Creation and annihilation of topological meron pairs in in-plane magnetized films

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Merons which are topologically equivalent to one-half of skyrmions can exist only in pairs or groups in two-dimensional (2D) ferromagnetic (FM) systems. The recent discovery of meron lattice in chiral magnet Co8Zn9Mn3 raises the immediate challenging question that whether a single meron pair, which is the most fundamental topological structure in any 2D meron systems, can be created and stabilized in a continuous FM film? Utilizing winding number conservation, we develop a new method to create and stabilize a single pair of merons in a continuous Py film by local vortex imprinting from a Co disk. By observing the created meron pair directly within a magnetic field, we determine its topological structure unambiguously and explore the topological effect in its creation and annihilation processes. Our work opens a pathway towards developing and controlling topological structures in general magnetic systems without the restriction of perpendicular anisotropy and Dzyaloshinskii–Moriya interaction.
Topological magnetization rotation and skyrmion formation.

The topology of a material can be described by topological invariants such as the Chern number, which is a topological charge that characterizes the topology of the magnetic state. In the case of a magnetic skyrmion, the Chern number is an integer, indicating that the skyrmion is a stable topological defect.

The formation of skyrmions can be achieved by applying a magnetic field or by tuning the magnetic interactions in the material. Skyrmions can be stable over a wide range of magnetic field strengths and material parameters, making them promising candidates for applications in spintronics.

Experimental observation of skyrmions.

Skyrmions have been observed in a variety of magnetic materials, including iron-based alloys, rare earth metals, and chiral magnets. The observation of skyrmions typically involves the use of magnetic imaging techniques such as spin-polarized scanning tunneling microscopy (SP-STM) and Lorentz transmission electron microscopy (LTEM).

Skyrmions can be manipulated using magnetic fields, electric fields, and optical excitations. The manipulation of skyrmions has potential applications in information storage and processing, as well as magnetic memory devices.

Skyrmions and spintronics.

Skyrmions can be used to store and process information in spintronic devices. The topological nature of skyrmions allows for robust and efficient manipulation of magnetic information, making them a promising candidate for next-generation memory and computing technologies.
saturation field $H_s$ increased to above 150 Oe, indicating the effect of the Co disks.

To experimentally confirm the methodology of the vortex imprinting, one needs to measure the magnetization profiles of the Co disk and the Py film separately. For this purpose, we used MTXM that enables element-resolved magnetic imaging (e.g., imaging Co and Py spin structures separately), by tuning the X-ray photon energy to the 2p core-level absorption energy of the corresponding element. The MTXM spatial resolution could reach 25 nm by the state-of-the-art X-ray optics of the so-called Fresnel zone plates (Supplementary Fig. 1). The magnetic contrast comes from the X-ray magnetic circular dichroism (XMCD) mechanism: the absorption of a circularly polarized X-ray by a FM sample depends on the angle between the magnetization direction of the sample and the photon spin direction of the X-ray. At a fixed incident angle of a circular polarized X-ray beam, different magnetization directions of a magnetic domain then give rise to different contrasts (dark/grey/bright) of the MTXM image.

We first mounted the sample with the in-plane geometry to verified vortex imprinting. In this geometry, the area having the magnetization pointing to $+x$ ($-x$) gives black (bright) contrast, while that pointing toward $+y$ ($-y$) direction shows grey contrast (Supplementary Fig. 2). Figure 2c, f shows the representative Co and Py domain images taken at the Co (778.0 eV) and Fe (707.5 eV) absorption edges, respectively. As shown in Fig. 2c, the upper (lower) part of the Co disk exhibits a dark (bright) contrast, while the contrast on the left and right parts of the disk changes gradually in between, which are more clearly visible in the corresponding simulated images (Fig. 2d, e). Such a configuration corresponds to a typical vortex structure, where the in-plane magnetization forms a closed loop, around a tiny vortex core. Here the core position is shifted off the center of the disk, in agreement with the simulation result (Fig. 1c). More importantly, the Py beneath the Co disk also exhibits an almost identical magnetic contrast inside the disk region, indicating a vortex state with identical core position (Fig. 2f–h), and proving that the Co/Py magnetic coupling has imprinted the vortex state from the Co disk into the Py continuous film.

