

RESEARCH ARTICLE

Graph Learning and Order Parameters Reveal a Solid-to-Conformal Phase Transition in Skyrmion Lattices

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ABSTRACT

Order-to-disorder transitions in skyrmion lattices have been explored under spatially uniform stimuli, such as thermal or magnetic fields, which are significant for controlling collective skyrmion behavior for spintronic applications. However, under directional driving by an electric current, how the order of a skyrmion lattice evolves beyond melting into a liquid remains unclear. Here we show that a current-driven skyrmion lattice does not enter a disordered phase, but instead undergoes a solid-to-conformal phase transition with periodically modulated local orientation, using in situ Lorentz transmission electron microscopy (L-TEM). Unsupervised graph learning, combined with complementary structural order parameters, enables direct real-time tracking of the lattice reordering. Correlation between orientational order and defect evolution reveals that the transition is mediated by transient dislocation proliferation during the development of the ordered state. These results establish a current-induced order-to-order skyrmion transition and uncover conformal ordering as a distinct nonequilibrium structural state in topological particle assemblies.

1 | Introduction

Magnetic skyrmions are robust, particle-like topological spin textures that can be efficiently manipulated by electric currents, making them attractive for low-energy information technologies such as neuromorphic and probabilistic computing [1–4]. When organized into lattices, skyrmions form a collective particle assembly in which structural order governs their driven motion [5–8], transport behavior [9–11], and device functionality [12, 13]. Revealing and tuning their collective organization under

external driving is therefore significant for both nonequilibrium topological physics and skyrmion-based devices [14–16].

The skyrmion-lattice phase transition has so far been understood largely within the framework of 2D melting [17–19]. In chiral magnets with Dzyaloshinskii–Moriya interaction, skyrmions form hexagonal lattice phases in a limited field–temperature window near the Curie temperature [20, 21]. When temperature or magnetic field is varied, melting is typically associated with defect-mediated loss of positional and orientational

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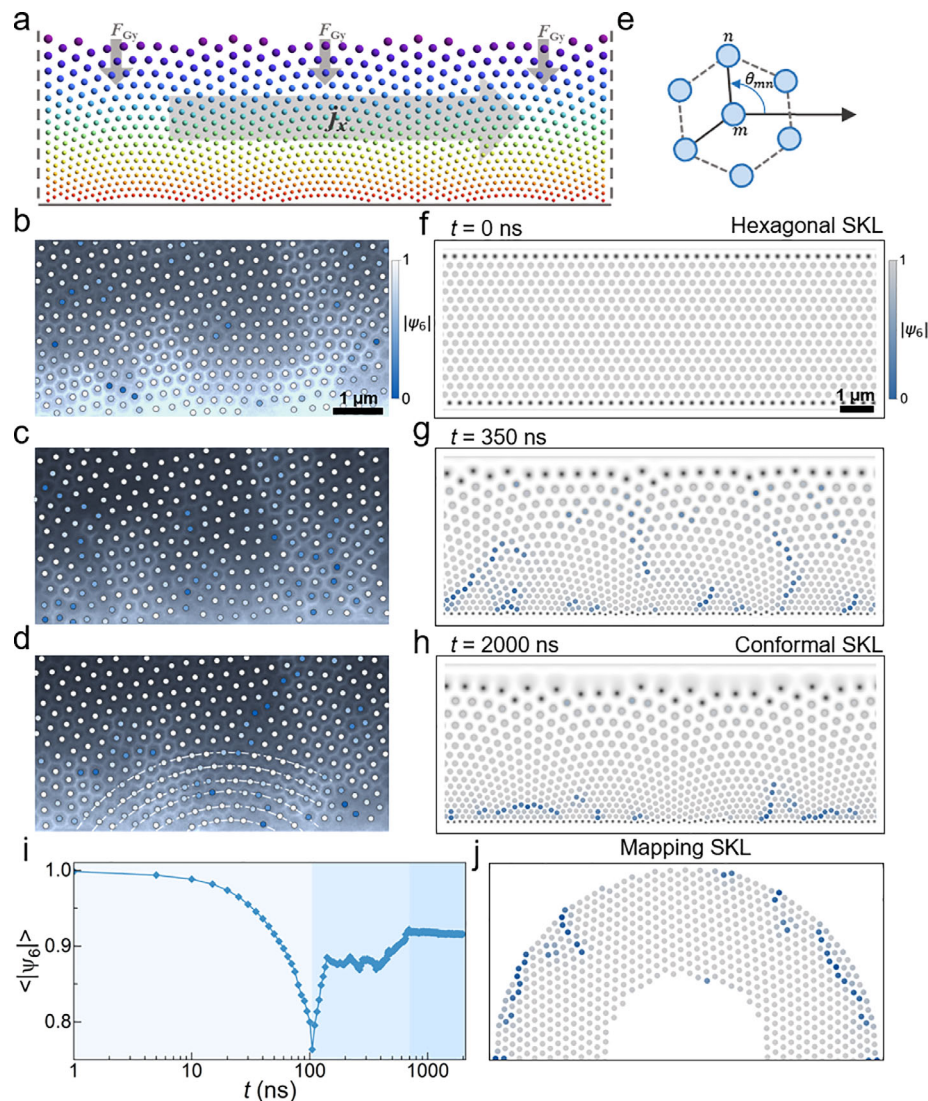


