

RESEARCH ARTICLE

Helicity-Dependent Ellipticity and Interstitial Vortices in Confined Anisotropic Skyrmions

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ABSTRACT

Skyrmions carry robust topology, yet their geometry is highly tunable and can shape interactions, dynamics and functionality. However, how geometric confinement couples to helicity and reshapes the effective energy landscape in intrinsically anisotropic skyrmions remains unexplored. Here we demonstrate that skyrmion ellipticity and its magnetic-field evolution are strongly helicity dependent in 500-nm-wide FeNiPdP nanostripes with anisotropic Dzyaloshinskii–Moriya interaction. Confinement compresses clockwise (CW)-helicity skyrmions toward near-circular profiles, whereas counterclockwise (CCW)-helicity skyrmions elongate along the nanostripe axis, breaking the reciprocal ellipticity relation expected in unconfined geometries. Increasing the perpendicular field further reveals a monotonic circularization of CW skyrmions but a clear nonmonotonic response for CCW skyrmions. Energy analysis shows that confinement reshapes the field-dependent energy landscape and shifts the optimal skyrmion geometry, giving rise to this nonlinear response. The nanostripe constraint also introduces a surface-localized interstitial vortex texture in anisotropic skyrmions that can evolve into a vortex pair, consistent with our micromagnetic simulations. Our results establish helicity-resolved confinement as a route to engineer anisotropic skyrmion morphology and emergent surface textures, enabling helicity-programmable shape and interaction control for multistate skyrmion-based devices.

1 | Introduction

Skyrmions are topologically nontrivial, particle-like textures characterized by integer topological charge [1–5]. They can be realized in diverse physical systems such as liquid crystals [6–9] and magnets [10–12]. In liquid crystals, skyrmions are

shaped by elasticity and often accompanied by topological defects [5, 6], giving rise to rich two- and three-dimensional morphologies [13–15]. Their long-ranged, elasticity-mediated interactions drive self-assembly and can be tuned through confinement and boundary anchoring [14–17]. External magnetic and electric fields can further steer their dynamics, enabling emergent magneto

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-electro-optic responses and offering a programmable route to reconfigurable functionalities through combined geometric and field control [9, 13, 16, 18].

Despite skyrmions being topologically robust, their internal textures remain readily deformable [19–22]. In magnetic materials, skyrmion morphology is highly sensitive to the local energy landscape [23–25]. Disorder and film inhomogeneity deform skyrmions through pinning [26–28], while asymmetric interactions can further bias their profiles when strain anisotropically modulates the Dzyaloshinskii–Moriya interaction (DMI) [19, 29]. When driven by electrical currents, skyrmions display internal deformation dynamics rather than rigid translation, as revealed by time-resolved x-ray microscopy with theoretical modeling in Pt/CoFeB/MgO multilayers [30, 31] and by Lorentz transmission electron microscopy (L-TEM) observations in Co₁₀Zn₁₀ [32]. Such deformations can substantially modify the skyrmion Hall angle, directly reshaping transport and dynamical response and hence underscoring texture geometry as a significant control parameter [30–34].

Geometric confinement provides another route to tune the shape of skyrmion. Boundary constraints can bias an otherwise isotropic skyrmion profile without changing the topological charge, often attributed to a boundary-induced chiral edge twist that competes with the skyrmion's perimeter canting [35, 36]. In dipolar-bubble systems (e.g., Fe₃Sn₂) [37, 38] and isotropic-DMI chiral magnets (e.g., FeGe) [35, 36, 39], confinement mainly imposes a geometric anisotropy that sets the deformation axis and magnitude, with little sensitivity to the skyrmion helicity. In magnets with anisotropic DMI of D_{2d} or S_4 symmetry, by contrast, the direction-dependent DMI breaks rotational symmetry and can stabilize distorted skyrmions whose elongation axis and helicity depend on orientation [40–44]. However, how confinement couples to helicity in such anisotropic skyrmions, and how it reshapes the energy landscape to steer deformation pathways and access distinct skyrmion states, remain insufficiently understood.

Here we report a helicity-resolved confinement response in anisotropic-DMI skyrmions hosted by 500-nm-wide Fe_{2.39}Ni_{1.05}Pd_{0.11}P (FeNiPdP) nanostripes. By combining L-TEM observations with micromagnetic simulations, we link the helicity-dependent ellipticity to a confinement-shaped energy landscape under magnetic field. We further observe a confinement-enabled, surface-localized interstitial vortex texture, consistent with our micromagnetic modeling. These findings establish geometric confinement as a practical route to engineer skyrmion morphology and surface textures, enabling helicity-programmable and multistate skyrmion spintronic devices.

2 | Results and Discussion

2.1 | Interplay of Anisotropic DMI and Confinement in Shaping Skyrmion Geometry

We first discuss the general principle of skyrmion geometry in magnets with different DMI vectors and anisotropies (Figure 1a–i). In chiral magnets with isotropic DMI, such as MnSi and FeGe [2, 10, 35], skyrmions typically exhibit a circularly symmetric shape with a fixed helicity (Figure 1a,b). By contrast,

in D_{2d} or S_4 magnets the anisotropic DMI takes the sign-reversing form $D \mathbf{m} \cdot (\hat{x} \times \partial_x \mathbf{m} - \hat{y} \times \partial_y \mathbf{m})$ (Figure 1c) [40–42], where D is the DMI strength and $\mathbf{m}$ is the unit magnetization, thereby stabilizing elliptically distorted skyrmions with two helicity states, clockwise (CW) and counterclockwise (CCW) (Figure 1d,e). Introducing an in-plane uniaxial magnetic anisotropy (Figure 1f), which can arise from geometric confinement in nanostripes, drives coaxial deformations. It therefore provides a route to selectively tune skyrmion ellipticity and enhance the ellipticity contrast between CW and CCW skyrmions (Figure 1g,h), as revealed by our simulations (Figure 1i; see details in Section 4). In an unconfined geometry, CW and CCW skyrmions deform symmetrically with orthogonal elongation axes, giving reciprocal ellipticities, $\rho_{CCW} = 1/\rho_{CW}$ (left panel in Figure 1i). Here $\rho = \lambda_x/\lambda_y$, where λ_x and λ_y denote the skyrmion boundary dimensions along the x and y directions of the nanostripe, respectively. Under nanostripe confinement, this reciprocity is broken, and the deformation becomes asymmetric, indicating that the confinement-induced uniaxial anisotropy modulates skyrmion geometry in a helicity-selective manner, yielding $\rho_{CCW} > 1/\rho_{CW}$ for the present nanostripe orientation (right panel in Figure 1i). Layer-resolved simulations further reveal a depth-dependent spin texture, evolving from Bloch-type in the central region to Néel-type toward the two surfaces with opposite radial senses (Figure S1). The approximate cancellation of the surface Néel components gives the thickness-integrated texture an overall Bloch-type character, consistent with the skyrmion configurations shown in Figure 1. The apparent CW/CCW sense depends on the viewing direction, whereas the intrinsic helicity and its coupling to skyrmion shape are defined in the fixed sample coordinate system.

