

RESEARCH ARTICLE

Interaction Between Three-Dimensional Topological Spin Textures With Layer-Dependent Sign Change Tunes Lattice Symmetry

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Received: 22 May 2026 | **Revised:** 20 August 2026 | **Accepted:** 27 August 2026

Keywords: Bloch points | layer-dependent interactions | Lorentz transmission electron microscopy | magnetic skyrmion | three-dimensional texture | topological spin texture

ABSTRACT

Three-dimensional (3D) topological spin textures host rich internal structures in thickness dimensions and enable emergent topological phenomena. However, whether their layer-resolved textures and internal singularities fundamentally modify intralayer interactions lies beyond rigid-tube interaction models and remains unexplored. Here we show that, in 3D hybrid skyrmion-antiskyrmion strings, the layer-dependent topology gives rise to interactions with a sign change across the film thickness, producing a switch between attraction and repulsion both among different layers within each texture and between neighboring 3D strings. This vertically asymmetric attractive-repulsive interaction drives a tunable transition between square and triangular string lattices, in agreement with our experiment. Computational simulations identify quadrupolar Bloch points as internal topological junctions whose vertical migration mediates the intralayer competition between repulsive skyrmion segments near the surfaces and attractive antiskyrmion segments in the interior. We further show that the averaged topological charge quantifies the relative thickness fractions of the two competing topological segments and robustly captures the lattice phase boundary over a broad range of magnetic parameters. These findings highlight the importance of the surface-bulk difference in topological materials and establish vertically asymmetric interactions as an intrinsic mechanism for topological phase control in 3D magnetic systems.

1 | Introduction

Magnetic (anti)skyrmions are topological quasiparticles with swirling spin textures that have emerged as robust information carriers for spintronic applications, owing to their nonvolatile stability, topological protection, and ultra-low energy controllability via spin, electric, and thermal currents [1–4]. Early

investigations focused primarily on two-dimensional (2D) thin films [5, 6], where skyrmion interactions were generally regarded as uniformly repulsive [7–9], or treated three-dimensional (3D) skyrmions as rigid tubes, with interactions defined at the tube scale and independent of internal spin structure [10–12]. Recently, however, it has become recognized that incorporating the third spatial dimension plays a pivotal role in unlocking emergent

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magnetic behaviors and enabling functionalities in 3D spintronic devices [13–16].

Advances in recent years have uncovered a diverse array of intrinsically 3D topological spin textures, such as skyrmion strings and their bifurcated variants [13, 17–19], vortex-antivortex loops [20], hopfions [21–23], and hybrid skyrmion-antiskyrmion string configurations [24–27], all exhibiting pronounced curvature nature along the thickness direction. One distinguishing feature of these 3D textures is the presence of Bloch points, which are zero-dimensional magnetic singularities where the magnetization vanishes [20, 28]. These singularities act as topological sources or sinks, enabling localized changes in topological charge [24, 25] and mediating dynamical processes such as domain wall motion [29, 30], vortex core and helicity reversal in dipolar magnets [31, 32], and skyrmion string elongation or pinning in chiral magnets [33–35]. They have been implicated in emergent effects, including gyrotropic-mode resonance [36] and curvature-induced magnetic anisotropy [37].

Among these diverse 3D topological textures, hybrid skyrmion-antiskyrmion strings [24–26] provide a compelling example wherein Bloch points play a key role in their internal topology. Recent real-space 3D tomographic imaging of noncentrosymmetric magnets with D_{2d} or S_4 symmetry revealed their layered spin configurations [25, 26, 38], stabilized by the interplay between magnetic dipole-dipole interactions and anisotropic Dzyaloshinskii-Moriya (DM) interaction [2, 24, 25]. These strings consist of surface layers hosting Néel-type skyrmions connected via quadrupolar-arranged Bloch points to a central antiskyrmion core [26]. Crucially, these singularities couple distinct spin layers and mediate transitions among skyrmions, antiskyrmions, and nontopological bubbles under external perturbations [24, 25, 39, 40]. However, despite these advances, the mechanisms by which Bloch points regulate the competition between surface and bulk interactions, and how this interplay determines the symmetry and stability of the lattice phase, remain unexplored, yet are essential for exploiting and controlling 3D magnetic textures.

Here we reveal an intrinsic mechanism of layer-dependent interaction, including a modulation of the sign in thickness dimensions within the hybrid skyrmion-antiskyrmion strings, through which local topological constraints determine lattice stability and symmetry. We establish a direct correlation between Bloch-point migration, vertically sign-reversing interactions, and macroscopic lattice symmetries, with possible implications for broader phenomena such as solid-solid phase changes [41, 42].

2 | Results and Discussion

2.1 | Layer-Dependent Spin Textures and Tunable Lattice Symmetry

A micromagnetic model is employed to study the 3D hybrid skyrmion-antiskyrmion string in tetragonal noncentrosymmetric magnets, where the total energy density

is given by [2, 25]:

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

here A , D , K_u , and M_s represent the exchange stiffness coefficient, anisotropic DM interaction strength, uniaxial anisotropy constant, and saturation magnetization, respectively. The normalized magnetization vector is $\mathbf{m} = \mathbf{M}/M_s$, $\mathbf{B}_{\text{ext}} = B \hat{z}$ stands for the external magnetic field, and $\mathbf{B}_d$ denotes the demagnetizing field.

