Magnetic skyrmion bundles and their current-driven dynamics

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Topological charge $Q$ classifies non-trivial spin textures and determines many of their characteristics. Most abundant are topological textures with $|Q| \leq 1$, such as (anti)skyrmions, (anti)merons or (anti)vortices. In this study we created and imaged in real space magnetic skyrmion bundles, that is, multi-$Q$ three-dimensional skyrmionic textures. These textures consist of a circular spin spiral that ties together a discrete number of skyrmion tubes. We observed skyrmion bundles with integer $Q$ values up to 55. We show here that electric currents drive the collective motion of these particle-like textures similar to skyrmions. Bundles with $Q \neq 0$ exhibit a skyrmion Hall effect with a Hall angle of ~62°, whereas $Q = 0$ bundles, the so-called skyrmioniums, propagate collinearly with respect to the current flow, that is, with a skyrmion Hall angle of ~0°. The experimental observation of multi-$Q$ spin textures adds another member to the family of magnetic topological textures, which may serve in future spintronic devices.

A magnetic skyrmion is a particle-like spin whirl (Fig. 1a) with an elementary topological charge $Q$, defined as $Q = 1/(4\pi) \int \mathbf{r} \cdot (\mathbf{m} \times \nabla \mathbf{m})$, which essentially counts how many times the magnetization vector field $\mathbf{m}$ at the position $\mathbf{r} = (x,y)$ winds around the unit sphere. Such integer-valued topological charge $Q$ induces the Magnus force acting on skyrmions, resulting in a sideways motion dubbed the skyrmion Hall effect. The non-zero topological charge of a magnetic skyrmion also manifests itself through the emergent electromagnetic field, giving rise to strong spin–electronic couplings and skyrmion motion under low current density. This property, together with its tunable nanometre-scale size, promises applications in future high-density and low-energy-consumption spintronic devices, including skyrmion racetrack memory, logical devices and artificial synapses for neuromorphic computing.

Like many elementary particles in nature, a skyrmion only has unit topological charge $Q = \pm 1$ (ref. 1). As an elementary quality in topological magnetism, it is fundamental to explore topological spin textures with other integer values of topological charge. Experiments have demonstrated non-zero high-$Q$ skyrmion cluster states that can be driven by current in the thin plate of chiral magnet FeGe (ref. 1). In addition, metastable multi-$Q$ skyrmionic textures with particle-like behaviour in two-dimensional (2D) chiral magnets have been theoretically predicted. A skyrmionium, or equivalently a $2\pi$-vortex (Fig. 1b), has a spin rotation angle of $2\pi$ from the centre to the periphery. Because $Q=0$ in a skyrmionium, the skyrmion Hall effect should be absent and the trajectory can be controlled easily. The high-$Q$ skyrmion bag state, or the skyrmion sack, was recently observed in liquid crystals and proposed in chiral magnets. In a magnetic system, a skyrmion bag comprises $N$ skyrmions inside a larger circular spin spiral (Fig. 1c). The topological charge of a bag is the summation of that of the centre skyrmions and the boundary helical stripe, as the integral in the definition of topological charge implies. The skyrmions inside the bag are conventional, with polarity $p=1$ and vorticity $v=1$, so that each skyrmion has the topological charge $Q=1$. The boundary helical stripe has the same vorticity but opposite polarity, so that $Q=-1$. As a result, the bag has $Q=N-1$. Owing to their high degrees of freedom and particle-like character, skyrmion bags have potential for spintronics applications such as interconnect devices.

Here, we report the unequivocal experimental realization of a type of three-dimensional (3D) multi-$Q$ skyrmionic textures and their response to current pulses in the thin plate of a B20-type chiral FeGe magnet by using in situ Lorentz transmission electron microscopy (TEM). Skyrmion bags persist in the interior of such magnetic objects and turn to multi-$Q$ chiral vortices around the surface. We have created these multi-$Q$ skyrmionic textures by inversely magnetizing the coexisting non-equilibrium state of skyrmions and spin spirals, and further found that the skyrmion Hall effects depend on the sign of their $Q$.