To investigate the helicity-dependent confinement control of anisotropic skyrmion morphology, we fabricated 500-nm-wide FeNiPdP nanostripes aligned along the [110] and $\bar{[110]}$ crystal axes of the S_4 symmetric crystal (Figure 1j; Figures S2 and S3), further supported by simulations for the $\bar{[110]}$ direction (Figure S4). Consistent with this geometry, L-TEM imaging at room temperature shows a helical state with wave-vector components both along and transverse to the confined edges (Figure 1k), revealing anisotropic DMI vectors lie parallel and perpendicular to the nanostripe edges (Figure S5). By tilting the sample while sweeping the magnetic field (see Figure S6), we generate a skyrmion chain with CW and CCW helicities at $B = 295$ mT (Figure 1l,m). The relative population of the two helicity states can be tuned by the in-plane magnetic-field component during the generation process [40, 41], in contrast to circular skyrmions, where skyrmion degeneracy is typically lifted by asymmetric sample geometry [45, 46] or local DMI [47]. The skyrmions with opposite helicities exhibit distinctly different ellipticities under the combined influence of anisotropic DMI (Figure S5) and confinement-induced shape anisotropy: CCW skyrmions are strongly elongated along the nanostripe axis (Figure 1n), whereas CW skyrmions are compressed in the transverse direction and become close to circular (Figure 1o), in agreement with micromagnetic simulations (right panel in Figure 1i). Notably, the asymmetric deformation of CW and CCW skyrmions indicates that the nanostripe boundary constraint is helicity-coupled in this anisotropic-DMI system, rather than acting as a helicity-insensitive geometric distortion as in isotropic-DMI systems [35, 36]. Similar helicity-dependent asymmetric morphologies are also observed in nanostripes with different widths