Figure 1a shows the layer-resolved spin configuration of the 3D hybrid skyrmion-antiskyrmion string, featuring a continuous transformation from surface Néel-type skyrmions to central bulk antiskyrmion. This transformation is mediated by two pairs of diagonally arranged Bloch points, each acting as a topological junction that bridges the surface spin textures and the mid-layer antiskyrmion on either side of the structure (Figure 1b–d). To quantify the layer-wise topology, we evaluate the topological charge in each slice as:

$$Q = \frac{1}{4\pi} \iint d^2r \mathbf{m} \cdot (\partial_x \mathbf{m} \times \partial_y \mathbf{m}) \quad (2)$$

which measures the wrapping of the local magnetization $\mathbf{m}(x, y)$ over the unit sphere. The topmost and bottommost layers exhibit $Q = -1$, while intermediate layers yield $Q = +1$ (Figure 1c), enabling a topological segmentation into two surface skyrmion layers (L_{Sk1} and L_{Sk2}), and a central antiskyrmion core (L_{ASK}) along the thickness L_z (Figure 1a). As shown in Figure 1b, the Bloch points coincide with localized energy density maxima in ε , yet the xy -averaged energy density in these layers remains lower than that at the surface (see Figure S1), indicating spatial energy density localization that facilitates topology change without destabilizing the overall structure.

We next experimentally examine how the hybrid skyrmion-antiskyrmion strings organize collectively into lattices. In our FeNiPdP samples with anisotropic DM interaction (see details in the Experimental Section), Lorentz transmission electron microscopy (LTEM) shows that the spin textures form a triangular lattice at 320 mT (Figure 1e). As the magnetic field increases, the lattice gradually transforms into a square geometry (Figure 1f,g). Quantitative nearest-neighbor analysis further quantifies this lattice reorganization (Figure S2). When the field is reduced back to zero, the triangular lattice reappears, indicating a reversible symmetry switching of the lattice (Figure S3). Moreover, the core vortex contrast observed in the LTEM images (Figure 1e–g) is consistent with the simulated characteristics of 3D hybrid skyrmion-antiskyrmion strings (Figure S4 in the Supporting Information), supporting the identification of the observed textures as hybrid structures. Micromagnetic simulations reproduce the magnetic field-driven triangular-to-square lattice evolution (Figure 1h–j), in good agreement with the LTEM observations. Notably, this lattice transformation proceeds without pronounced changes in the square-shape morphology of the individual string texture, suggesting an effective intertexture interaction-driven transition rather than a transformation of the topological objects themselves (see Figure S5). This transition behavior differs from previously reported D_{2d} -symmetric antiskyrmion lattices [43–45],

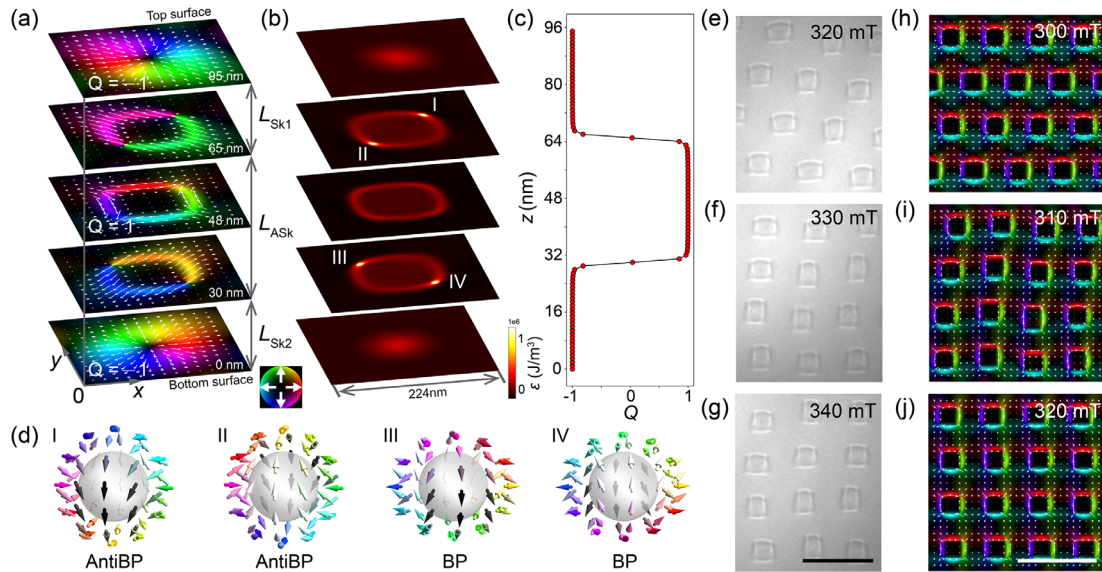


FIGURE 1 | 3D hybrid skyrmion-antiskyrmion string and tunable lattice geometry. (a) In-plane magnetization distributions at selected xy -slices along the thickness L_z . The slice position and topological charge Q are labeled in the lower-left and lower-right corners, respectively, illustrating a transformation from Néel-type skyrmions ($Q = -1$) to antiskyrmions ($Q = +1$). Bloch points (BPs) mark the boundary between surface and bulk regions, segmenting the structure into three topological components: the top and bottom surface skyrmion layers (L_{Sk1} , L_{Sk2}) and the central antiskyrmion (L_{ASk}). (b) Layer-resolved energy density ϵ distributions, showing localized maxima near the BPs and anti-Bloch points (AntiBPs). (c) Topological charge Q as a function of thickness z . (d) Schematic illustrations of the BP and AntiBP structures corresponding to the four extrema in (b). (e–j) Magnetic field-driven triangular-to-square lattice transition observed by LTEM in FeNiPd magnet (e–g) and reproduced by micromagnetic simulations (h–j). Scale bars: 500 nm (experiment) and 400 nm (simulation).

likely because magnetic parameters reshape the texture geometry and effective intertexture interactions.