FIGURE 1 | L-TEM observation and orientational-order ψ_6 analysis of a conformal skyrmion lattice. (a) Schematic of current-driven conformal structure, where the Magnus force F_{Gy} drives transverse skyrmion accumulation and forms a rainbow-like lattice pattern. (b–d) Experimentally obtained ψ_6 maps overlaid on L-TEM images of a current-driven skyrmion lattice in a $\text{Co}_9\text{Zn}_9\text{Mn}_2$ thin plate measured at $B = 151$ mT, including (b) the initially stabilized hexagonal SKL with $\langle |\psi_6| \rangle = 0.87$, (c) the disordered intermediate state after 20 current pulses (500 ns, 6.25×10^9 A $\cdot$ m $^{-2}$) with $\langle |\psi_6| \rangle \approx 0.79$, and (d) the conformal SKL after an additional 29 pulses with $\langle |\psi_6| \rangle \approx 0.85$. (e) Schematic illustration of the definition of the local orientational order parameter ψ_6 . (f–h) Simulated ψ_6 maps under $j_x = 4 \times 10^{10}$ A $\cdot$ m $^{-2}$, showing (f) the ideal hexagonal SKL at $t = 0$ ns, (g) the transient disordered state at $t = 350$ ns, and (h) the conformal SKL at $t = 2000$ ns, with spatial gradients in lattice constant and skyrmion density while retaining local hexagonal order. (i) Time evolution of the spatially averaged orientational order parameter $\langle |\psi_6| \rangle$. (j) Inverse conformal mapping of the conformal SKL.

correlations, closely related to the Kosterlitz–Thouless–Halperin–Nelson–Young theory [22–25]. Analogous pathways are well established in a range of 2D particle assemblies, including colloids and superconducting vortices [26, 27], and have recently been observed in skyrmion-hosting systems including bulk Cu_2OSeO_3 , van der Waals Fe_3GaTe_2 , and thin-film CoFeB [18, 20, 21]. These studies define an order-to-disorder paradigm for skyrmion-lattice melting under nearly uniform thermodynamic control.

Electric current introduces a fundamentally different route because it drives skyrmions directionally rather than tuning the lattice uniformly [28, 29]. Through skyrmion Hall motion arising from the Magnus force F_{Gy} (Figure 1a), current injection can induce transverse skyrmion accumulation and their

spatially anisotropic lattice deformation instead of homogeneous disordering [30–32]. Current-driven skyrmion lattices have indeed revealed rich nonequilibrium dynamics, including rotation, drift, and compression under directional forcing [33–35]. These responses imply that electric current does not merely mobilize skyrmions, but actively reshapes their collective organization. However, current-driven skyrmion studies have mainly emphasized their trajectories, velocities, and transport responses [36–38], while the accompanying transformation of lattice order remains largely unexplored.

In this work, we show that a skyrmion lattice undergoes a transition from a solid ordered state into a conformal ordered phase driven by electrical current, rather than melting into

a disordered liquid. The conformal state is a distinct ordered phase characterized by spatially graded lattice spacing with periodically modulated local orientation, forming a rainbow-like pattern (Figure 1a). Combining Lorentz transmission electron microscopy (L-TEM) with micromagnetic simulations, we capture this nonequilibrium lattice reorganization in real space. To quantify the transition, we introduce a conformal order parameter and employ unsupervised graph learning to resolve the local structural evolution across the transition. Analysis of orientational correlations and defect dynamics further uncovers the microscopic pathway by which conformal order emerges under current driving. These real-time insights into lattice evolution are an essential basis for understanding and ultimately controlling its phase behavior.

2 | Results

2.1 | Current-Driven Solid-to-Conformal Phase Transition in the Skyrmion Lattice

We first investigate how the skyrmion Hall effect-induced compression transforms skyrmion-lattice order beyond simple disordering. Using Lorentz transmission electron microscopy (L-TEM), we directly observe the real-space evolution of a skyrmion lattice in a $\text{Co}_0\text{Zn}_0\text{Mn}_2$ thin plate. Starting from a hexagonal skyrmion lattice stabilized at 151 mT, we applied nanosecond current pulses (500 ns, $\sim 6.25 \times 10^9 \text{ A m}^{-2}$) to drive skyrmion motion (Figure 1b–d). The skyrmion positions in each L-TEM image were automatically identified using a machine-vision pipeline (see Method), from which the local orientational order parameter ψ_6 , schematically illustrated in Figure 1e, was calculated to quantify local hexagonal order. For the m -th skyrmion, ψ_6 is defined as

$$\psi_6(\mathbf{r}_m) = \frac{1}{N_m} \sum_{n=1}^{N_m} e^{i6\theta_{mn}} \quad (1)$$