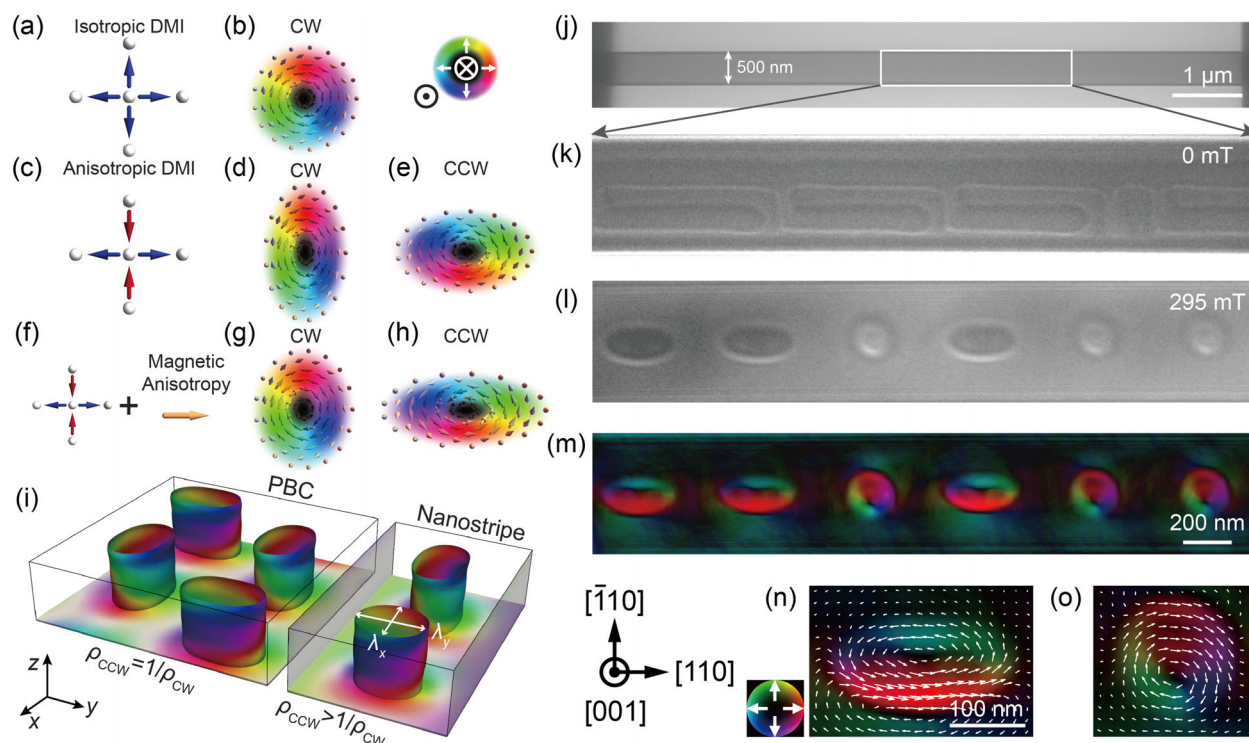


FIGURE 1 | Interplay of anisotropic DMI and confinement in skyrmion geometry. (a–h) Schematics of skyrmions stabilized by different interactions. (a, b) Isotropic DMI stabilizes circular skyrmions with a fixed CW helicity. (c–e) Anisotropic DMI stabilizes elliptical skyrmions, where CW and CCW helicities can coexist with nearly identical shapes. (f–h) Adding magnetic anisotropy induces distinct morphologies: the CW skyrmion circularizes (g), while the CCW skyrmion elongates (h). (i) Simulated skyrmion tubes (isosurface at $m_z = 0.5$). Under periodic boundary condition (PBC), opposite helicities show reciprocal ellipticities $\rho_{\text{CCW}} = 1/\rho_{\text{CW}}$; in confined nanostripes, confinement breaks this reciprocity, yielding $\rho_{\text{CCW}} > 1/\rho_{\text{CW}}$. A color wheel indicating spin orientation is shown near (b). (j) TEM image of a confined FeNiPdP nanostripe with a width of 500 nm. (k, l) Under-focus L-TEM image showing ground-state helical domains at zero field (k) and elliptical skyrmions at 295 mT (l). (m–o) Reconstructed in-plane induction field maps indicate helicity-dependent skyrmion geometry: CCW skyrmions are more elongated (n), whereas CW skyrmions are constrained (o), along the $[110]$ and $[110]$ directions, respectively.

(Figure S7), further supporting the confinement-induced nature of this effect.

2.2 | Helicity-Dependent Skyrmion Ellipticity With Magnetic Field

We further tune the skyrmion ellipticity by varying the external magnetic field B_{ext} (applied perpendicular to the film plane). At a relatively low field of 177 mT, elliptical skyrmions with CW and CCW helicities nucleate near the center of the nanostripe and display comparable ellipticities, with helical domains coexisting along both side edges (Figure 2a). As B_{ext} increases (Figure 2b–f), these helical domains shrink and evolve into CCW-helicity elliptical skyrmions (Figure 2d,e), thereby increasing the spacing between neighboring skyrmions. Skyrmions with different helicities exhibit distinct field-dependent morphological evolution: although both shrink in overall size with increasing B_{ext} , CW skyrmions circularize monotonically, whereas CCW skyrmions become more elongated at intermediate fields (Figure 2a–e). This contrast reflects a confinement-induced in-plane uniaxial anisotropy that biases the deformation by compressing λ_y while extending λ_x . At higher field of 356 mT, the CCW skyrmions appear to slightly re-circularize rather than continuing to elongate (Figure 2f).

We then quantify this helicity-dependent shape evolution by extracting skyrmion contours from L-TEM images using an automated pipeline that combines deep-learning segmentation (SAM2) [48] with OpenCV-based refinement (see Figure S8). From these contours, we quantified the characteristic dimensions λ_x and λ_y of CCW and CW skyrmions as a function of B_{ext} , yielding the field-dependent ellipticities ρ (Figure 2g). The two helicity states exhibit distinct deformation trends. For CW skyrmions, ρ_{CW} increases monotonically with B_{ext} and reaches $\rho_{\text{CW}} \approx 0.9$ at the higher field, indicating a nearly circular profile. In contrast, CCW skyrmions show a nonmonotonic evolution: ρ_{CCW} first increases and then decreases with increasing B_{ext} . This helicity-dependent behavior is absent in unconfined samples, where CW and CCW skyrmions remain nearly identical with increasing field (see Figure S9 and S10). The similar nonmonotonic CCW evolution is observed in a 600-nm-wide nanostripe, although with a weaker response than in the 500-nm-wide nanostripe (see Figure S11). We further performed micromagnetic simulations to verify whether the observed non-linear evolution originates from nanostripe confinement (see details in Section 4). The simulations reproduce the monotonic field evolution of ρ_{CW} and the nonmonotonic response of ρ_{CCW} in confined geometry (Figure 2h), and confirm the robustness of the helicity asymmetry against thickness variations (Figure S12).