2.2 | Intrinsic Origin of Layer-Dependent Sign-Changing Interactions in 3D Textures

To explore the thickness-wise origin of the lattice geometry change, we first analyze how the effective intralayer coupling evolves across the thickness of the hybrid string. We analyze their energy density contributions under controlled lattice perturbations while varying paired D and M_s (Figure 2a,b). A small variation in lattice spacing ($a \pm \Delta x$, with $\Delta x = 2$ nm) is introduced to assess the effective coupling between neighboring textures and to probe layer-dependent in-plane interactions while preserving the internal spin structure. Accordingly, we define the surface-layer averaged energy density for skyrmions as $\bar{\epsilon}_{xy-Sk} = [\bar{\epsilon}_{xy}(z = 0) + \bar{\epsilon}_{xy}(z = 95)]/2$, and the mid-layer averaged energy density for antiskyrmion as $\bar{\epsilon}_{xy-ASk} = [\bar{\epsilon}_{xy}(z = 47) + \bar{\epsilon}_{xy}(z = 48)]/2$, where $\bar{\epsilon}_{xy}(z)$ denotes xy -averaged energy density at the z -layer. As shown in Figure 2a,b, $\bar{\epsilon}_{xy-Sk}$ decreases while $\bar{\epsilon}_{xy-ASk}$ increases with increasing lattice spacing across all parameter sets. This opposite behavior, also evident from the arrows in the insets, reflects an interaction asymmetry: surface skyrmion textures become less tightly bound at larger spacing, resulting in a decrease in interaction energy, whereas mid-layer antiskyrmions experience weaker attraction, leading to higher energy. These trends indicate that surface layers are subject to repulsive interactions, while mid-layers are attractively coupled.

To quantify this intralayer attractive–repulsive interaction, we compute the layer-resolved energy density variation, $\Delta\bar{\epsilon}_{xy}$,

defined as the difference in energy density between perturbed lattice constants $a \pm \Delta x$ and the reference spacing a . This calculation is performed across all 96 layers for $D = 0.22$ mJ/m², $M_s = 570$ kA/m. The effective interaction force can be approximated as $\mathbf{F} \propto -\nabla\bar{\epsilon}$ with volume change neglected. As shown in Figure 2c, the surface regions (L_{Sk1} and L_{Sk2}) exhibit $\Delta\bar{\epsilon}_{xy} < 0$ for increased spacing ($a + \Delta x$) and $\Delta\bar{\epsilon}_{xy} > 0$ for reduced spacing ($a - \Delta x$), both resulting in $F > 0$, indicative of repulsive forces. A reversed trend is observed within the mid-layer region (L_{ASk}), where $\Delta\bar{\epsilon}_{xy}$ implies $F < 0$, corresponding to attractive coupling. The nearly unchanged total energy density across perturbations (see Figure S6) suggests that the response arises from a vertical redistribution of energy rather than a global energy change. The $\Delta\bar{\epsilon}_{xy}$ profiles obtained for different Δx values and simulation protocols show consistent interaction profiles (see Figures S7 and S8). This layer-dependent interaction is further illustrated schematically in Figure 2d by the normalized magnetic charge density for the top and bottom skyrmion layers and the mid-layer antiskyrmion. In particular, the mid-layer antiskyrmion exhibits alternating vertical Bloch lines, consistent with an attractive interaction in the interior, whereas the surface skyrmion layers remain repulsive.

Notably, the crossover point between repulsive and attractive regimes coincides with the vertical position of the Bloch point layer (dashed lines in Figure 2c), identifying the Bloch point as a topological boundary mediating distinct intralayer coupling behaviors. Further analysis of uniform skyrmion and antiskyrmion tubes without Bloch points, where all layers share the same topological charge ($Q = \pm 1$), reveals a persistent vertical force imbalance shaped by their internal spin configurations (see Figure S9). This intralayer interaction asymmetry is not driven