where N_m denotes the number of nearest neighbors of the m -th skyrmion, and θ_{mn} is the angle of the bond connecting the m -th and n -th skyrmions with respect to a reference direction, chosen here as the horizontal x -axis. Figure 1b–d shows representative L-TEM images overlaid with the extracted ψ_6 maps during current-driven lattice evolution (see details in Figure S1). The magnitude $|\psi_6|$ measures the local sixfold orientational order, with larger values corresponding to a more hexagonally ordered local environment. We further average $|\psi_6|$ over all identified skyrmions to obtain the global orientational order, denoted as $\langle |\psi_6| \rangle$. For the initial hexagonal SKL (Figure 1b), the global average value $\langle |\psi_6| \rangle = 0.87$ indicates a well-ordered hexagonal configuration. After 20 current pulses, the lattice became partially disordered (Figure 1c), and $\langle |\psi_6| \rangle$ decreased to approximately 0.79. Upon application of a further 29 pulses with the same amplitude, the skyrmions gradually accumulated near the sample boundary due to the skyrmion Hall effect, giving rise to a spatially graded lattice that evolved into a conformal skyrmion lattice (Figure 1d). In this final state, $\langle |\psi_6| \rangle$ recovered to approximately 0.85, differing from the initial hexagonal SKL by only ~ 0.02 . Thus, the current-driven transformation involves transient disordering followed by recovery of local hexagonal order, rather than a monotonic loss of orientational order. The accompanying spatial reorganization is also reflected in the skyrmion density, which gradually develops a weak gradient during current driving (Figure S1).

Micromagnetic simulations reproduce the same transient loss and recovery of orientational order under Hall motion-induced compression. Starting from an ideal hexagonal lattice at $t = 0$ ns, the simulated state exhibits nearly uniform sixfold order, with $\langle |\psi_6| \rangle$ close to unity (Figure 1f,i). At $t = 350$ ns, compression strongly distorts the lattice, producing a disordered transient configuration accompanied by a sharp decrease in $\langle |\psi_6| \rangle$ (Figure 1g,i). With continued current injection, the system self-organizes into a conformal lattice at $t = 2000$ ns, characterized by pronounced gradients in lattice constant and skyrmion density while recovering strong local sixfold order, with $\langle |\psi_6| \rangle$ saturating at approximately 0.92 (Figure 1h,i). The nonmonotonic evolution of $\langle |\psi_6| \rangle$ in the simulations closely matches the experimental trend (Figure 1b–d), confirming that directional current driving does not simply melt the skyrmion lattice into a disordered state. Compared with the ideal hexagonal SKL, the final conformal lattice shows only an approximately 0.08 reduction in $\langle |\psi_6| \rangle$. The inverse conformal mapping in Figure 1j further supports the conformal nature of this state, as the spatially graded lattice is mapped back to an approximately hexagonal distribution [39, 40], consistent with the ideal conformal structure generated from a hexagonal skyrmion lattice shown in Figure S2. These results show that directional current driving does not simply melt the skyrmion lattice into a disordered state, but instead drives a transition from an initial hexagonal skyrmion-lattice solid phase to a conformal ordered phase through transient loss and subsequent recovery of local hexagonal order.

2.2 | Conformal Phase Revealed by the Conformal Order Parameter

The conformal phase is not merely a density-modulated lattice, but a distinct ordered state with periodically modulated local orientation (Figure 2a–c). To characterize this orientational texture, we define the local lattice orientation angle as $\alpha = \arg(\psi_6)/6$. Owing to the sixfold rotational symmetry of the skyrmion lattice, α is folded into the range from -30° to $+30^\circ$, where the two endpoints are geometrically equivalent (Figure 2d). In the solid phase, α remains close to 0° throughout the system, indicating a nearly uniform lattice orientation and long-range orientational order (Figure 2a). At $t = 240$ ns, the spatial distribution of α becomes highly irregular, indicating a disordered quasi-liquid state that serves as an intermediate stage in the solid-to-conformal transition (Figure 2b). In the steady conformal phase, by contrast, α develops a pronounced spatial periodicity, varying continuously from $+30^\circ$ to 0° and then to -30° within each period (Figure 2c). The corresponding line profiles of α at representative times are shown in Figure S3.

To resolve this periodic orientational modulation quantitatively, we calculate the transverse orientational correlation function,

$$C_\alpha(\Delta x) = \langle \cos [6(\alpha_i - \alpha_j)] \rangle_{|x_j - x_i| \approx \Delta x} \quad (2)$$

where x_i and x_j denote the transverse coordinates of two skyrmions. The factor of 6 accounts for the sixfold rotational symmetry of the skyrmion lattice. Figure 2e shows $C_\alpha(\Delta x)$ at representative stages of the transition. In the solid phase, $C_\alpha(\Delta x)$ remains close to unity over the full range of Δx , consistent