Creation of skyrmion bundles

In real chiral magnet samples, the third dimension causes profound differences in spin textures. The skyrmion forms a tube, which generates monopoles, or chiral magnetic bobbers when broken, twisted along the third dimension. In this case, the topological charge $Q$ is specified in each layer of a 3D magnetic configuration because the topological charge is only defined in a 2D plane. To explore the possibility of multi-$Q$ states and analyse the detailed spin textures therein, we performed simulations on a thin FeGe plate with a thickness of $t = 150$ nm using the measured magnetic parameters of FeGe (see Methods section for details of the MuMax3 calculations). Relaxing a uniformly stacked skyrmion bag with topological charge.

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Q = 5 as the initial state, we obtained a stable 3D texture very different from the simple stacking of skyrmion bags in the thickness direction because of the conical magnetization background (Supplementary Fig. 1 and Supplementary Note 1). As shown in Fig. 1d, the skyrmion bags only persist in the interior of the sample. On approaching the sample surfaces, the central skyrmions twist and merge with the surrounding spin spiral. Therefore, the skyrmion bag gradually deforms into a complex chiral vortex structure at the sample surface. Detailed analysis showed that the surface vortex also has a topological charge of Q = 5 (Supplementary Fig. 2). The topological charge Q actually has the same value in each sliced layer (Supplementary Fig. 3 and Supplementary Video 1). Given their geometries, these new topological textures with interior skyrmion bags only and surficial multi-Q chiral vortices are termed skyrmion bundles, in analogy to the vortex bundles in superconductivity. The Lorentz TEM technique is only sensitive to variations in the in-plane magnetic component integrated along the electron trajectory. The average in-plane magnetization of the simulated Q = 5 skyrmion bundle is shown in Fig. 1e, with the magnetic contrast of the boundary spin spiral being weaker than that of the skyrmions inside owing to the aforementioned 3D modulation of the skyrmion bundle.

Considering the simulated results, a thin plate of B20-type FeGe of identical thickness (t = 150 nm) was employed to demonstrate the formation of skyrmion bundles. FeGe has a high Curie temperature at Tc ≈ 278 K. The ground state at zero magnetic field consists of a magnetic spiral with a relatively small period L0 ≈ 70 nm. When a magnetic field B was applied perpendicular to the plate, the magnetic spiral states transferred to magnetic skyrmion tubes of Q = −1 (Q = 1) for a positive (negative) magnetic field (Extended Data Fig. 1). Because the transition is first order, a coexisting non-equilibrium state of the skyrmions and spin spirals is allowed and is the precursor of the skyrmion bundles. Using a field-cooling procedure (Extended Data Fig. 1), we created the mixed state at zero field and low temperature (T = 95 K), as shown in Fig. 2a. Because a negative field was applied for field-cooling, skyrmion tubes with Q = 1 (white dots) nucleated from the spiral background. Afterwards, a positive field was gradually turned on. Although Q = 1 skyrmion tubes are not thermodynamically stable in positive fields, they can typically survive in the non-equilibrium metastable state in moderate positive fields (Fig. 2b). Most of the skyrmion tubes disappeared on further increasing the field to B ≈ 200 mT, but the ones left, which are represented by white dots, formed a cluster of six skyrmions encircled by a dark ring (Fig. 2c). Analysis using the transport-of-intensity equation (TIE) enabled in-plane magnetization mapping, which revealed that the surrounding circular spiral with weak contrast (Fig. 2d) has the opposite rotation sense compared with the skyrmions inside. This experimental result is in good agreement with the theoretical one (Fig. 1e), clearly indicating a skyrmion bundle of Q = 5. The skyrmion bundle persisted after its creation, even when the field was reduced. Repeating all this from the field-cooling step, skyrmion bundles could always be generated, but the number of skyrmion tubes in the bundle varied and depended on the initial magnetic configurations.