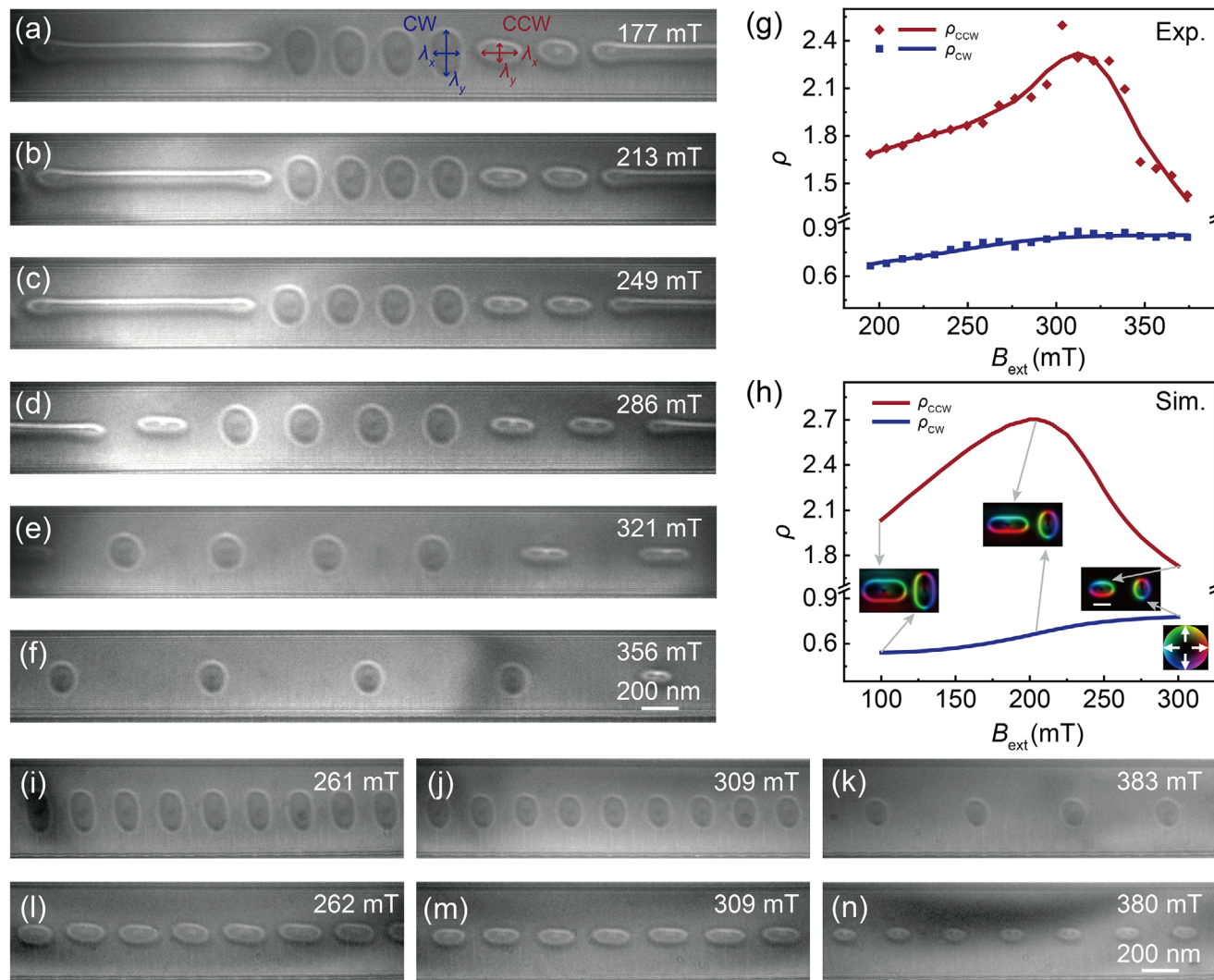


FIGURE 2 | Helicity-dependent skyrmion ellipticity with magnetic field. (a–f) Over-focus L-TEM images showing coexisting CW and CCW skyrmions in a 500-nm-wide nanostripe with increasing out-of-plane magnetic fields. λ_x and λ_y in (a) denote the characteristic size parameters along the x and y directions, respectively. (g) Experimentally measured field dependence of the skyrmion ellipticity, $\rho = \lambda_x/\lambda_y$, for CW and CCW helicities, extracted from (a–f) using an automated image-analysis workflow (see Figure S8). (h) Simulated $\rho(B_{\text{ext}})$, consistent with the experimental results in (g). Insets show representative spin textures at three characteristic fields; scale bar, 200 nm. (i–n) Over-focus L-TEM images of single-helicity skyrmions in a 600-nm-wide nanostripe at different fields: CW skyrmions gradually circularize (i–k), whereas CCW skyrmions exhibit field-enhanced elongation followed by broadening (l–n).

We next isolate the role of helicity by converting the mixed-helicity chain into single-helicity configurations (Figure S6), forming either a pure CW skyrmion chain (Figure 2i–k) or a pure CCW skyrmion chain (Figure 2l–n). Under confinement, L-TEM observations confirm that the field response remains helicity selective in the single-helicity chains: the CW skyrmion chain evolves toward a more circular profile (Figure 2i–k), whereas the CCW chain shows a pronounced elongation at intermediate fields followed by slight broadening at higher fields (Figure 2l–n). These helicity-dependent trends persist regardless of whether the chain starts from a mixed or single-helicity state, indicating that the deformation is governed by the field-dependent confinement landscape rather than by magnetic history or neighboring skyrmion helicity arrangement. Residual edge helical domains may slightly affect the low-field compression of CCW skyrmions, but do not alter the overall helicity-selective trend.

2.3 | Confinement-Shaped Energy Landscape for Helicity-Dependent Ellipticity

To elucidate the different morphology of the CW/CCW skyrmions, we employ a simplified Belavin–Polyakov model [49, 50] (see details in Section 4). The anisotropic DMI contributes $E_{\text{DMI}} = 4\pi D(\lambda_x - \lambda_y)\sin\gamma$, with γ the helicity (in-plane spin rotation), and favors an elliptical distortion with a helicity-locked elongation axis. In the absence of confinement, this yields nearly degenerate elliptical skyrmions of opposite helicities with comparable distortions. Under nanostripe confinement, boundary conditions introduce an effective in-plane anisotropy that breaks the degeneracy and provides an energetic basis for the ellipticity asymmetry observed in Figure 2. To capture the confinement effect, we include an in-plane anisotropy term and compute the anisotropy energy E_{xy} as a function of the ellipticity ρ