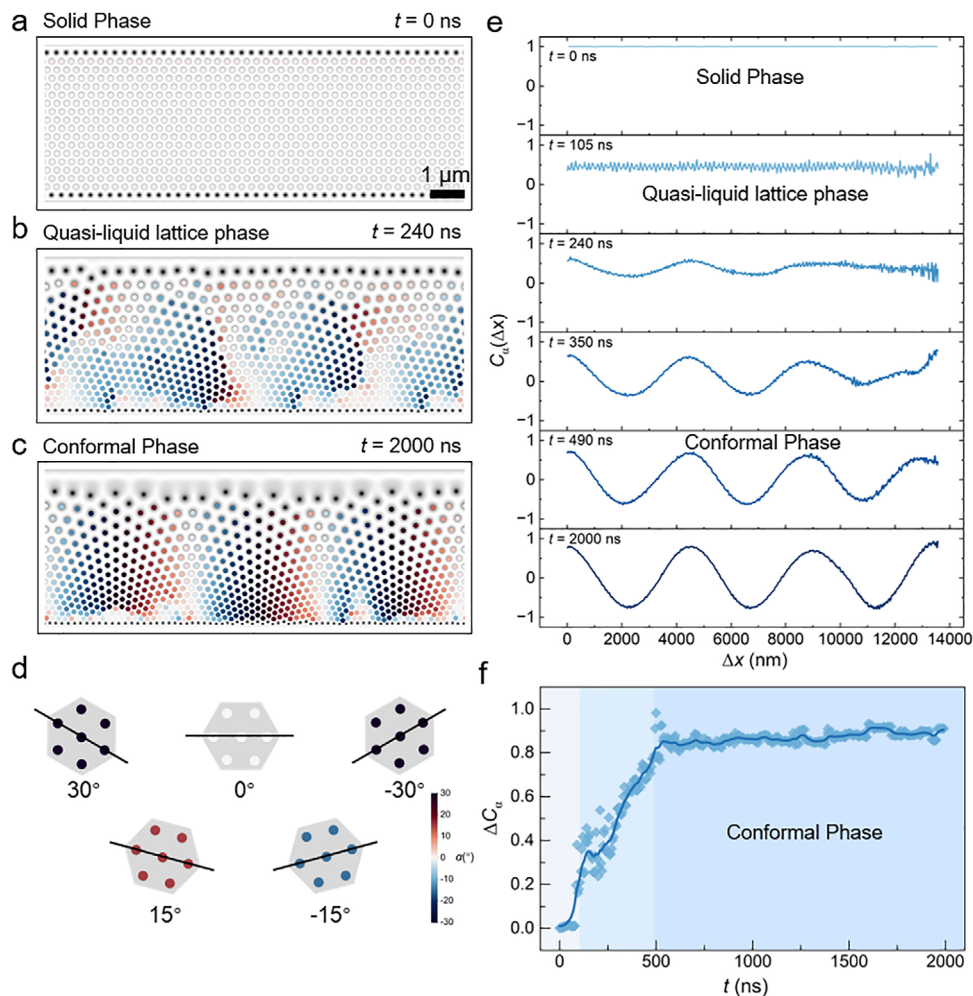


FIGURE 2 | Conformal phase revealed by the conformal order parameter. (a–c) Spatial distributions of the local orientation angle α , revealing the evolution of skyrmion-lattice orientational order from the solid phase (a) with nearly uniform long-range order, through a disordered quasi-liquid phase (b) at $t = 240$ ns characterized by irregular spatial variations of α , to the conformal phase (c) exhibiting periodic spatial modulation of α . (d) Definition of the local lattice orientational angle α , obtained from the phase of the local sixfold orientational order parameter and folded into the range from -30° to $+30^\circ$. (e) Transverse orientational correlation function $C_\alpha(\Delta x)$ showing the development of an oscillatory modulation during conformal ordering. (f) Time evolution of the conformal order parameter ΔC_α .

with a uniform orientational field. At the earlier time of $t = 105$ ns, the correlation is already strongly suppressed, reflecting the loss of orientational coherence in the quasi-liquid state. With continued current injection, $C_\alpha(\Delta x)$ develops a stable oscillatory modulation. From $t = 490$ to 2000 ns, the correlation function exhibits three robust periods, matching the three-period conformal structure observed in Figure 2c.

The oscillation amplitude of $C_\alpha(\Delta x)$ then provides a natural measure of conformal ordering. We therefore define the conformal order parameter as

$$\Delta C_\alpha = \frac{1}{2} \left[\max_{\Delta x} C_\alpha(\Delta x) - \min_{\Delta x} C_\alpha(\Delta x) \right] \quad (3)$$

The time evolution of ΔC_α reveals the emergence and stabilization of the conformal phase (Figure 2f). ΔC_α remains close to zero in the initial solid phase, increases during the reorganization from the quasi-liquid state, and then saturates once the conformal phase is established. The conformal ordering remains robust

under different boundary conditions and over a broad range of system widths, although ΔC_α gradually decreases with increasing width (Figure S4). It is also modulated by the nonadiabatic spin-transfer torque, with a weaker nonadiabatic contribution favoring a higher degree of conformal ordering (Figure S5). Thus, ΔC_α captures the emergence of periodic local-orientation modulation and serves as an effective order parameter for identifying the conformal phase.

