Supplementary Material

“Direct imaging of a zero-field target skyrmion and its polarity switch in a chiral magnetic nanodisk”

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1. Sample fabrication

B20-type FeGe was synthesized in a cubic anvil-type high-pressure apparatus, as described in detail in Ref. 18 of the main text. Nanodisks for observation using transmission electron microscopy (TEM) were prepared in a focused ion beam (FIB) dual beam scanning electron microscope (SEM) (Helios Nanolab 600i, FEI) equipped with a gas injection system (GIS) and micromanipulator (Omniprobe 200+, Oxford). Details of the sample fabrication procedure are illustrated in Supplementary Video 1.

2. Off-axis electron holography

Off-axis electron holograms were recorded using an accelerating voltage of 300 kV in an FEI Titan 60-300 TEM equipped with an ultra-bright field emission electron gun (XFEG) and two electrostatic biprisms. For magnetic imaging, experiments were carried out in Lorentz mode, with the conventional microscope objective lens switched off. An external magnetic field was applied to the specimen parallel to the incident electron beam direction, i.e., normal to its plane, using the magnetic field of the partially-excited conventional microscope objective lens. The sample temperature was controlled between 380 and 95 K by using a liquid N₂ cooling holder (Gatan model 636).

The voltage applied to the electrostatic biprism was 100 V, resulting in an overlap width of ~1,000 nm, a holographic interference fringe contrast of 23% and a holographic interference spacing of ~2.8 nm at a nominal magnification of 49 k×. At each temperature and each value of the external magnetic field, 30 sample electron holograms and 30 vacuum reference electron holograms with 6 s exposure time were recorded, in order to improve the signal-to-noise ratio. Real space phase and amplitude images were reconstructed from the recorded electron holograms using a standard fast Fourier transform (FFT) algorithm in Holoworks software (Gatan) and using custom-made software written in the Semper image processing language.

The electrostatic contribution to the recorded phase shift was obtained by recording electron holograms at room temperature. Since the Curie temperature of FeGe $T_c$ is ~278 K, there was no magnetic contribution to the phase shift at room temperature (~300 K), as shown in Supplementary Fig. S2a. A typical phase image recorded at $\mu_0H \sim 0$ mT and $T \sim 95$ K contains both electrostatic and magnetic contributions to the phase (Supplementary Fig. S2b). After careful alignment, including translation, rotation and magnification, followed by subtraction of the mean inner potential contribution to the phase recorded at room temperature, the magnetic contribution to the phase could be retrieved (Supplementary Fig. S2c). A magnetic induction map (Supplementary Fig. S2e and 2f) could be obtained from the magnetic phase image by adding contours to it and superimposing colors determined from the first derivatives of the magnetic phase shift.
As stated above, the mean inner potential contribution to the total phase was removed by taking the difference between electron holographic phase images recorded at room temperature and at 95 K. As the diffraction contrast conditions can be slightly different between the two temperatures, small changes in sample tilt by 1~2° was required to avoid strong diffraction effects at some values of applied magnetic field. In some cases, the strongly diffracting regions at the edges of the FeGe disk resulted in phase wrapping errors (Figs S2a, b). After minimization of small misalignment and phase wrapping errors, the magnetic phase image was smoothed slightly (Fig. S2c). Figure S3 shows all of the resulting magnetic phase images for Type 1 and Type 2 target skyrmions. Remaining edge artifacts in some of the phase images were typically 5-10 nm in size and localized. Given the widths of the circular edge twists (~20-30 nm) and the trends visible during magnetic reversal, these artifacts are not thought to affect the fidelity of the results or the validity of the conclusions.

