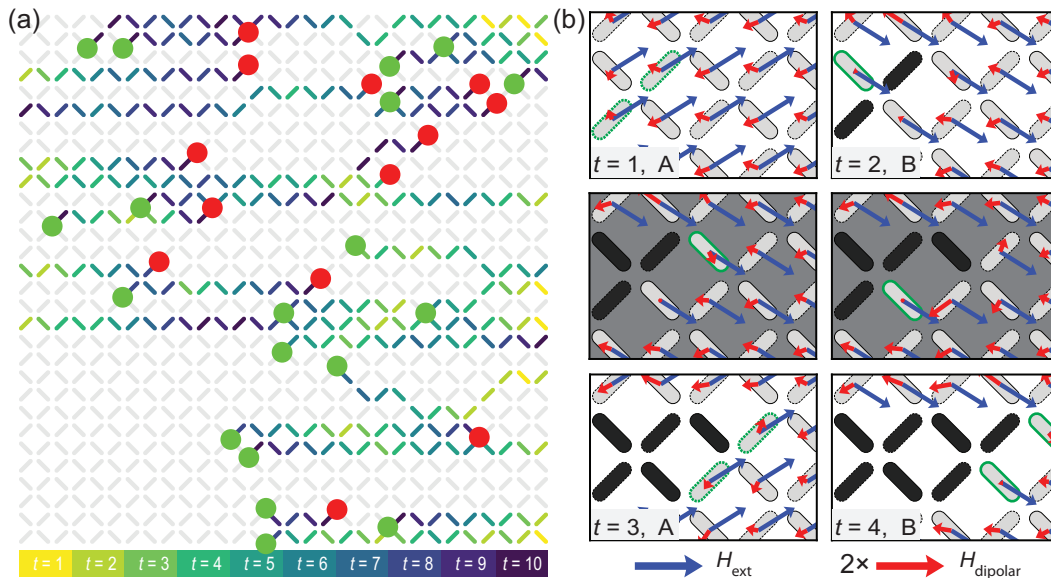


FIG. 7. Bi-string monopole motion at clocking angle $\theta = 32^\circ$. (a) Color-coded image showing the time evolution of monopole motion for $\theta = 32^\circ$ at 13 mT. Red and green dots show magnetic emergent charges. (b) Dipolar fields (red arrows) and external fields (blue arrows), as modeled using FLATSPIN. For visualization, the dipolar field arrow length is increased by a factor of 2. The green outline highlights the next magnet(s) to switch. The dark-gray boxes show consecutive nanomagnet switching for clocking step $t = 2$.

switching of magnets along the horizontal rows, which in turn acts as a new branch for the A field.

The subsequent A and B fields continue to create branches that unlock neighboring magnets. This interplay of row and diagonal switching gives rise to the observed bi-string monopole motion at $\theta = 32^\circ$.

For even higher clocking field strengths, we find the branching to be more pronounced, and extended 2D or ferromagneticlike domains emerge (see the Supplemental Material, Fig. S2 [31]). These monopole dynamics at an intermediate clocking angle are in contrast to the previously reported 1D monopole strings typically found in kagome and square ASI [9,10,20].

V. CONCLUSION

In conclusion, we have demonstrated controlled and stepwise motion of magnetic monopole charges in a square ASI using astroid clocking with global fields. In particular, we show how the rich spectrum of emergent monopole dynamics is controlled in the experiment by the clocking field angle. Moreover, by adjusting the clocking field strength, we can control the magnetic configuration down to a single ASI element level. The observed dynamics range between string-like propagation along the rows, characteristic zigzag motion across rows, and collective motion giving rise to extended 2D domains.

We show how stepwise magnetization reversal using astroid clocking gives access to a large number of microstates, in contrast to the limited number of states which are accessible when using linear field sweeps.

Our approach for controlled monopole propagation in this work can readily be extended to other ASI geometries, paving the way for new clocking protocols that could uncover novel emergent phenomena. Furthermore, we believe that the dynamic control of monopole propagation pathways demonstrated in this work, as well as access to a vast number of microstates, could promote the realization of ASI devices for reconfigurable magnonics, magnetricity, and neuromorphic computing.

ACKNOWLEDGMENTS

These experiments were performed at beamline BL24-CIRCE at ALBA synchrotron with the collaboration of ALBA staff. The Research Council of Norway is acknowledged for support to the Norwegian Micro- and Nanofabrication Facility, NorFab, Project No. 295864. The samples were fabricated at NTNU NanoLab. This work was funded by the Norwegian Research Council through TEKNOKONVERGENS project SPINTER (Grant No. 331821) and by the European Union's Horizon 2020 Programme FET-Open SpinENGINE (Grant No. 861618).

DATA AVAILABILITY

The data that support the findings of this article are openly available [32].

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