2.3 | Unsupervised Phase Identification via Graph Neural Networks

To identify local structural states without predefined phase labels or manually selected order-parameter thresholds, we construct an unsupervised graph-learning framework that learns directly from local lattice geometry (Figure 3a). This approach enables probabilistic phase decomposition in real space and provides a data-driven description of coexisting structural states during the solid-to-conformal transition.

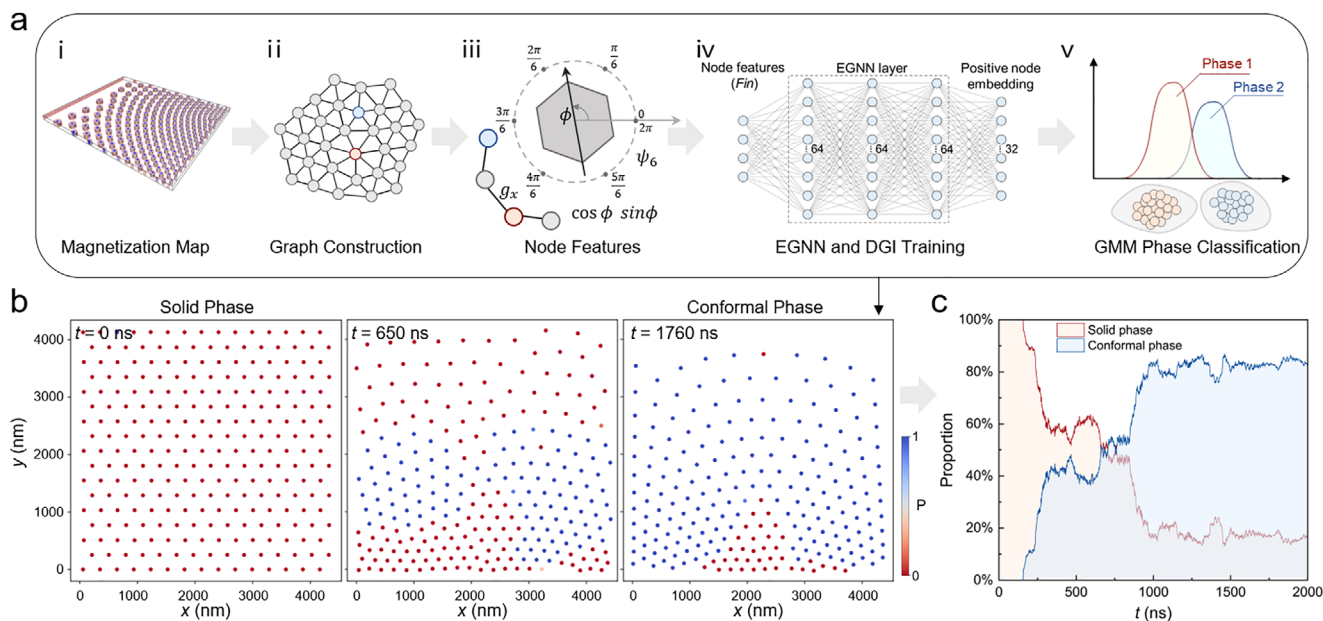


FIGURE 3 | Graph neural networks-driven unsupervised phase identification. (a) Workflow of the deep-learning pipeline. Starting from the magnetic configuration (i), a Delaunay triangulation is performed to construct the local lattice graph and extract node features (ii). The structural features and nearest-neighbor connectivity are then used to compute node descriptors (iii), which serve as inputs to the equivariant graph neural network (EGNN) (iv). After three EGNN message-passing layers, latent node embeddings are obtained and subsequently clustered in the feature space using a Gaussian mixture model (GMM) (v), yielding a probabilistic two-class classification. (b) Real-space phase classification at different times. The lattice initially appears as a fully solid-like phase at $t = 0$ ns, gradually evolves into a mixed two-phase state, and eventually transforms into a conformal lattice phase during the dynamical evolution. (c) Temporal evolution of the phase fractions. As the electric current is progressively injected, the fraction of particles belonging to the conformal lattice phase increases and eventually saturates.

The workflow begins by converting each magnetic configuration into a graph representation of the skyrmion lattice, where individual skyrmions serve as nodes, and Delaunay triangulation defines the edges (Figure 3a (i, ii)). Each node is described by physically motivated features, including $|\psi_6|$, $\sin \phi$, $\cos \phi$, and the orientational-gradient descriptor g_x , where $\phi = \arg(\psi_6) = 6\alpha$ (Figure 3a (iii)). The amplitude $|\psi_6|$ quantifies local hexagonal order, whereas g_x captures spatial variations in bond orientation associated with lattice distortion and conformal rotation. The graph is then encoded by an equivariant graph neural network (EGNN) [41, 42] and trained using Deep Graph Infomax (DGI) self-supervision (Figure 3a (iv)) [43]. A two-component Gaussian mixture model (GMM) is then applied in the learned embedding space to decompose the lattice into coexisting structural states (Figure 3a (v)) [44]. This unsupervised workflow yields node-resolved phase maps and frame-averaged phase fractions, allowing the solid-to-conformal transition to be quantified in real space.