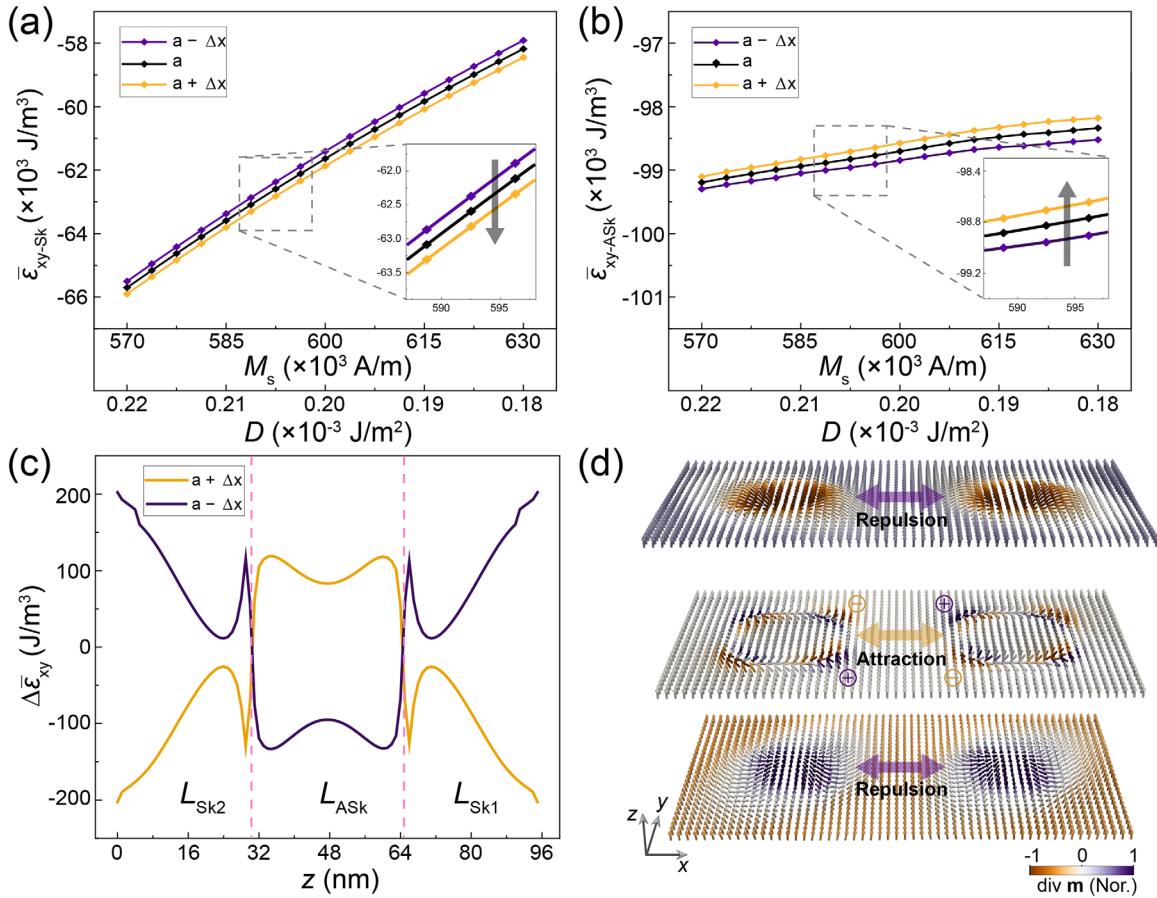


FIGURE 2 | Intrinsic origin of layer-dependent sign-changing interactions in 3D textures. (a, b) Layer-averaged energy densities for (a) surface regions ($\bar{\epsilon}_{xy-Sk}$) and (b) mid-layer region ($\bar{\epsilon}_{xy-ASK}$) as functions of material parameters (D , M_s) under controlled lattice perturbations Δx . Insets show the energy density variation trend with increasing lattice spacing, as indicated by arrows. (c) Layer-resolved energy density change $\Delta \bar{\epsilon}_{xy}$, as a function of vertical position z , showing the differential energy density response to lattice spacing perturbation across layers. The crossover point, marked by dashed pink lines, coincides with the Bloch point layer, indicating a topological boundary between surface (L_{Sk1} and L_{Sk2}) and mid-layer (L_{ASK}) regions. (d) Schematic of the normalized magnetic charge density for the top and bottom skyrmion layers and the mid-layer antiskyrmion, illustrating the layer-dependent interaction. Adjacent positive and negative charges along the alternating vertical Bloch lines in the interior are associated with attraction (yellow arrows), whereas the surface skyrmion layers remain repulsive (purple arrows).

by a single energy term such as the DM interaction or dipolar interaction, but results from the interplay of multiple competing contributions (see Figure S10).

2.3 | Energetic Differences Between Distinct Lattice States

We next carried out micromagnetic simulations and symmetry analysis and identified two distinct lattice configurations stabilized under different magnetic parameters: [25, 46] a triangular lattice at $D = 0.18 \text{ mJ/m}^2$, $M_s = 630 \text{ kA/m}$ (Figure 3a and see Figure S11), and a square lattice at higher $D = 0.22 \text{ mJ/m}^2$ and lower $M_s = 570 \text{ kA/m}$ (Figure 3b and see Figure S11). The corresponding in-plane field distributions, $|B_{xy}|/\mu_0 M_s$, averaged along the thickness, reveal characteristic flux-closure geometry of the two lattices. In the square lattice, antiskyrmions retain a square geometry resulting from isotropic binding to nearest neighbors along both x - and y -directions, forming a fourfold coordination network with two $2'$ rotational and two m' mirror symmetries

(Figure 3b). In contrast, the triangular lattice exhibits anisotropic binding, with strong coupling to two nearest neighbors along the x -axis and suppressed interactions with the remaining four, resulting in a distorted sixfold coordination and breaking the diagonal mirror symmetry while preserving only two $2'$ symmetries intact (Figure 3a). This variation in flux-closure geometry arises from the diagonal polarity pattern of magnetic volume charges, $\rho_{mag} = -M_s \nabla \cdot \mathbf{m}$, which exhibits alternating polarities along the diagonal and modulates the intertexture coupling (see Figure S12). A degenerate triangular lattice configuration with stronger y -axis binding exhibits similar distortion behavior (see Figures S11 and S13).