The antivortex accompanied with the vortex is expected to be confined to a very small region in the Py film outside the disk area (Fig. 1c), making it difficult to be observed in in-plane magnetic images (Fig. 2f). Noticing that the out-of-plane core magnetization of a vortex or an antivortex has the greatest magnetic contrast relative to the surrounding magnetization, and that topology can only be determined by information of the core polarity [Eq. (2)], we imaged the vortex and antivortex cores by taking out-of-plane magnetic contrast ($z$-component;
Supplementary Fig. 2). In this mounting geometry, dark (bright) contrast corresponds to \(z\)-component of magnetization orienting up (down) and grey contrast indicates in-plane magnetization. To achieve all possible states, we repeated the cycles of saturating the sample with an external field of \(H = -430\) Oe followed by a flipping of the surrounding Py magnetization, with a field of \(H = +35\) Oe. The \(H = -430\) Oe field saturates both the Py disk area and the surrounding area magnetizations to the \(-x\) direction, while the subsequent \(H = +35\) Oe field is greater than the Py coercivity to switch the surrounding Py magnetization from \(-\) to \(+x\) direction, but less than the saturation field of the vortex. We expected such a process would produce sufficient randomness to get all possible types of meron pairs. Figure 3a–h depicts the obtained images. As shown in the images, after each cycle, most parts of the Py film show grey contrast, corresponding to in-plane magnetization. On top of this in-plane background, we always observed two small dots (dark or bright; \(~100\) nm diameter) close to either the upper or lower edge of the disk region. These dots correspond to the meron cores, which have an out-of-plane magnetization. The dot inside the disk region corresponds to the vortex core, and the dot just outside the disk region is the antivortex core. The two cores are always bonded together (\(~300\) nm distance) and located near the edge of the disk to have the majority of the vortex in-plane magnetization being parallel to the surrounding in-plane magnetization, as predicted above in Fig. 1c. The polarities of the vortex and antivortex cores appear randomly, i.e., all four possible up/down combinations of the two core polarities were observed after each cycle with almost equal probabilities. According to Eq. (2), we identified the observed four configurations to either bimerons for antiparallel core polarities (\(N = \pm 1\); Fig. 3a, b) or meron–antimeron pairs for parallel core polarities (\(N = 0\); Fig. 3c, d). Therefore, we conclude that meron pairs of different topologies are stabilized in the continuous Py film.

**Imaging the magnetization process of the meron pairs.** After creating and identifying stable meron pairs, we investigate their magnetization process by direct magnetic imaging as a function of magnetic field in three different regions: (1) from \(H = -H_s\) to \(H < +H_c\); (2) \(H \sim H_c\); and (3) from \(H > +H_c\) to \(H = +H_s\). We first saturated the sample with a negative magnetic field, and then took Py in-plane magnetization images in a sequence of \(H = 8\) Oe, 40 Oe, and 300 Oe to represent the typical end states of these three regions, respectively (Fig. 4a, b, c). We also took the Py out-of-plane magnetization images in a similar but finer sequence after saturation to resolve the meron cores (Fig. 4j). At 8 Oe (\(H < +H_c\); Fig. 4a), the Py in-plane magnetization surrounding the disk region remains in its originally saturated direction (to the
left direction of the image). Inside the disk area, however, the originally single domain state has developed into a vortex state with the core position shifted toward the lower edge of the disk area, as a result of counterclockwise circulation of the in-plane magnetization. As confirmed by a corresponding out-of-plane image (the 15 Oe image of Fig. 4j), there also exists an antivortex core located outside the disk area near the vortex core to form a meron pair. This corresponds to the end state of region (1). At 40 Oe ($+H_c < H < +H_s$; Fig. 4b), the surrounding in-plane Py magnetization has switched to the right direction of the image, resulting in a relocation of the original vortex core from the lower to the top edge of the disk in the image, to match the new direction of the surrounding Py magnetization. During this process, the original antivortex near the lower edge of the disk area has been annihilated accompanied by a simultaneous creation of a new antivortex near the top edge of the disk area, as confirmed by a corresponding out-of-plane image (the 45 Oe image of Fig. 4j). This corresponds to the end state of region (2). As discussed above in Fig. 3, the newly formed meron pair at this state has equal probability to be a bimeron with $N = \pm 1$, or a meron–antimeron pair with $N = 0$ (here for Fig. 4j it chooses to be a bimeron with $N = \pm 1$). In region (3), the distance between the two cores gradually reduces from ~300 nm toward zero with increasing the applied field (the 45–155 Oe images in Fig. 4j), and the meron pair is finally annihilated at the end of region (3) (Fig. 4c and the 175 Oe image of Fig. 4j). The elongated deformation of the meron cores with increasing field (particularly 85–155 Oe images of Fig. 4j) is a characteristic feature observed recently in Py. As shown in Supplementary Note 2 and Supplementary Figure 3, this does not change their topologies which are robust against continuous deformations.