Data-driven phase maps reveal a continuous real-space reorganization of the skyrmion lattice during the solid-to-conformal transition (Figure 3b). At the initial stage ($t = 0$ ns), nearly all skyrmions are assigned to the solid-like lattice phase. Upon current injection, regions with distinct local structural characteristics emerge within the lattice. At $t = 650$ ns, the system enters a broad coexistence regime, where solid-like and conformal regions occupy different spatial domains. With further evolution, the conformal phase progressively expands and becomes dominant. By $t = 1760$ ns, it occupies most of the system, indicating that conformal ordering develops through the gradual conversion

of local lattice environments rather than through an abrupt collective transformation.

The corresponding phase fractions (Figure 3c) further quantify this process. With increasing current-injection time, the fraction of skyrmions assigned to the conformal phase increases continuously, while the solid-like fraction decreases accordingly. At longer times, the conformal-phase fraction approaches a plateau, suggesting that the lattice reaches a dynamically stable conformal state. The smooth evolution of the phase fractions, together with the extended real-space coexistence, demonstrates that the solid-to-conformal transition proceeds through progressive local structural reorganization. This spatially resolved picture is consistent with the order-parameter analysis in Figure 2, where the gradual increase of ΔC_α captures the same continuous transition toward conformal ordering. More importantly, the unsupervised framework goes beyond global order-parameter analysis by resolving local lattice states at the node level, enabling rapid phase identification after training, and reducing the dependence on manually selected thresholds or predefined phase labels.

2.4 | Defect-Mediated Conformal Ordering

We further apply orientational-correlation analysis [20, 21] to the current-driven solid-to-conformal transition to reveal how local orientational order is reorganized during conformal-lattice formation. Figure 4 shows that the transition proceeds through the coupled evolution of orientational correlations and lattice

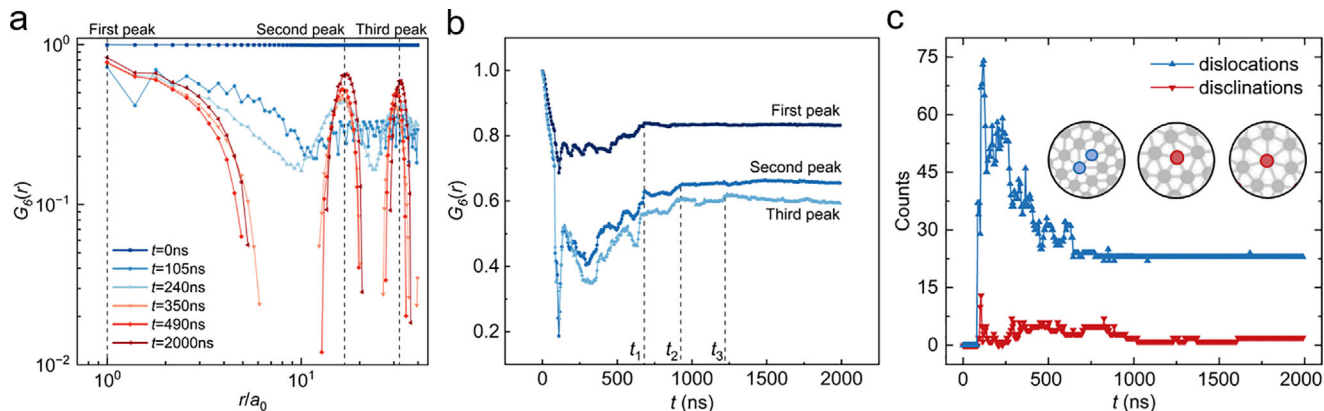


FIGURE 4 | Orientational correlations and defect evolution across the solid-to-conformal transition. (a) Sixfold orientational correlation function $G_6(r) = \langle \psi_6(\mathbf{r}_m) \psi_6^*(\mathbf{r}_n) \rangle_{|\mathbf{r}_m - \mathbf{r}_n| = r}$, averaged over all skyrmion pairs separated by r , at representative stages of the transition. The first, second, and third peaks correspond to short-, intermediate-, and long-range orientational correlations, respectively. (b) Time evolution of the three peak values of $G_6(r)$. t_1 , t_2 , and t_3 mark the onset of stabilization of the first, second, and third peaks, respectively. (c) Time evolution of the counts of dislocations and disclinations during the transition.

defects. Unlike thermal-fluctuation-driven melting [18, 21], this transition connects one ordered lattice state to another rather than producing an orientationally disordered phase. Specifically, we examine the evolution of the orientational correlation function [24],

$$G_6(r) = \langle \psi_6(\mathbf{r}_m) \psi_6^*(\mathbf{r}_n) \rangle_{|\mathbf{r}_m - \mathbf{r}_n| = r} \quad (4)$$

where $\mathbf{r}_m$ and $\mathbf{r}_n$ denote the positions of the m -th and n -th skyrmions, respectively, and the average is taken over all skyrmion pairs separated by r . In the initial solid phase, $G_6(r)$ remains close to unity over the measured distance range, indicating nearly uniform orientational coherence across the lattice (Figure 4a). During the early stage of current driving, up to $t = 240$ ns, the correlation curve decays strongly with distance: short-distance correlations remain relatively high, whereas intermediate- and longer-distance correlations are markedly reduced. Neighbouring skyrmions therefore retain local hexagonal alignment, while orientational coherence over larger regions is disrupted. From $t = 350$ ns onward, oscillatory features emerge at larger r , and the second and third correlation maxima become increasingly pronounced. This evolution shows that conformal-lattice formation rebuilds intermediate- and longer-range orientational correlations in a spatially modulated form, rather than restoring the nearly uniform orientational coherence of the initial solid phase.