**Magnetic field-induced transitions**

The topological charge of the skyrmion bundle is tunable using cascading topological transitions induced by a varying magnetic field. A skyrmion bundle with 18 skyrmions inside was used as a representative demonstration (Fig. 2e). It persisted up to B ≈ 160 mT. Further increment of the field annihilated one skyrmion tube inside, while the boundary spin spiral remained robust. The topological transitions were reversible, and the skyrmion bundle fully recovered upon reducing the field to zero.
charge was thus reduced by 1. Such topological transitions, successively killing skyrmions, continued over a broad field range of 160 mT < B < 320 mT, with a magnetic bundle with Q = 0 appearing at B ≈ 235 mT. Such a skyrmion bundle has only one skyrmion tube wrapped inside it (Supplementary Fig. 3), and therefore it is the generalization of the skyrmionium in 3D (ref. 19). Interestingly, on further increasing the field to ~321 mT, the internal skyrmion tube disappeared and the outside spin spiral shrank to a normal skyrmion tube with Q = −1. This behaviour validates the topological equivalence between the surrounding spin spiral and the Q = −1 skyrmion, in spite of the visible difference in their magnetic configurations.

Figure 2f shows the field-driven evolution of the topological charge. Reversing the fields of the entire process generated skyrmion bundles with negative topological charge (Extended Data Fig. 2b). By combining the field-cooling process and the field-driven cascading topological transition, a complete set of topological charge values was achieved with bundles containing up to 56 skyrmions (Fig. 2g and Extended Data Fig. 2).

Current-driven motion

The multi-Q skyrmion bundles discovered in this study are not only novel magnetostatic states, but also quasiparticles in current-driven dynamics. A microdevice composed of a 150-nm-thick FeGe thin plate and two electrodes was fabricated for in situ Lorentz TEM observation (Extended Data Fig. 3a). All the skyrmion bundles moved collectively under an applied current.

Figure 3a shows a representative sequence of selected Lorentz TEM images of a Q = 18 skyrmion bundle after successive nano-second pulsed stimulations with a typical current density of j ≈ 4.0 × 1010 A m−2 applied in the −x direction. The pulse width was set to 80 ns with a frequency of 1 Hz (Extended Data Fig. 3). Despite a slight rotation, the skyrmion bundle moved as a rigid body in the x direction, opposite to the direction of current flow (Supplementary Videos 2), and it moved in the opposite direction when the current was reversed (Fig. 3b and Supplementary Video 3). A transverse motion in analogy to the skyrmion Hall effect was also observed4–6. Both longitudinal motion and the Hall effect were observed up to the Q = 55 bundle in our experiment (Supplementary Video 4). The dynamics of the single magnetic bundle are similar to the skyrmion aggregate reported by Yu et al.14. However, they are two different magnetic objects in essence. Magnetic bundles are stable magnetic objects with particle-like dynamic behaviour, and they remain separate and stable even when they get close to each other. In contrast, skyrmion aggregates easily merge when they get close owing to the attractive forces between them (Extended Data Fig. 4 and Supplementary Video 5)4–6, giving rise to the stochastic nature of the skyrmion number. Moreover, the aforementioned field-induced cascading topological transition and the skyrmionium with Q = 0 are beyond an assembly of normal skyrmions.
The trajectory of the Q = 18 skyrmion bundle reveals a linear relation between the displacement and time (Fig. 3c), as expected for normal skyrmions. Linear fitting under various current densities \( j \) showed that both the longitudinal and transverse velocities, \( v_x \) and \( v_y \), respectively, are proportional to the current density (Fig. 3d). The skyrmion Hall effect is qualitatively described by the Hall angle \( \theta_H \), defined as \( \tan \theta_H = v_y/v_x \) (ref. 5). The \( \theta_H-J \) curve indicates that \( \theta_H \) is about 60° (Fig. 3e).