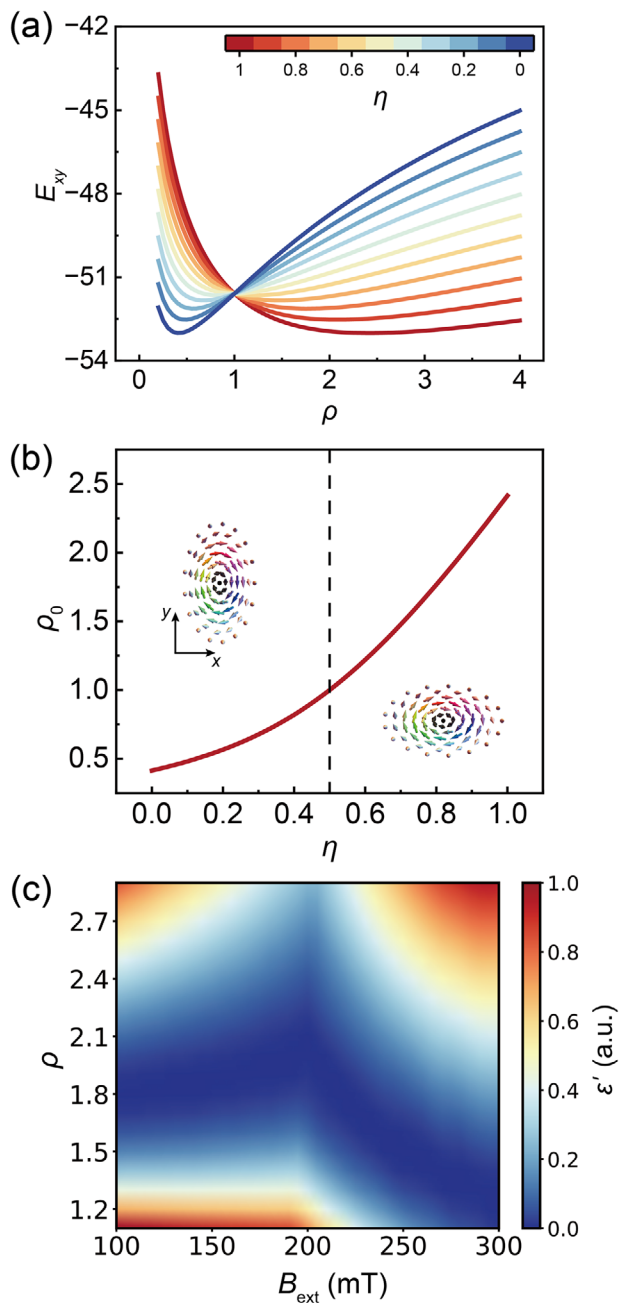


FIGURE 3 | Confinement-shaped energy landscape underlying helicity-dependent ellipticity. (a) In-plane anisotropy energy E_{xy} as a function of ellipticity ρ for different relative anisotropies $\eta = K_x/(K_x + K_y)$, where K_x and K_y are the anisotropy strengths along x and y , respectively. (b) Optimal ellipticity ρ_0 extracted from the minima in (a) plotted versus η . Insets and dashed guides indicate that for $\eta < 0.5$ the y -axis anisotropy dominates, leading to elongation of skyrmions along y ($\rho_0 < 1$), whereas for $\eta > 0.5$ the x -axis anisotropy dominates and elongation switches to x ($\rho_0 > 1$). (c) Heat map of the normalized energy density of CCW skyrmions, defining an effective energy landscape in the ρ - B_{ext} parameter space. $\epsilon' = 0$ marks the energetically favored configuration at each field (optimal ellipticity). With increasing field, the optimal ρ first increases and then decreases, consistent with the experimental and micromagnetic results (Figure 2g,h).

for different $\eta = K_x/(K_x + K_y)$, where K_x and K_y are the anisotropy strengths along x and y , respectively (Figure 3a). For each η , $E_{xy}(\rho)$ exhibits a minimum that defines the optimal ellipticity ρ_0 , and $\rho_0(\eta)$ increases monotonically with η (Figure 3b): the preferred elongation switches from y ($\rho_0 < 1$) to x ($\rho_0 > 1$) direction across $\eta = 0.5$. Accordingly, in our nanostripes confinement selects an in-plane easy axis along the nanostripe direction (x -axis), biases the two helicities unequally, and hence breaks the reciprocity, yielding $\rho_{CCW} > 1/\rho_{CW}$ (Figure 2).

This simplified model captures the basic energetic origin of the CW-CCW ellipticity asymmetry but does not account for the nonlinear evolution of ρ_{CCW} with field, because the demagnetizing energy, which becomes particularly important under nanostripe confinement and varies with magnetic field, is not included. We therefore perform full micromagnetic calculations that include all relevant energy contributions, including the field-dependent dipolar interaction that governs the optimal skyrmion size and deformation under confinement (see details in Section 4). Figure 3c shows a heat map of the normalized energy density ϵ' for CCW skyrmions, defining an effective energy landscape in the ρ - B_{ext} parameter space. The valley of this landscape marks the energetically preferred configuration at each field and follows a nonmonotonic trajectory, with ρ first increasing and then decreasing as B_{ext} rises. The trajectory closely tracks the experimentally measured and simulated evolution of ρ_{CCW} (Figure 2g,h). These results indicate the anomalous field dependence of ρ_{CCW} stems from the confinement-modified energy landscape that is continuously reshaped as B_{ext} increases.

2.4 | Interstitial Surface-Vortex Emergence

Furthermore, in the high-field regime, additional surface magnetic textures emerge as the inter-skyrmion spacing increases. Over-focus and Under-focus L-TEM images acquired at 330 mT show weak, additional dark (Figure 4a) and bright (Figure 4b) magnetic contrasts appearing in the interstitial regions between neighboring skyrmions. Phase map reconstructed from the paired images (Figure 4c), together with the corresponding magnetization textures (Figure 4d), identifies these features as a CW-helicity vortex state. Such interstitial vortex textures have not been reported in dipolar or isotropic-DMI skyrmion nanostripes [51, 52]. Upon increasing the field to 348 mT, the interstitial texture changes from a single-vortex state to a vortex-pair configuration (Figure 4e-h). The L-TEM contrasts and the reconstructed phase/magnetization maps indicate that two vortices share the same helicity. With further field increase, the vortex contrasts gradually weaken and eventually vanish as the system approaches magnetic saturation (see Figure S13). Width-dependent observations show that such ordered interstitial surface vortices are absent in unconfined samples and emerge only under strong lateral confinement in the 500-nm-wide nanostripe (see Figure S7). Their one-to-two evolution with increasing inter-skyrmion spacing resembles the core evolution of elongated skyrmions, where one central vortex-like core develops