These symmetry differences are reflected in the radially averaged in-plane induction field map in Figure 3c, $\bar{b}_{xy}(\theta) = |\bar{B}_{xy}|(\theta)/|\bar{B}_{xy}|$, extracted from the central textures of Figure 3a,b. Here θ is the angle between the radial direction and the $+x$ -axis, and $|\bar{B}_{xy}|$ is the averaged in-plane field. As shown in Figure 3c, the square lattice exhibits fourfold angular symmetry with minima at $\theta = 45^\circ + n \cdot 90^\circ$ ($n = 0, 1, 2, 3$), consistent with its diagonal

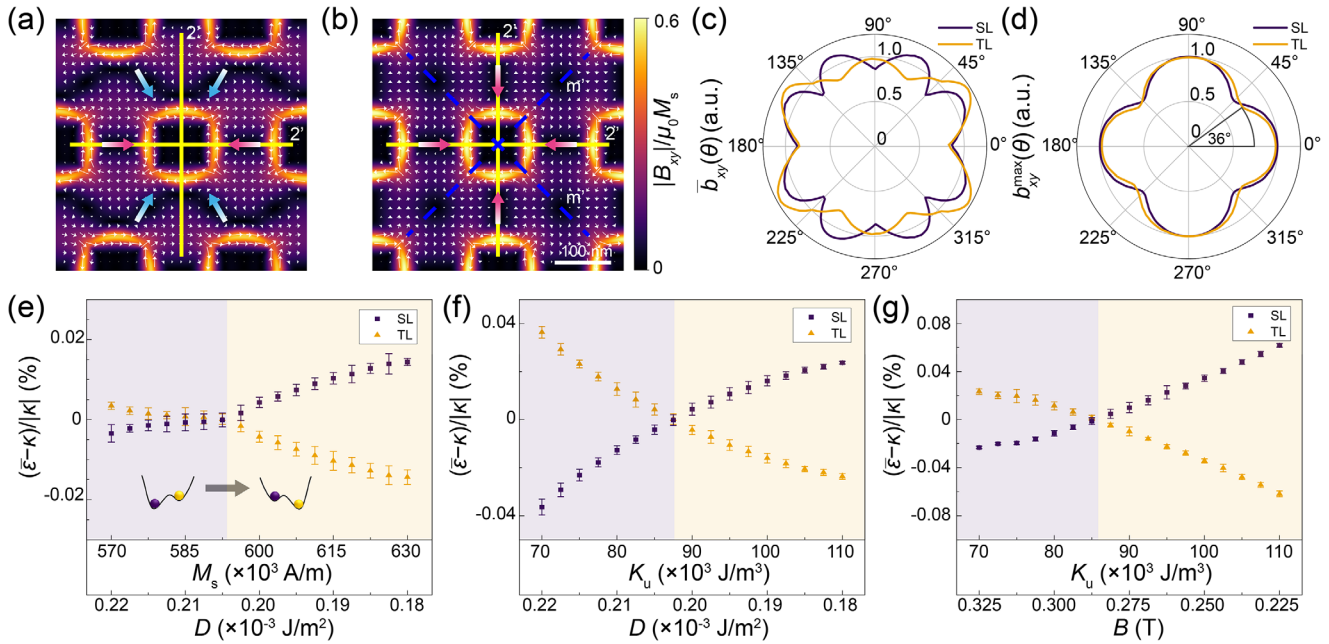


FIGURE 3 | Energetic differences between distinct lattice states. (a, b) In-plane field distributions $|B_{xy}|/\mu_0 M_s$ averaged along the thickness direction for the (a) triangular lattice (TL) and (b) square lattice (SL), obtained at $D = 0.18$ mJ/m², $M_s = 630$ kA/m and $D = 0.22$ mJ/m², $M_s = 570$ kA/m, respectively. Solid yellow lines and dashed blue lines indicate the $2'$ rotational and m' mirror symmetry elements. Pink and blue arrows indicate dominant coupling directions. (c) Angular profiles of the radially averaged in-plane field $\bar{b}_{xy}(\theta)$ of the central unit cell, showing fourfold angular symmetry in the square lattice and a multi-lobed, non-periodic profile in the triangular lattice, indicating symmetry breaking. (d) Maximum-normalized radial in-plane field $b_{xy}^{\max}(\theta)$, capturing outer-core deformation. In the triangular lattice, field minima are shifted by approximately 9° relative to the square lattice, quantifying lattice-induced shape distortion. (e–g) Normalized energy density difference between square and triangular lattices as functions of (e) M_s and D , (f) K_u and D , and (g) K_u and B . Error bars represent statistical variation across simulations with slightly perturbed initial conditions. Background color indicates the relatively stable phase: square (purple) and triangular (orange). Insets show schematic energy landscapes.

flux closure structure. In contrast, the triangular lattice yields a non-periodic, multi-lobed profile with reduced symmetry due to anisotropic coupling. To further quantify the lattice-imposed shape deformation of an individual string texture, we evaluate the maximum-normalized radial profile of the in-plane field (Figure 3d), $b_{xy}^{\max} = |B_{xy}|_{\max}(\theta)/|B_{xy}|_{\max}$, which emphasizes the outer geometry of the spin texture. In the square lattice, $b_{xy}^{\max}(\theta)$ exhibits symmetric minima consistent with $\bar{b}_{xy}(\theta)$, while in the triangular-lattice phase the minima are shifted by approximately 9° , indicating lattice-induced shape distortion of the individual texture's outer geometry. Despite their differing lattice symmetries, both states exhibit qualitatively similar local spin textures and comparable trends in layer-resolved energy density profiles, although the analysis is performed at slightly different vertical layers due to structural differences (see Figures S14 and S15). These similarities suggest a nontrivial mechanism beyond texture deformation or global energy density redistribution [47], possibly involving a reorganization of topological segments along the vertical direction.