The threshold current density \( j_{c1} \), required for the motion of skyrmion bundles is \( (2.5 - 4.0) \times 10^{10} \text{ A m}^{-2} \), depending on the topological charge \( Q \). Smaller particle-like magnetic objects, including the skyrmionium, single skyrmion and low-\( Q \) skyrmion bundles, have, in general, high values, suggesting that they are more easily pinned by localized defects (Extended Data Fig. 5). Such threshold current densities are two orders of magnitude smaller than that required for domain walls, and even one order of magnitude smaller than that of interfacial skyrmions. When the current density is larger than a threshold value \( j_{c2} = 4.5 \times 10^{10} \text{ A m}^{-2} \), skyrmion bundles become unstable during their motion, which can be attributed to inevitable Joule heating at large currents. It should be noted that the relatively high depinning current density \( j_{c2} \) and low \( j_{c1} \) give rise to a very small experimentally operational window of current density, which might be expanded by reducing the depinning current density in the helimagnets with high purity or spin-polarization.

**Q-related skyrmion Hall effect.** Longitudinal motions of both the \( Q = 0 \) skyrmion bundle, or the equivalent 3D skyrmionium, and the single skyrmion were observed as well, as shown in Fig. 4a,b. Excitingly, the skyrmion Hall effect does vanish for the skyrmionium owing to its zero \( Q \) and vanishing Magnus force (Supplementary Video 6). The slight deviation of the trajectory from the \( x \) direction can be reasonably attributed to the pinning of defects or disorders. More importantly, when the current direction was reversed, collinear motion in the opposite direction was also observed (Extended Data Fig. 6), further supporting the absence of the skyrmion Hall effect. The single skyrmion tube nucleated from the 3D skyrmionium has \( Q = -1 \), and hence the skyrmion Hall effect reappears, but the transverse motion is in the \(-y\) direction instead (Fig. 4b and Supplementary Video 7), which is consistent with the theoretical prediction.

The trajectories of the magnetic skyrmion bundles (\( Q > 0 \)), 3D skyrmionium (\( Q = 0 \)) and skyrmion (\( Q = -1 \)) are summarized in Fig. 4c. The skyrmion Hall effect is clearly seen for the \( Q \neq 0 \) skyrmionic textures and the vanishing skyrmion Hall effect for the \( Q = 0 \) 3D skyrmionium. The Q-dependent Hall angle is shown in Fig. 4d, which reveals that the sign of the Hall angle is determined by the sign of the topological charge. Moreover, the absolute value of the Hall angle \( |\theta_H| = 62 \pm 5° \) is almost independent of the current density \( j \), external field \( B \) (Extended Data Fig. 7) and non-zero \( Q \) (Fig. 4d and Extended Data Fig. 8). Such universal behaviour of the skyrmion Hall effect in bulk materials is different from previously reported observations on interfacial skyrmions or skyrmion bubbles in magnetic multilayers, in which the Hall angle \( \theta_H \) depends on the current density \( j \) and external field \( B \). For skyrmion bubbles in multilayers with diameters \( d \) and domain wall widths \( \gamma_{dw} \) (\( \gamma_{dw} < d \)), the shape factor \( \eta \), defined as \( \eta = \pi d/(8 \gamma_{dw}) \), may be strongly affected by the deformations of moving skyrmion bubbles, resulting in a drive-dependent Hall effect.
For the multi-Q skyrmion bundles, the Hall angle in the real system is the sum of the intrinsic and extrinsic contributions (see Supplementary Note 2 for details)\(^3\). The intrinsic \(\theta_H\) relates to a system without impurities and approximates to \(\theta_H \approx \arctan[(\alpha - \beta) \eta Q]\), where \(\alpha\) is the intrinsic Gilbert damping parameter of the material and \(\beta\) is the non-adiabatic constant\(^2\).

Numerical calculations show that for bundles, \(\eta\) is approximately proportional to \(Q\) (Fig. 5a), such that \(\theta_H\) is not strongly dependent on the topological charge \(Q\). Three-dimensional dynamics simulations using the measured magnetic parameters confirmed the weak dependence of \(\theta_H\) on \(Q\). The deviation of \(\theta_H\) depends on the magnetic parameters and is reduced to \(\sim 2^\circ\) as the coefficient \(\alpha - \beta\) increases to 0.65 (Fig. 5b). This relatively small variation in \(\theta_H\) is consistent with the results for 2D skyrmion bags\(^2\).