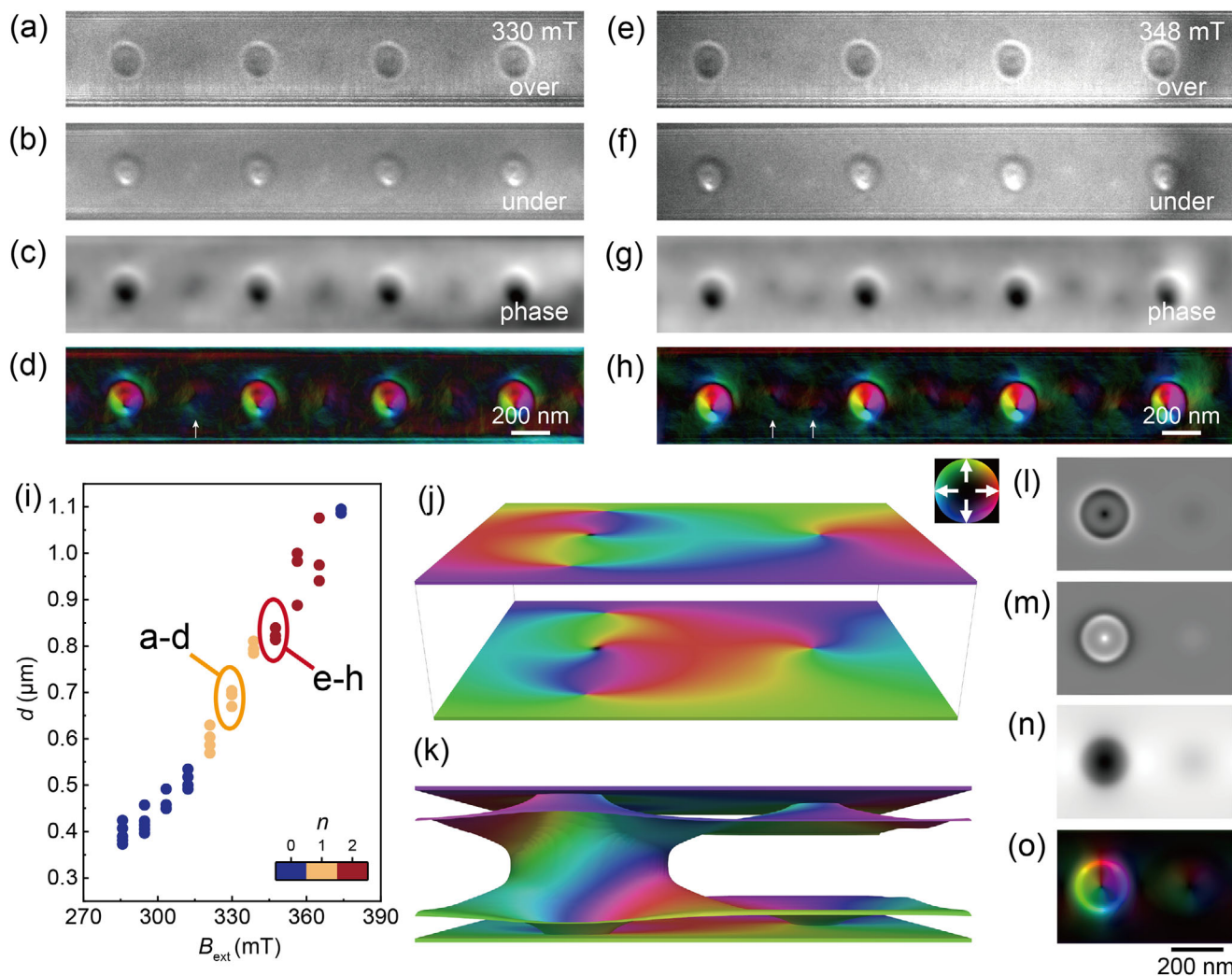


FIGURE 4 | Interstitial surface-vortex emergence in the high-field regime. (a–d) Skyrmion chain and surface-vortex formation at $B = 330$ mT: Over-focus (a) and under-focus (b) L-TEM images, the phase map (c), and the in-plane induction field map (d) identify a single surface vortex between neighboring skyrmions (as indicated by white arrow in (d)). (e–h) At $B = 348$ mT, the corresponding over-/under-focus images (e, f), phase map (g), and induction field map (h) show a pair of surface vortices between neighboring skyrmions (as indicated by white arrows in (h)). (i) Inter-skyrmion spacing d as a function of field B_{ext} , extracted from (a–h) and Figure S13. Point color denotes the number n of surface vortices between adjacent skyrmions. (j, k) Simulated magnetization textures of a skyrmion (left) and a surface vortex (right): top and bottom surface layers (j) show a vertical core for the skyrmion but not for the vortex; the $m_z = 0.95$ isosurface (k) indicates that the skyrmion spans the film thickness, whereas the surface vortex remains confined near the surface. (l–o) Simulated L-TEM contrast and reconstructions for a skyrmion–vortex configuration: Over-focus (l), Under-focus (m), phase map (n), and in-plane induction field map (o), consistent with the experimental results in (a–d).

into two end-localized vortex-like features upon elongation (see Figure S14).

Figure 4i summarizes the skyrmion spacing d and the number of surface vortices n as functions of the external field B_{ext} . As B_{ext} increases, d grows monotonically, accompanied by a clear sequence of interstitial surface states: no vortices are observed at small spacings; a single vortex emerges once d reaches ~ 0.55 μm ; a vortex pair becomes favored for $d \geq 0.8$ μm , approximately; and the vortices are suppressed when d approaches ~ 1.0 μm . These vortices are surface-localized flux-closure textures enabled by confinement-induced redistribution of the demagnetizing field as neighboring skyrmions move apart, which reduces the demagnetizing energy by favoring a single interstitial vortex at smaller d and a vortex-pair configuration at larger d . The vortex

circulation remains uniform across interstitial regions and seems independent of the helicities of adjacent skyrmions. At higher fields, increasing out-of-plane polarization suppresses in-plane circulation, and the vortex disappears near saturation.

The interstitial vortex shows much weaker L-TEM contrast compared with a skyrmion, and is further supported by a consistent 3D picture from micromagnetic simulations (Figure 4j,k). Figure 4j compares the spin textures at the top and bottom surfaces and shows that, unlike a skyrmion which retains a pronounced out-of-plane core on both surfaces, the interstitial vortex remains predominantly in-plane at the surfaces, with a small topological charge ~ 0.1 (Figure S15). The corresponding 3D rendering (Figure 4k) further indicates that the vortex does not form a tube-like texture spanning the full film thickness, implying

a limited through-thickness extent. Using these simulated configurations as input, the calculated L-TEM contrasts, phase maps, and magnetization textures (Figure 4l–o) closely reproduce the experimentally measured contrast patterns.