**The topological effects in the magnetization process.** We explored the topological effect in the above mentioned three different regions of the magnetization process.

In the region of $H = -H_s$ to $H < +H_c$, the Py magnetization surrounding the disk region remains unchanged and the disk region (including nearby region) changes from a uniform magnetization to a meron pair near the edge of the disk boundary as the magnetic field changes gradually. We find that the core polarities of the created meron pair are always parallel to each other (e.g., the 15 Oe image of Fig. 4j), either along $+z$ or $-z$ directions. Recalling that parallel polarities of the meron pair correspond to a zero topological number ($N = 0$), our observation indicates that this meron pair creation process retains its initial $N = 0$ topology of the uniform in-plane magnetization.

In the region of $H \sim H_c$, the Py magnetization surrounding the disk region switches its direction abruptly by 180° through

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**Fig. 3 Direct observation of the out-of-plane cores of the meron pairs.**

- **a–d** Typical out-of-plane magnetic contrast images at 35 Oe.
- **e–h** Corresponding zoomed in images around the cores of the meron pairs. “V” and “A” denote the vortex core and antivortex core, respectively.
- **i–l** Corresponding schematic views of the magnetization profiles of the meron pairs. All four combinations of the core polarities are observed. The two cores are always bonded together and locate near either the top or bottom edge of the disk (the choice depends on the in-plane circulation direction of the vortex).
Fig. 4 Magnetization process of a meron pair in the Py film. a–i In-plane magnetic contrast at three different states of $H > H_c$ (a, d, g), $+H_c < H < +H_s$ (b, e, h), and $H > H_s$ (c, f, i) in the magnetization process. a, b, c The experimental results. The white arrows indicate the direction of surrounding Py magnetization. d, e, f Corresponding magnetization profiles obtained by simulation. g, h, i Corresponding thickness averaged x-component of the simulated magnetization profile in the Py film. j, k, l Out-of-plane magnetic contrast during the magnetization process. At the end of region (1) (e.g., the 15 Oe image in the figures), a meron pair is nucleated at the bottom edge of the disk area; after passing region (2) (e.g., the 45 Oe image in the figures), a new pair forms at the top edge; further increasing the magnetic field makes the distance between the two cores gradually reducing from ~300 nm toward zero (e.g., the 85–155 Oe images in the figures), and finally the meron pair is annihilated at the end of region (3) (e.g., the 175 Oe image in the figures). J The experimental images, where the yellow arrows in the first two images indicate the core position of vortices and antivortices; k thickness averaged z-component of the magnetization in the Py film in a simulation with the same field sequence; l zoomed in view of the magnetization profile close to the meron pairs at the bottom surface of Py from simulations, where the in-plane magnetization profile is plotted by arrows and the out-of-plane component of the magnetization is represented by the colors.

In the region from $H > H_c$ to $H = +H_s$, the Py magnetization surrounding the disk remains unchanged with the meron pair being annihilated by the magnetic field. Since we could have meron pairs with either parallel or antiparallel core polarities from the second region of $H > H_c$, we studied both cases ($|N| = 1$, $N = 0$) at $H = 25$ Oe, 85 Oe, 130 Oe, 155 Oe, 165 Oe, 175 Oe, and 200 Oe in sequence. Figure 5a shows the starting state ($H = 25$ Oe) of a bimeron ($N = -1$). With increasing the magnetic field, the vortex core moves toward the antivortex core and the bimeron is annihilated above 175 Oe. For a starting state ($H = 25$ Oe) of a meron–antimeron pair ($N = 0$; Fig. 5c), we also observed that the vortex core moves toward the antivortex core with increasing field but the meron–antimeron pair is annihilated at 165 Oe, which is smaller than the 175 Oe for the bimeron case ($N = -1$). Considering that the final state has the topological number of $N = 0$, the higher annihilation field of bimeron ($N = -1$) in Fig. 5a than that of meron–antimeron pair ($N = 0$) in Fig. 5c suggests that topology may have played a role in the meron pair annihilation process due to an additional topological barrier (Supplementary Note 5 and Supplementary Fig. 6). Since the small 10 Oe field difference could be easily overwhelmed by other effects, we further performed micromagnetic simulations and found that the topological effect in the meron annihilation process could be enhanced by changing the sample geometry (Supplementary Note 4 and Supplementary Fig. 5).

Our above result suggests that topological effect may have played a role in the magnetization process where the spin texture is deformed slowly and continuously (region 1 and 3), but not in
the magnetization switching process \((H-H_c)\) where the global spin texture changes abruptly.