Such a small variation in \(\theta_H\) is within the error margin of our experiments. Impurities in real materials induce the extrinsic Hall angle\(^3\), which is inversely proportional to the current density and can be estimated to be in the range \(-50 - 65^\circ\) (for details on the estimation, see Supplementary Note 2.2). Generally, the value of \(\alpha\) is typically less than 0.1 in ferromagnetic metals\(^3\), so the intrinsic
Hall angle $\theta_H$ is less than 15°. Thus, the total $\theta_H$ is roughly in agreement with the experimental value of 62 ± 5°. Note that the quantitative calculation of $\theta_H$ in the real system is difficult and beyond the scope of the present work owing to the unknown $\alpha - \beta$ and the lack of exact information on impurities.

Conclusions
We have experimentally demonstrated that skyrmion bundles are stable, high-degree topological configurations and can be driven by current with varying Hall angles ordered by the sign of their topological charges. We expect that skyrmion bundles can be realized in a wide range of chiral magnets. Variable multi-Q magnetic states tunable by the magnetic field and drivable by electric current hold great promise for future spintronic devices, such as skyrmionium-based racetrack memory and atomic nucleus-like information encoding devices. In addition to collective motions as quasiparticles, further advances in the electrical reading and writing of the zoo of multi-Q skyrmion bundles invites extensive future investigations.

Online content
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Methods

Definition of the topological charge $Q$. The definition of $Q$ in a rotationally symmetric spin texture is clearer if the cylindrical coordinate is introduced. Setting the origin at the rotation centre, the spin at the polar coordinate $r = (r \cos \varphi, r \sin \varphi)$ has the polar angle $\theta$ and the azimuthal angle $\Phi$. Due to rotation symmetry, $\Phi$ has $\varphi$-dependence as $\Phi(\varphi) = \varphi + \gamma$, where the integer $\gamma$ is the vorticity and the residual angle $\varphi \in [-\pi, \pi]$ is the helicity. On the other hand, $\theta$ only has $r$-dependence, and the difference $p = \cos \Theta(r = \infty) - \cos \Theta(r = 0)$ defines the polarity. The polarity, vorticity and helicity uniquely define a skyrmion texture, and the topological charge is simply $Q = pv$.

Preparation of FeGe crystals. B20-type FeGe single crystals were grown by the chemical vapour transport method with a mixture of stoichiometric iron (Alfa Aesar, purity >99.9%), germanium (Alfa Aesar, purity >99.9%) and transport agent $I_2$. The B20-type FeGe crystallized in a temperature gradient from 560 to 300°C, forming nearly pyramidal shaped crystals with the space group $P6_3/m$.

Fabrication of FeGe microdevices. FeGe thin plates with a thickness of $t \approx 150 \text{ nm}$ for TEM magnetic imaging were fabricated by the lift-out method using a focused ion beam and scanning electron microscopy dual beam system (Helios Nanolab 600i, FEI) in combination with a gas injection system and a micromanipulator (Omniprobe 200+, Oxford).

TEM measurements. Magnetic imaging was carried out using a TEM instrument (Talos F200X, FEI) operated at 200 kV in the Lorentz Fresnel mode. The objective lens was switched off to provide field-free conditions. A single-tilt liquid-nitrogen (Talos F200X, FEI) operated at 200 kV in the Lorentz Fresnel mode. The objective lens was switched off to provide field-free conditions.

Micromagnetic simulations. Micromagnetic simulations were performed using MuMax3. The sum of the free-energy terms can be written as:

$$
e = f \{ \varepsilon_{\text{ex}} + \varepsilon_{\text{dis}} + \varepsilon_{\text{Zeeman}} + \varepsilon_{\text{dem}} \} \, d\mathbf{r}$$