To further evaluate the relative stability of the two lattice configurations, we calculate the total energies of the square and triangular lattices as a function of $D \sim M_s$ (Figure 3e). To isolate the intrinsic energy density difference, we define the normalized energy density difference as $(\bar{\epsilon} - \kappa)/|\kappa|$ with $\kappa = (\bar{\epsilon}_{SL} + \bar{\epsilon}_{TL})/2$ (see Figure S16), where $\bar{\epsilon}$ is the energy density of the square ($\bar{\epsilon}_{SL}$) or triangular ($\bar{\epsilon}_{TL}$) lattice configuration. This normalization removes global offsets and system-size effects, enabling direct comparison

between the two phases. As shown in Figure 3e, the square lattice becomes energetically favored at higher D and lower M_s (purple region), whereas the triangular lattice dominates in the opposite regime (orange region). These energy trends, indicated by the background color and panel-inset energy landscape schematic, reveal a clear reversal in the relative stability of the two lattice types as the parameters vary, indicating a geometry change in the energetically preferred configurations. Additional parameter sweeps over $D \sim K_u$ and $B \sim K_u$ (Figure 3f,g) yield similar square-to-triangular lattice transition, confirming the robustness of the lattice response and its broad tunability across different magnetic parameter pairs.

2.4 | Bloch-Point Shift Governs the $\bar{Q}$ -Defined Phase Boundary

Figure 4a–c further show the square–triangular lattice phase boundaries for the three magnetic parameter combinations of $D \sim M_s$, $D \sim K_u$, $B \sim K_u$. The solid pink lines mark the corresponding boundaries separating the square and triangular lattice geometries. In particular, Figure 4c reveals a magnetic field-driven lattice-geometry transition, where the lattice is triangular at low magnetic fields and becomes square at higher fields. Under experimentally relevant parameter conditions, the transition occurs at approximately 310 mT in the simulations, in close correspondence with the experimentally observed transition field (Figure 1e–g), supporting the consistency between the simulation

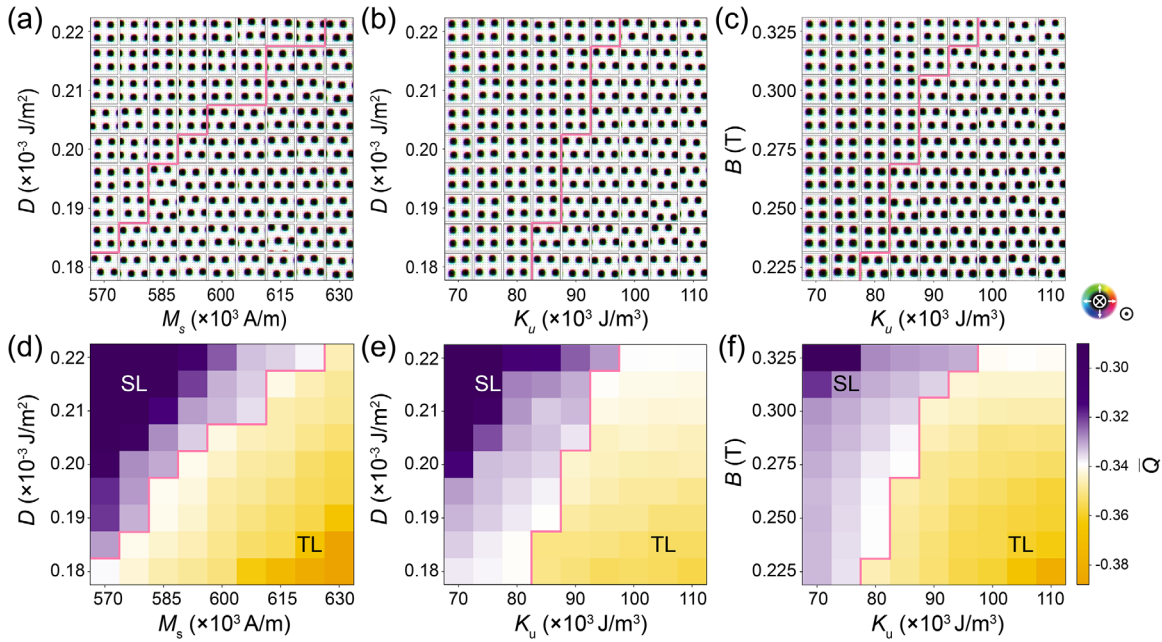


FIGURE 4 | Bloch-point shift governs the $\bar{Q}$ -defined phase boundary. (a–c) Lattice phase diagrams in three parameter spaces: (a) $D \sim M_s$; (b) $D \sim K_u$; (c) $B \sim K_u$. (d–f) Corresponding $\bar{Q}$ maps computed from the full 3D textures in (a–c): (d) $D \sim M_s$; (e) $D \sim K_u$; (f) $B \sim K_u$. The values of $\bar{Q}$ are represented by the color scale bar. Pink lines denote the lattice phase boundary separating the square and triangular phases.

parameter regime and the measured system. Extended phase diagrams further demonstrate the robustness of the triangular-square lattice transition across a broad parameter space (see Figure S17).