3 | Conclusion

Geometric confinement provides a practical route to reshape skyrmions, but it often acts as a primarily geometric anisotropy with limited sensitivity to internal texture degrees of freedom. Here we show that anisotropic-DMI FeNiPdP provides a qualitatively different regime: nanostripe confinement produces a helicity-resolved skyrmion geometry and breaks the reciprocal ellipticity expected in an unconfined geometry, indicating that confinement can couple to helicity when the preferred chiral twist is intrinsically direction dependent. The field-dependent evolution of ellipticity is also helicity selective. Experiment and simulation agree that ρ_{CW} evolves smoothly toward isotropy, while ρ_{CCW} varies nonmonotonically: it first increases at intermediate fields and then decreases upon further field increase, implying a field-driven shift of the preferred distortion under confinement. This helicity-selective response reflects a field-dependent, confinement-modified energy balance arising from competing exchange, anisotropic DMI, uniaxial anisotropy, magnetic dipolar, and Zeeman terms, which we quantify using an effective energy landscape $\varepsilon'(\rho, B_{\text{ext}})$. The valley of $\varepsilon'(\rho, B_{\text{ext}})$ defines the optimal shape by tracing the ellipticity $\rho(B_{\text{ext}})$ that minimizes the effective energy at each field. Its nonmonotonic evolution (increase then decrease) closely matches the measured ρ_{CCW} , indicating that the CCW skyrmion continuously adapt their deformation to the field-dependent shift of the energy minimum under confinement. Confinement also reorganizes the interstitial background at high fields, enabling a surface-localized, flux-closure vortex state between neighboring skyrmions as their spacing increases, which can evolve from a single vortex to a vortex-pair configuration upon further field increase. These findings establish geometric confinement as a practical knob to program helicity-dependent skyrmion morphology and emergent interstitial textures in anisotropic-DMI systems, and may further inform the engineering of more complex confined spin textures such as hopfion-like 3D solitons [53–55], providing opportunities to tune topological Hall transport and related spintronic functionality [30, 51, 52].

4 | Experimental Section

4.1 | Sample Preparation

Single-crystalline FeNiPdP bulk crystals with S_4 symmetry were grown by a self-flux method using high-purity Fe, Ni, and Pd metals and red phosphorus sealed in an evacuated quartz tube. The thoroughly mixed raw materials were first sealed in a quartz tube and annealed at 1100°C for 3 days to ensure homogeneity. The reacted materials were then resealed in a pointed-bottom quartz tube and processed in a Bridgman furnace. The tube was slowly translated from the hot zone (980°C) to the cold zone (910°C) over 6 days to promote single-crystal growth. The target tetragonal phase was mechanically separated from the resulting ingot. The bulk crystals were examined by Laue diffraction (see

Figure S2). Crystal orientations were examined by selected-area electron diffraction, and the chemical composition was measured by energy-dispersive x-ray spectroscopy (see Figure S3). Confined FeNiPdP nanostripe (001) thin plates for L-TEM observation were fabricated by dual-beam focused ion beam (FIB), with a carbon layer deposited on the top and bottom edges to define the confinement and protect against ion-beam damage. The nanostripe thickness is approximately 180 nm, as measured by scanning electron microscopy (SEM) (Figure S16).

4.2 | L-TEM Observations and Fresnel Image Simulations

L-TEM observations were performed at room temperature using a JEM-F200 (JEOL) transmission electron microscope operated at 200 kV. Under- and over-focused L-TEM images exhibit bright–dark contrast arising from the in-plane component of the magnetic induction field averaged over the plate thickness. In-plane magnetic induction field maps were reconstructed using transport-of-intensity equation (TIE) analysis implemented in QPt software (HREM Co.). A perpendicular magnetic field parallel to the electron beam was applied by tuning the objective-lens current. L-TEM Fresnel images were simulated with a custom-built code. The simulations compute the electron phase shift induced by the in-plane magnetization by integrating the magnetic vector potential along the beam direction. The vector potential was obtained by solving the corresponding vector Poisson equation, and the resulting phase was used to generate defocused Fresnel contrast.

4.3 | Micromagnetic Simulations

Micromagnetic simulations were performed using the open-source, GPU-accelerated code MuMax3 [56], modified to incorporate anisotropic DMI consistent with the FeNiPdP system [4, 41, 57]. The total magnetic energy density is given by

$$\varepsilon = A(\nabla \mathbf{m})^2 + D\mathbf{m} \cdot (\hat{x} \times \partial_x \mathbf{m} - \hat{y} \times \partial_y \mathbf{m}) - K_u(\mathbf{m} \cdot \hat{z})^2 - M_s \mathbf{m} \cdot \mathbf{B}_{\text{ext}} - \frac{1}{2} M_s \mathbf{m} \cdot \mathbf{B}_d \quad (1)$$

here A , D , K_u , and M_s denote the exchange stiffness, DMI strength, uniaxial anisotropy constant, and saturation magnetization, respectively. The normalized magnetization is $\mathbf{m} = \mathbf{M}/M_s$. The external field is $\mathbf{B}_{\text{ext}} = B_{\text{ext}} \hat{z}$, and $\mathbf{B}_d$ is the demagnetizing field. Unless otherwise stated, the parameters used in our simulations were $A = 8.1 \text{ pJ m}^{-1}$, $D = -0.15 \text{ mJ m}^{-2}$, $M_s = 600 \text{ kA m}^{-1}$, and $K_u = 50 \text{ kJ m}^{-3}$. The flake thickness was fixed at 200 nm and discretized using a $5 \text{ nm} \times 5 \text{ nm} \times 5 \text{ nm}$ cell size. Periodic boundary conditions were applied along the nanostripe axis. For Figure 2h, the nanostripe geometry was $820 \text{ nm} \times 450 \text{ nm} \times 200 \text{ nm}$ (Figure 2h); two skyrmions with CW and CCW helicities were first stabilized at 100 mT and then relaxed under fields increased in 5 mT increments, and the helicity-dependent ellipticity was extracted by OpenCV-based contour analysis. For the surface vortex simulations (Figure 4j,k), a single CW skyrmion was initialized in a $700 \text{ nm} \times 450 \text{ nm} \times 200 \text{ nm}$ nanostripe and energy-minimized at 320 mT; to facilitate surface vortex formation, the uniaxial anisotropy constant was slightly reduced to $K_u = 40 \text{ kJ}$

m^{-3} , yielding the coexistence of a bulk skyrmion and a surface vortex.