where exchange energy $\varepsilon_{\text{ex}} = A_{\text{ex}}(\partial_i \mathbf{m}^2 + \partial_i \mathbf{m}^\perp + \partial_i \mathbf{m}^\parallel)$, Dzyaloshinskii-Moriya interaction (DMI) energy $\varepsilon_{\text{DMI}} = D_{\text{DMI}} \mathbf{m} \cdot (\nabla \times \mathbf{m})$, Zeeman energy $\varepsilon_{\text{Zeeman}} = -\mathbf{M} \cdot \mathbf{B}_{\text{ext}}$, $\mathbf{m}$ with the external magnetic field $\mathbf{B}_{\text{ext}}$ and demagnetization energy $\varepsilon_{\text{dem}} = -\frac{1}{2} \mathbf{M} \cdot \mathbf{B}_{\text{dem}}$, $\mathbf{m}$ with the demagnetization field $\mathbf{B}_{\text{dem}}$. Here, $\mathbf{m} = (m_x, m_y, m_z)$ is the normalized units continuous vector field, which represents the magnetization $\mathbf{M} = M_s \mathbf{m}$. $A_{\text{ex}}$, $D_{\text{DMI}}$, and $\mathbf{M}$ are the exchange interaction, DMI interaction and saturation magnetization, respectively. $\mathbf{B}_{\text{dem}}$ is the demagnetization field. We set a typical value for the saturation magnetization for FeGe as $M_s = 384 \text{ kA m}^{-1}$ (ref. 2). The exchange interaction $A_{\text{ex}} = 3.25 \text{ pJ m}^{-2}$ was determined from the fit to the field-dependence of magnetization evolution.

DMI interaction $D_{\text{DMI}} = 4\pi A_{\text{ex}} / L_0 = 5.834 \text{ mJ m}^{-2}$ was obtained from the zero-field spin spiral period $L_0 = 70 \text{ nm}$ (ref. 2). We set the cell size as $4 \times 4 \times 3 \text{ nm}^3$. We obtained the equilibrium spin configurations using the conjugate-gradient method.

Data availability

The data that support the plots provided in this paper and other findings of this study are available from the corresponding author upon reasonable request due to the huge volume (over 200 GB) of raw data in this study.

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Author contributions

H.D. supervised the project. H.D. and J.T. conceived the experiments. W. Wei synthesized the FeGe single crystals. J.T. and Y.W. fabricated the FeGe microdevices and performed the TEM measurements. J.T. performed the simulations. H.D., J.T. and J.Z. prepared the manuscript. All authors discussed the results and contributed to the manuscript.

Competing interests

The authors declare no competing interests.