Interestingly, we find that the lattice geometry change is accompanied by a systematic vertical shift of the Bloch point layer. As the system evolves between square and triangular configurations, the Bloch point, which marks the interface between surface and bulk topological textures (Figure 1), moves along the vertical direction, suggesting an internal redistribution of spin structures associated with the lattice change. To quantify this effect, we calculate the averaged topological charge $\bar{Q} = \frac{1}{L_z} \int Q(z) dz$, where $Q(z)$ denotes the topological charge of the slice at thickness z . Because the surface skyrmion segment carries a topological charge of -1 , a smaller $\bar{Q}$ corresponds to a larger surface-skyrmion fraction, which enhances surface-mediated repulsion and hence promotes the triangular lattice.

The calculation is performed across three magnetic parameters of $D \sim M_s$, $D \sim K_u$, $B \sim K_u$ as shown in Figure 4. Notably, the square-triangular phase boundary consistently occurs at a critical value of $\bar{Q}$ across all parameters sets: $\bar{Q}_{D \sim M_s} = -0.336$ (Figure 4a), $\bar{Q}_{D \sim K_u} = -0.339$ (Figure 4b), and $\bar{Q}_{B \sim K_u} = -0.340$ (Figure 4c). These values, obtained as statistical averages within the phase boundary regions, are tightly clustered around -0.34 , establishing $\bar{Q}$ as a robust and consistent threshold for the lattice change. The consistent correlation between $\bar{Q}$ and the phase boundary indicates that the lattice change arises from the vertical redistribution of spin textures, which mediates the layer-dependent balance between repulsive and attractive interactions (Figure 2). The $\bar{Q}$ -dependent analysis of lattice configurations and energies under fixed magnetic parameters further shows that

Bloch-point-associated redistribution regulates the interaction balance underlying the lattice transition (Figure S18). This mechanism allows localized energetic imbalances within individual layers while maintaining global energy minimization across the entire system. The thickness-dependent phase diagram $B \sim L_z$ further supports the lattice transition (Figure S19). Although the critical value of $\bar{Q}$ shows a slight dependence on sample thickness and may vary with other system conditions such as disorder and boundary conditions, $\bar{Q}$ remains a quantitative descriptor of the internal topological redistribution associated with the transition.

3 | Conclusion

In summary, we have demonstrated that layer-dependent interactions between repulsive surface skyrmions and attractive mid-layer antiskyrmions mediate the phase change in 3D hybrid skyrmion-antiskyrmion strings. This mechanism explains our experimental observations of square-triangular lattice change in magnets with anisotropic DM interaction (Figure 1). It is fundamentally distinct from that in isotropic skyrmion systems in chiral magnets, where lattice symmetry is typically tuned via in-plane field or magnetic anisotropy [12, 47, 48]. Micromagnetic simulations combined with energy perturbation analysis reveal a vertical division of interaction character, quantitatively described by the averaged topological charge $\bar{Q}$. The robust correlation between $\bar{Q}$ and the lattice phase boundary across various magnetic parameter sets ($D \sim M_s$, $D \sim K_u$, $B \sim K_u$) confirms that the lattice change emerges from the internal reorganization of vertically coupled textures balancing attractive and repulsive forces. Importantly, this vertical force sign reversal is not exclusive to our 3D hybrid skyrmion-antiskyrmion strings but also emerges in pure 3D skyrmion and antiskyrmion tubes

(see Figure S9), and persists even in chiral magnets like FeGe (see Figure S20). These findings suggest that the 3D interlayer force-balance picture may provide insights into collective organization of 3D topological structures beyond magnetic systems, including liquid-crystal systems where spatially distributed topological textures can also determine lattice formation and reorganization [49–51]. This broader applicability suggests that thickness-wise interaction asymmetry is a generic feature of 3D topological textures, and contrasts significantly with conventional models that assume uniform inter-skyrmion repulsion or treat 3D textures as rigid entities [8, 11], without resolving the depth-dependent spin texture and resultant force imbalance revealed in our work.

These findings establish 3D magnetic textures as highly tunable topological states whose lattice symmetry and Hall response can be controlled by layer-dependent internal structures and interactions (see Figure S21). Such surface-bulk coupling provides a robust route to reconfiguring 3D spin structures and enables adaptable topological functionalities in 3D spintronic devices, including memory, logic, and neuromorphic components [15, 16, 22].

4 | Experimental Section

4.1 | Sample Preparation and L-TEM Observations

Single-crystalline $(\text{Fe}_{0.6}\text{Ni}_{0.31}\text{Pd}_{0.09})_3\text{P}$ (FeNiPdP) was synthesized by a self-flux growth procedure. High-purity Fe, Ni, and Pd metals were mixed with red phosphorus, loaded into an evacuated quartz tube, and heated at 1100 °C for 3 days to obtain a homogeneous precursor. The product was then transferred to a pointed-bottom quartz tube, resealed under vacuum, and grown in a Bridgman furnace by translating the tube from 980 °C to 910 °C over 6 days. Crystal orientation was determined by selected-area electron diffraction, and composition was verified by energy-dispersive x-ray spectroscopy. Thin lamellae for LTEM were prepared using a dual-beam focused ion beam system.

LTEM measurements were performed on a JEOL JEM-F200 operated at 200 kV. Magnetic contrast was recorded using under- and over-focus conditions, where the bright–dark features originate from the in-plane component of the magnetic induction averaged through the specimen thickness. The magnetic field normal to the thin plate (parallel to the electron beam) was applied by adjusting the objective-lens current.