3. Numerical simulations

Micromagnetic simulations were performed using Mumax3 software for the real sample geometry. The nanodisk (diameter \(d = 160\) nm and thickness \(t = 90\) nm) was divided into discretized grids with cell dimensions of \(2.35\) nm \(\times\) \(2.35\) nm \(\times\) \(1.41\) nm. Free boundary conditions were used in all directions. Material parameters for cubic FeGe included a saturation magnetization of \(384\) kA m\(^{-1}\), a Dzyaloshinskii-Moriya interaction of \(1.58\) mJ m\(^{-2}\) and a Heisenberg exchange constant of \(8.78\) pJ m\(^{-1}\). Here, we ignore the contribution of magnetocrystalline anisotropy, which is negligibly small for FeGe when compared with other energy terms [31]. The ground state was obtained by relaxing different possible (spin helix, conical and skyrmion) initial states. By comparing the final energies of these states, we found that the target skyrmion has the lowest energy. Unless otherwise stated, the demagnetization field was included in the calculations.
**FIG. S1:** Schematic diagram and off-axis electron hologram of an FeGe cylindrical nanodisk. **a,** Schematic illustration of the sample attached to a Cu chip for electron holography. The sample was produced using FIB milling in a dual beam system equipped with a gas injection system and an Omniprobe 200+ micromanipulator. The process is shown schematically in Supplementary Video 1. A similar procedure was used to fabricate larger disks for Lorentz TEM. The surrounding layer must be thin enough for the nanodisk to be overlapped with a vacuum reference wave during off-axis electron holography. **b,** Off-axis electron hologram of the FeGe nanodisk. The distance between the vacuum and the sample edge is approximately 120 nm. The [110] high-resolution TEM image inset was recorded after tilting the sample by 13.5°, suggesting that the cylindrical axis of the nanodisk deviates by 13.5° from [110].
Fig. S2: Phase images of the nanodisk. a, Electrostatic (mean inner potential) contribution to the phase recorded at room temperature ($T \sim 300$ K); b, Total phase image (containing both the mean inner potential and the magnetic contribution) recorded at $T \sim 95$ K; c, Magnetic contribution to the phase alone obtained by evaluating the difference between the phase images recorded at room temperature and at 95 K. The image has been smoothed slightly; d, First derivatives of the magnetic phase image in c, used to create the color map shown in e and the magnetic induction map shown in f. The phase contour spacing in f is 0.05 rad.

Fig. S3: Magnetic phase images for a, Type 1 and b, Type 2 structures inside the FeGe nanodisk. The number in each sub-image denotes the applied magnetic field. Some phase unwrapping errors are present at the edges of the disk.
Fig. S4: Diameter of the central skyrmion plotted as a function of applied magnetic field for a Type 1 target skyrmion. Such a non-monotonic evolution indicates that the edge twist is more easily compressed than the central skyrmion.

Fig. S5: Fully relaxed magnetization configurations starting from different initial states. The energy in units of $10^{16}$J is marked at the bottom of each image. The red numbers correspond to the smallest energy in each column. The four initial states are random, helical, conical and skyrmion states. The first row shows relaxed configurations obtained by considering both the three-dimensional magnetic structure and the demagnetization effect. The lowest energy state is the target skyrmion in this
case, but it changes to a disordered helical state in a 2D nanodisk (second row). The third row shows that the lowest energy corresponds to the disordered helical state if the demagnetization field is omitted. As a result, the target skyrmion cannot be formed at equilibrium no matter what initial state is chosen. The color wheel is the same as that in Fig. 2 in the main text. The numbers in the last row give the energies of the states from the first row once the demagnetization field energy is switched off.

**Fig. S6:** Simulated magnetic field dependence of the diameter of the central skyrmion in a Type 1 target skyrmion. The corresponding simulated magnetic configurations are shown.
**Fig. S7:** Magnetic configurations during a target skyrmion polarity switch. Cross-sections in the yz plane are shown. The applied magnetic field is 320 mT. Bloch points are marked by white arrows.  

**a,** The magnetic configuration at $t \sim 0$ ns takes the form of a horn-like tube. White lines mark the boundary of the central skyrmion.  

**b,** The diameter of central skyrmion becomes narrower under time evolution.  

**c and d,** Emergence of two Bloch points at $t \approx 0.149$ ns.  

**e and f,** Two Bloch points propagate from the interior to opposite surfaces of the disk.  

**g,** One of the Bloch points arrives at the upper surface of the nanodisk at $t \approx 0.167$ ns.  

**h,** The other Bloch point arrives at the lower surface of the disk $t \approx 0.204$ ns and the polarity switch of the target skyrmion is complete.
**Fig. S8:** Three-dimensional spin texture around the transition from $\pi$ to $2\pi$ vortices. The color wheel is the same as that in Fig. 2 of the main text.

**Fig. S9:**

**a,** Energies of fully relaxed states calculated as a function of demagnetization field strength. The system was relaxed from four initial states. Different values of saturation magnetization were used to tune the demagnetization energy, while keeping other interactions unchanged. The helical state has lower energy than the target skyrmion when the demagnetization field is smaller than 0.4 times the original value.

**b,** Twist angle $\phi$ of the central skyrmion plotted as a function of height for different values of the demagnetization field that are multiplied by the original value. $\phi$ is the angle of the edge spins in each layer from the tangential direction, as shown in the inset. The twist angle changes from negative to positive from the lower to the upper surface (see Fig. 4c). The spin twists are almost unchanged with demagnetization field.