Figure 4b further quantifies the progressive reconstruction of orientational correlations at short, intermediate, and long ranges by tracking three representative maxima of $G_6(r)$. The short-range maximum remains comparatively high throughout the evolution and reaches its steady value first at t_1 , whereas the intermediate- and longer-range maxima are more strongly suppressed and recover more gradually, approaching their steady-state plateaus at t_2 and t_3 , respectively, with $t_1 < t_2 < t_3$. The delayed recovery at larger distances shows that conformal-lattice formation does not restore the nearly uniform orientational coherence of the initial solid phase, but instead rebuilds orientational correlations progressively from local hexagonal alignment to larger length scales.

The orientational reconstruction is closely correlated with the defect evolution shown in Figure 4c. During the early destabilization of the solid lattice, dislocations increase rapidly and reach a maximum, whereas disclinations rise only weakly. As the conformal phase develops, dislocations decrease markedly, while disclinations gradually decline and then stabilize. This defect trajectory differs from thermally driven skyrmion-lattice melting, where both defect types proliferate toward the liquid state [18, 21]. The non-monotonic evolution of $G_6(r)$ can therefore be understood as a consequence of this defect-mediated process: larger-scale orientational coherence is first disrupted by the accumulation of dislocations and then rebuilt as the defect density decreases during conformal-lattice formation. These results identify the solid-to-conformal transition as a defect-mediated reorganization between ordered lattice states, rather than an order-disorder melting process.

3 | Discussion

Our results demonstrate experimentally a current-driven skyrmion-lattice reorganization pathway that transforms the lattice into a distinct ordered conformal skyrmion phase, fundamentally different from thermally driven order-disorder melting. The L-TEM observations directly reveal the current-induced structural reorganization and the formation of a spatially modulated lattice with graded spacing and orientation. Micromagnetic simulations further resolve the underlying evolution of lattice order, revealing a non-monotonic pathway in which larger-scale orientational coherence is first disrupted by dislocation accumulation and then rebuilt into a spatially modulated conformal order. In the simulations, the recovery of intermediate- and longer-range correlations in $G_6(r)$, together with the decrease of defect density, demonstrates that the final state is a reconstructed ordered phase rather than a remnant of disorder. The combined experimental and simulation results therefore establish that the conformal phase is not merely a density-compressed lattice, but an ordered state with spatially graded lattice spacing and modulated local orientation, in which local angular coordination is largely preserved despite

substantial global deformation. The conformal order parameter ΔC_α , extracted from the simulations, provides a quantitative measure of this emergent order, establishing the solid-to-conformal transition as a defect-mediated order-to-order transformation driven by Hall motion-induced compression.

Beyond structural analysis, unsupervised graph learning applied to the simulated configurations enables direct identification of the heterogeneous transition landscape from local lattice geometry. Without predefined phase labels or manually selected thresholds, the EGNN-DGI-GMM framework resolves local lattice states at the node level and captures the progressive conversion from solid-like to conformal phase regions. Once trained, the framework enables rapid phase identification in subsequent frames, highlighting the value of AI-based analysis for detecting phase evolution in driven topological matter.

4 | Methods

4.1 | Sample Preparation and L-TEM Observation

Single crystals of $\text{Co}_0.5\text{Zn}_{0.5}\text{Mn}_2$ were synthesized using the Bridgman growth technique [45]. A thin lamella along the (001) crystallographic direction was subsequently fabricated from the bulk crystal by focused ion beam milling. Selected-area electron diffraction was used to verify the crystallographic orientation, while energy-dispersive X-ray spectroscopy confirmed the phase purity and elemental composition. The magnetic textures were imaged in real space by Lorentz transmission electron microscopy using a JEOL-F200 microscope. To stimulate skyrmion motion during observation, pulsed voltages generated by an arbitrary waveform generator were applied to the sample, enabling controlled current-driven dynamics of the skyrmion lattice.