4.2 | Computational Simulation Parameters

Simulations are carried out using the open-source GPU-accelerated micromagnetic code MuMax3 [52–54], which we modified to incorporate anisotropic DM interaction compatible with the S_4 symmetry of the $(\text{Fe}, \text{Ni})_3\text{P}$ system [25]. Unless otherwise specified, the exchange stiffness is set to $A = 8$ pJ/m, the DM interaction strength to $D = 0.2$ mJ/m², the saturation magnetization to $M_s = 600$ kA/m, and the uniaxial anisotropy constant to $K_u = 90$ kJ/m³. An external magnetic field $\mathbf{B}_{\text{ext}} = B \hat{z}$ is applied with $B = 0.3$ T. The flake thickness is fixed at 96 nm. All simulations used discretization cell sizes of 4 nm $\times$ 4 nm $\times$ 4 nm or smaller, with 2 nm $\times$ 2 nm $\times$ 2 nm used

for the energy-density calculations. To account for the pinning effects present in experiments and reproduce the associated intermediate states during the phase transition, a 1% randomness in the magnetic anisotropy is incorporated into the simulations (Figure 1h). All simulations were performed under periodic boundary conditions.

To generate energetically stable spin textures, the magnetization was evolved according to the Landau-Lifshitz-Gilbert (LLG) equation [55, 56]:

$$\frac{\partial \mathbf{m}}{\partial t} = -\frac{\gamma}{1+\alpha^2} (\mathbf{m} \times \mathbf{m}_{\text{eff}} + \alpha (\mathbf{m} \times (\mathbf{m} \times \mathbf{B}_{\text{eff}}))) \quad (3)$$

where γ represents the gyromagnetic ratio, α is the Gilbert damping coefficient, and $\mathbf{B}_{\text{eff}}$ denotes the effective field comprising contributions from the external field, demagnetizing field, exchange field, anisotropic DM interaction field, anisotropy field, and thermal fluctuations. The first term describes the precession of magnetization around $\mathbf{B}_{\text{eff}}$, and the second term represents damping toward equilibrium. Starting from an initial lattice configuration, Equation (3) is first solved at zero temperature using only the damping term to obtain a metastable relaxed state. The system then evolved at a finite temperature of $T = 600$ K for $t \geq 40$ ns, with the thermal field:

$$\mathbf{B}_{\text{therm}} = \eta(\text{step}) \sqrt{\frac{2\mu_0 \alpha k_B T}{B_{\text{sat}} \gamma_{\text{LL}} \Delta V \Delta t}} \quad (4)$$

included to simulate thermal fluctuations [52], where damping parameter $\alpha = 0.03$, k_B is the Boltzmann constant, B_{sat} is the saturation magnetization expressed in Tesla, γ_{LL} is the gyromagnetic ratio, ΔV is the cell volume, Δt is the time step and $\eta(\text{step})$ a random vector from a standard normal distribution whose value is changed after every time step. The thermal field introduces stochastic perturbations, allowing the magnetic texture to escape local metastable states and evolve toward a stable configuration. After thermalization, the temperature is reset to zero and the system is further relaxed using the damping term. A final energy minimization is performed using the conjugate gradient method. This procedure allows the system to escape local energy minima and relax toward a lower-energy quasi-equilibrium configuration.

For the energy calculations in Figure 3, the initial states used for the statistical analysis were first relaxed by energy minimization under each prescribed parameter set. The resulting 17 independent configurations were then re-imported into simulations with the same parameters and independently minimized to obtain the statistical data for that parameter set. This procedure ensures that the energy calculation is insensitive to the choice of initial state, thereby confirming the robustness of the calculated results.

Acknowledgements

This work is supported by the National Key Research and Development Program of China (Nos. 2025YFA1411002, 2022YFA1203902, 2022YFA1204003), Advanced Materials-National Science and Technology Major Project (No. 2025ZD0618001), the National Natural Science Foundation of China (Nos. 52471249, 92263203, 12474247, 12241401), Beijing Natural Science Foundation (No. F252072), and the China-Germany Collaboration Project (No. M-0199). Yusheng Hou acknowledges the

support from the Guangdong Provincial Key Laboratory of Magnetoelectric Physics and Devices (Grant No. 2022B1212010008) and the Research Center for Magnetoelectric Physics of Guangdong Province (Grant No. 2024B0303390001). Jan Masell acknowledges funding from the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) under the Project No. 547968854. Xichao Zhang acknowledges support from the Grants-in-Aid for Scientific Research from JSPS KAKENHI (Grants Nos. JP25K17939 and JP20F20363). We thank the Materials Processing and Analysis Center, Peking University, for assistance with TEM sample preparation. This work was also supported by the Synergetic Extreme Condition User Facility (SECUF) and the Laboratory of Microfabrication, IOP CAS. We thank the high-pressure synergetic measurement station (A9) of the Synergetic Extreme Condition User Facility (SECUF) for supporting the FIB microfabrication. During the preparation of this manuscript, the authors used GPT-5 (accessed March 2026) for English-language editing and stylistic polishing throughout the manuscript. All AI-assisted revisions were critically reviewed and verified by the authors for scientific accuracy, clarity, and appropriateness. The authors reviewed the entire manuscript and took full responsibility for its accuracy, integrity, and final content. No confidential, sensitive personal, or human-participant data were provided to the tool.

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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