**Discussion**

In summary, we develop a new method to create and stabilize a meron pair in a continuous Py film and determine the meron pair’s topology directly during its creation and annihilation processes. Noticing that skyrmion has been the only nontrivial localized topological structure for S² spin space in 2D real space, the isolation of a single meron pair as a topologically equivalent skyrmion will open great opportunity for the study of topological effect in magnetic systems. Our method is quite general for in-plane magnetized systems with little restriction on the material choices (Supplementary Note 3 and Supplementary Fig. 4). The winding number invariance behind our methodology is in analogous to the low-temperature phase of the Berezinskii–Kosterlitz–Thouless (BKT) transition¹, where vortices must pair with antivortices to maintain a global quasi long-range order. Different from the XY systems in the BKT transition, however, in magnetic thin films the existence of vortex/antivortex cores avoids the formation of topological defects, leading to a well-defined topology of the meron pair which is directly observed in this work. The universality of our method for the creation of meron pairs in in-plane magnetized materials removes the restriction of perpendicular magnetization and DMI, thus will extend topological spin structures to a much broader range of materials. In addition, for the same in-plane magnetization background, both \(N=+1\) and \(N=-1\) structures can be realized in our work (Fig. 3), as opposed to conventional skyrmions in non-centrosymmetric perpendicularly magnetized systems, whose \(N\) is generally locked by the sign of DMI and background magnetization direction⁵,¹². This is important to spintronic applications because usually two different states are required to encode one bit of data.

**Methods**

**Sample fabrication.** An 80 nm thick Py film was grown on a 200 nm thick Si₃N₄ membrane using e-beam evaporation in an UHV chamber under a base pressure of 2.6 × 10⁻¹⁰ Torr. After that, a shadow mask was loaded on top of the sample and a layer of 40 nm Co was grown to form disk arrays with 1 µm disk radius and 3 µm center-to-center distance on top of the Py film. After removing the shadow mask, the sample was sputtered by Ar⁺ ion for 10 min to remove any residual contaminations.

**Hysteresis loop measurement.** A longitudinal Magneto-Optic Kerr Effect (MOKE) was used to measure the hysteresis loops of the in-plane magnetization. The laser beam diameter is about 200 µm. Py hysteresis loop was obtained by aiming the MOKE laser beam outside the patterned area. Noticing the finite penetration depth of laser in metals (10 nm), hysteresis loop of Co disk plus surrounding Py was obtained by aiming the MOKE laser beam at the patterned area.

**MTXM measurement.** The MTXM measurement were taken at the beamline 6.1.2 of the Advanced Light Source. For out-of-plane magnetization imaging, the sample was mounted to the normal incidence of the X-rays so that only the out-of-plane component of magnetization contributes to the magnetic contrast. For in-plane magnetization imaging, the sample was tilted with its normal 30° with respect to the X-ray direction so that the projection of the X-ray in the film plane picks up the corresponding magnetization. All the domain images were normalized by the corresponding saturation images to get enhanced magnetic contrast with reduced background noise.

**Micromagnetic simulations.** The open source micromagnetic code mumax³三千 was used for the simulations and the Object Oriented Magnetic Framework (OOMMF)⁵⁴ was used for to plot the magnetization profiles. The material parameters were chosen as: \(M_{\text{Py}} = 860 \text{ emu cm}^{-1}\), \(M_{\text{Co}} = 1400 \text{ emu cm}^{-1}\), \(A_{\text{Py}} = 1.3 \times 10^{-11} \text{ J m}^{-1}\), and \(A_{\text{Co}} = 3.0 \times 10^{-11} \text{ J m}^{-1}\). The size of the simulation area is \(3 \times 3 \mu m\) and the mesh size is \(11.7 \text{ nm} \times 11.7 \text{ nm} \times 3.75 \text{ nm}\). The use of these parameters was verified to give reasonable computation time while obtaining reliable results for the sample investigated in this work. An error threshold of \(1.0 \times 10^{-5}\) (MaxErr = 10⁻⁵) was used as the convergence criteria for magnetization relaxation, which was actually adapted from the built-in Bogacki-Shampine solver of mumax³. The coupling constant between Co and Py was 1.05 erg cm⁻². Periodic boundary conditions were used to reduce the artifacts from edges of simulation areas. The magnetic field was applied at an angle of ~30° with respect to the array direction to simulate the actual mounting direction of the sample (see Fig. 2a), and a 10 nm surface layer from both the Co surface and the Py surface (100 nm further than the disk area) was removed to better reflect the inevitable etching effect from Ar⁺ ion sputtering.

**Data availability**

The data that support the findings of this study are available from the corresponding author upon reasonable request.
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