4.2 | Micromagnetic Simulations

Micromagnetic simulations were performed using the MuMax3 package [46], which numerically integrates the Landau–Lifshitz–Gilbert equation including the Zhang–Li spin-transfer torque under current injection. The magnetization dynamics follow:

$$\frac{d\mathbf{m}}{dt} = -\gamma \mathbf{m} \times \mathbf{H}_{\text{eff}} + \alpha \mathbf{m} \times \frac{d\mathbf{m}}{dt} - (\mathbf{v}_s \cdot \nabla) \mathbf{m} + \beta \mathbf{m} \times [(\mathbf{v}_s \cdot \nabla) \mathbf{m}] \quad (5)$$

Here, $\mathbf{m}$ denotes the normalized magnetization vector, γ is the gyromagnetic ratio, α is the Gilbert damping coefficient, $\mathbf{v}_s$ is the spin drift velocity, and $\mathbf{H}_{\text{eff}}$ is obtained from the functional derivative of the total magnetic energy with respect to the magnetization. The third term represents the adiabatic spin-transfer torque, which describes the translational driving of the local magnetization texture by the spin-polarized current along the electron drift direction. The fourth term corresponds to the nonadiabatic spin-transfer torque, which accounts for an additional transverse torque arising from nonadiabatic effects, with its magnitude characterized by the parameter β . The material parameters were selected to approximate the effective magnetic properties of the Co–Zn–Mn chiral magnet system reported experimentally [47]. In the simulations, we used a saturation magnetization $M_s = 1.1 \times 10^5 \text{ A} \cdot \text{m}^{-1}$, exchange stiffness $A_{\text{ex}} = 2.8 \times 10^{-11} \text{ J} \cdot \text{m}^{-1}$, bulk

Dzyaloshinskii–Moriya interaction constant $D = 1.2 \times 10^{-3} \text{ J} \cdot \text{m}^{-2}$. The computational domain used in Figure 1 consists of a grid of $680 \times 256 \times 8$ cells with a uniform cubic discretization of 20 nm. Periodic boundary conditions were applied along the x direction, while the y direction remained open.

4.3 | Graph-Based Unsupervised Framework

To identify the conformal phase in a spatially resolved and label-free manner, we construct a graph-based unsupervised learning framework for the skyrmion lattice (Figure 3a). For each frame, individual skyrmions are first detected from the out-of-plane magnetization map $m_z(x,y)$ (Figure 3a (i)), and their centroid positions are taken as graph nodes. The skyrmion configuration is then represented as an undirected graph.

$$G = (V, E), V = \{r_i\}_{i=1}^N, E = \{(i, j) \mid (i, j) \in \text{Del}(V)\} \quad (6)$$

where r_i denotes the position of the i -th skyrmion, and $\text{Del}(V)$ denotes the Delaunay triangulation constructed from the node positions in V . Accordingly, E is the set of edges connecting Delaunay-neighboring skyrmions. This construction provides a natural description of the local lattice topology (Figure 3a (ii)).

To distinguish the conformal phase from the solid-like lattice, each node is described by a compact set of bond-orientational features,

$$\mathbf{x}_i = [\cos\phi_i, \sin\phi_i, |\psi_6(i)|, g_x(i)] \in \mathbb{R}^4 \quad (7)$$

where $\mathbb{R}^4$ denotes the 4D real-valued feature space, and

$$\phi_i = \arg[\psi_6(i)] = 6\alpha_i \quad (8)$$

Here, α_i is the local lattice orientation angle defined in Figure 2d, $|\psi_6|$ characterizes the degree of local hexagonal order, and g_x describes the spatial variation of lattice orientation along the driving direction. As illustrated in Figure 3a (iii), these descriptors are chosen to capture the structural characteristics most relevant to the present transition. The resulting graph is encoded by an equivariant graph neural network, which incorporates both local structural descriptors and geometric relations between neighboring skyrmions and is therefore well suited for structurally distorted lattices (Figure 3a (iv)). The encoder is trained in a self-supervised manner using Deep Graph Infomax, so that the learned embedding reflects the intrinsic structural organization of the lattice rather than any manually defined classification.

After training, the node embeddings z_i from all frames are analyzed using a two-component Gaussian mixture model, which yields the posterior probability,

$$\gamma_i^{(k)} = p(k \mid z_i) \quad (9)$$

where z_i is the embedding of node i , k denotes the GMM component, and $\gamma_i^{(k)}$ is the probability that node i belongs to component k . The two components are identified as the solid-like and conformal-like states according to their structural characteristics.

For each frame, the fraction of component k is defined as

$$f_k = \frac{1}{N} \sum_{i=1}^N \gamma_i^{(k)} \quad (10)$$

where N is the total number of skyrmion nodes in the frame. This quantity tracks the evolution of the solid-like and conformal-like components during current driving. The corresponding real-space maps and component fractions are shown in Figure 3b,c, respectively.

Author Contributions

L.P. supervised the work and designed the experiments. W.Z., S.L., G.Z., and L.P. performed the simulations and data analysis. W.Z. and S.L. developed and implemented the CNN-related code. S.F. and T.X. grew the single-crystal materials. Q.L. and H.L. fabricated the samples. W.Z. and Q.L. performed the L-TEM measurements. G.R.Z. contributed to funding acquisition and discussion of the results. W.Z. and S.L. drafted the manuscript. L.P. led the major revision and finalization of the manuscript with input from G.Z., J.Y. and Y.H. All authors discussed the results and contributed to the final version of the manuscript.

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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 on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

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Supporting Information

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