4.4 | Belavin–Polyakov (BP) Model for Elliptical Skyrmions

The elliptical skyrmion texture is constructed within the Belavin–Polyakov (BP) model by applying an anisotropic coordinate rescaling to the BP skyrmion solution [49, 50], which is scale-invariant in the pure-exchange limit. Introducing different length scales λ_x and λ_y along two orthogonal axes deforms the circular BP skyrmion into an ellipse while preserving its topology. The corresponding spin texture can be written as:

$$\begin{aligned} m_x &= \frac{2x\lambda_x\lambda_y^2\cos\gamma - 2y\lambda_x^2\lambda_y\sin\gamma}{x^2\lambda_y^2 + y^2\lambda_x^2 + \lambda_x^2\lambda_y^2} \\ m_y &= \frac{2x\lambda_x\lambda_y^2\sin\gamma + 2y\lambda_x^2\lambda_y\cos\gamma}{x^2\lambda_y^2 + y^2\lambda_x^2 + \lambda_x^2\lambda_y^2} \\ m_z &= -\frac{x^2\lambda_y^2 + y^2\lambda_x^2 - \lambda_x^2\lambda_y^2}{x^2\lambda_y^2 + y^2\lambda_x^2 + \lambda_x^2\lambda_y^2} \end{aligned} \quad (2)$$

here, λ_x and λ_y denote the characteristic size parameters of the skyrmion along the x and y directions, respectively, thereby defining its ellipticity $\rho = \lambda_x/\lambda_y$. The parameter γ specifies the in-plane spin rotation, that is, the skyrmion helicity. Within this BP-based parametrization, we consider a simplified energy functional including exchange, anisotropic DMI, and an effective in-plane anisotropy that mimics geometric confinement.

We first evaluate the exchange contribution:

$$E_{ex} = A \int d^2r \left[\left(\frac{\partial \mathbf{m}}{\partial x} \right)^2 + \left(\frac{\partial \mathbf{m}}{\partial y} \right)^2 \right] \quad (3)$$

which yields,

$$E_{ex} = 4\pi A \frac{\lambda_x}{\lambda_y} \left(1 + \frac{\lambda_y^2}{\lambda_x^2} \right) \quad (4)$$

after substituting Equation (2). The exchange energy is minimized at $\lambda_x = \lambda_y$, indicating that exchange alone favors an isotropic, circular skyrmion.

We next include the anisotropic DMI term:

$$E_{DMI} = D \int d^2r \left[\mathbf{m} \cdot \left(\hat{x} \times \frac{\partial \mathbf{m}}{\partial x} - \hat{y} \times \frac{\partial \mathbf{m}}{\partial y} \right) \right] \quad (5)$$

which gives,

$$E_{DMI} = 4\pi D (\lambda_x - \lambda_y) \sin\gamma \quad (6)$$

anisotropic DMI locks the elongation axis to the helicity: for $\gamma = +\pi/2$ (CCW), the DMI energy is reduced by elongation along x ($\rho > 1$), whereas for $\gamma = -\pi/2$ (CW) it favors elongation along y ($\rho < 1$). In the absence of confinement, the interplay of exchange interaction and anisotropic DMI thus yields nearly degenerate elliptical skyrmions with opposite helicities and comparable distortions.

To model confinement-induced in-plane anisotropy in nanostripes, we introduce in-plane anisotropy terms:

$$E_{xy} = \int d^2r \left[K_x (\hat{x} \cdot \mathbf{m})^2 + K_y (\hat{y} \cdot \mathbf{m})^2 \right] \quad (7)$$

where K_x and K_y denote the anisotropy strengths along the x and y directions, respectively. Substituting Equation (2) into Equation (7) shows that the integral does not converge with the cutoff radius R , but instead diverges logarithmically, $\sim \ln R$; we therefore evaluate E_{xy} using a finite cutoff radius R (see Figure S17). We define $\eta = K_x/(K_x + K_y)$ and normalize the anisotropy scale by setting $K_x + K_y = 1$. This effective in-plane anisotropy selects a preferred elongation axis and provides an energetic basis for helicity-dependent ellipticity.

4.5 | Energy Density Calculation for CCW Skyrmions Within the BP Model

To reproduce the nonlinear evolution of the CCW skyrmion ellipticity, we turn to the full model considering all the energy term realistic in real material defined in Equation (1) and numerically evaluate the energy density of BP-model elliptical skyrmions (Equation 2). The energy densities were computed in MuMax3 for a 700 nm $\times$ 450 nm $\times$ 200 nm nanostripe with periodic boundary conditions along x . For each (ρ, B_{ext}) , we obtained an effective energy density by minimizing over the overall skyrmion size $L = \sqrt{\lambda_x\lambda_y}$,

$$\varepsilon_{eff}(\rho, B_{ext}) = \min_L \varepsilon(\rho, B_{ext}, L) \quad (8)$$

This procedure removes the size degree of freedom and yields an effective energy landscape $\varepsilon_{eff}(\rho, B_{ext})$ only by the deformation ρ and the field B_{ext} .

To quantify the energetic cost of deviating from the optimal ellipticity at a given magnetic field, we define the relative energy:

$$\Delta\varepsilon(\rho, B_{ext}) = \varepsilon_{eff}(\rho, B_{ext}) - \min_{\rho} \varepsilon_{eff}(\rho, B_{ext}) \quad (9)$$

which measures the energy penalty for imposing a non-optimal ellipticity at that B_{ext} . For comparison across different fields, we normalize $\Delta\varepsilon$ by the global maximum over the full (ρ, B_{ext}) space:

$$\varepsilon'(\rho, B_{ext}) = \frac{\Delta\varepsilon(\rho, B_{ext})}{\max_B \left[\max_{\rho} \Delta\varepsilon(\rho, B_{ext}) \right]} \quad (10)$$

The normalized maps $\varepsilon'(\rho, B_{ext})$ are shown in Figure 3c.

Author Contributions

Shangrun Lu: investigation, data curation, software, and writing – original draft. **Qingfa Luo:** investigation and data curation. **Yizhou Liu:** data curation, investigation, and methodology. **Shaohua Fan:** investigation, methodology, and resources. **Haoting Lu:** investigation. **Jiajia Liu:** methodology and investigation. **Guanghui Han:** investigation. **Xiaoting Tian:** investigation. **Fanqi Meng:** investigation and

methodology. **Zhaochu Luo**: investigation. **Jinbo Yang**: investigation, resources, and writing – review and editing. **Yanglong Hou**: supervision, funding acquisition, and writing – review and editing. **Licong Peng**: conceptualization, investigation, data curation, supervision, funding acquisition, project administration, writing – original draft, and writing – review and editing.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

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

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