Additional information

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Extended Data Fig. 1 | Field and temperature dependence of magnetic phase diagram. **a**, Magnetic phase diagram of a 150-nm thick FeGe plate. **b**, In-plane magnetization mappings of a skyrmion lattice with $Q = -1$ at $T = 270\,\text{K}$ and $B \approx 200\,\text{mT}$. **c**, In-plane magnetization mappings of a skyrmion lattice with $Q = 1$ at $T = 270\,\text{K}$ and $B \approx -200\,\text{mT}$. The scale bars in **b** and **c** are 100 nm. **d**, Transitions from helical domains at zero field and $T = 260\,\text{K}$ to the mixed skyrmions and spirals occur by increasing the negative field to $B \approx 0\,\text{mT}$. The mixed state persists during a negative field cooling process at $B \approx -70\,\text{mT}$. The zero-field mixed state at $T = 95\,\text{K}$ are finally achieved by decreasing the field to zero. The scale bars in **d** are 500 nm. SS, FM, PM, and SkL represent spin spirals, ferromagnetic state, paramagnetic state and skyrmion lattice, respectively. Defocus value in **d** is $-1000\,\mu\text{m}.$
Extended Data Fig. 2 | In-plane magnetic configurations of several typical magnetic skyrmion bundles with varying topological charges. The magnetic contrasts were retrieved by TIE analysis. a, Skyrmion bundles with varying topological charge, at $B \approx 100$ mT. b, Skyrmion bundles with a negative topological charge $Q = 1 - N$ at $B \approx -100$ mT. The scale bars are 100 nm.
Extended Data Fig. 3 | FeGe microdevice for the in-situ Lorentz experiments. a, Overall view of the FeGe microdevice obtained from scanning electron microscopy imaging. An FeGe thin plate was electronically connected to a microchip using the ion-beam-deposited platinum (PtC) as the electrode. Ion-beam-deposited carbon with electrical resistance greater than that of FeGe by three orders was deposited on the FeGe thin plate as a protection layer. Two narrow FeGe regions of thickness ~90 nm were fabricated on the two sides of the 150-nm thick FeGe thin plate for high-resolution TEM measurements. b, An 80-ns pulsed current profile applied in the microdevice. c, A high-resolution TEM image of the FeGe thin plate with the inset showing the TEM diffraction, revealing that the FeGe thin plate is a (111) crystal plane.
Extended Data Fig. 4 | Current-induced motion of skyrmion aggregates and bundles. **a**, Typical merging processes of two separated skyrmion aggregates ($Q = -3$ and $-2$, respectively) into one ($Q = -5$) when the distance between them decreases under the action of current pulses. **b**, Dynamics of two adjacent skyrmion bundles ($Q = 1$ and $2$, respectively) under the action of current pulses, respectively. In the whole process, the two skyrmion bundles keep stable even when they get closer. **c**, The averaged merging probability ($<p>$) of two adjacent skyrmion aggregates (blue dots line) and bundles (black dots line) with respect to their distance, $d$, defined as the central distance of their two nearest skyrmions. $p$ is counted as the “1” or “0” if the two adjacent skyrmion bundles (clusters) merge or not after a single current pulse. $<p>$ is sampled over a number of current pulses marked beside the data points. The statistical events of magnetic aggregates comprise of wide groups, e.g., $Q = -2$ and $Q = -3$, $Q = -2$ and $Q = -7$, $Q = -2$, $Q = -4$, $Q = -4$ and $Q = -10$ etc. The statistical events of magnetic bundles are obtained from three groups, i.e., $Q = 1$ and $Q = 2$, $Q = 0$ and $Q = 14$, and $Q = 1$ and $Q = 12$. The distance $d$ is rounded up the times of period of spin helix in FeGe ($\sim 70$ nm). $<p>$ increases as $d$ decreases for the magnetic aggregates. In contrast, the surrounding spiral of each skyrmion bundle protects the internal skyrmions from breaking down, resulting in the high stability of nearby magnetic bundles against current. The current density $j \sim 4.2 \times 10^{10}$ A m$^{-2}$ and $B \sim 100$ mT. The number and direction of current pulses is marked at the top of the corresponding panels. The numbers in **a** and **b** mark the topological charge. The pulse width is set to be 80 ns. The scale bar is 400 nm.
Extended Data Fig. 5 | Q-dependent low critical current density $j_c$. Small objects including skyrmionium, single skyrmion and low-Q skyrmion bundles have in general high values, suggesting that they are more easily pinned by localized defects.
Extended Data Fig. 6 | Current-driven motion of the skyrmionium. The current density is \( j \approx 4.2 \times 10^{10} \text{ A m}^{-2} \). The magnetic field is \( B \approx 100 \text{ mT} \). The scale bars in all panels are 400 nm.
Extended Data Fig. 7 | Dependence of skyrmion Hall angle $\theta_H$ on the magnetic field. Representative snapshots of the current-driven motion of a $Q = 36$ skyrmion bundle at $B \sim 70$ mT and a current density of $j \sim 4.0 \times 10^{10}$ A m$^{-2}$ in the $-x$ direction. The Lorentz images were obtained under the out-of-focus conditions with the defocus value of $-1000 \mu$m. b, Trajectories of the bag at various external fields. c, Magnetic field $B$ dependence of skyrmion Hall angle $\theta_H$. The scale bars in panel a are 500 nm.
Extended Data Fig. 8 | Current-driven motion of magnetic bundles with a, Q = 2, and b, Q = 5. The current density is \( j \sim 4.2 \times 10^{10} \text{A m}^{-2} \), and the magnetic field is \( B \sim 100 \text{mT} \). The Lorentz images were obtained under the out-of-focus conditions with a defocus value of \(-1000 \mu\text{m} \). The scale bars in all figures are 500 nm.