Scanning for skyrmions: Scientists directly image skyrmion cluster state transitions in iron-germanium nanodisks

May 26 2016, by Stuart Mason Dambrot

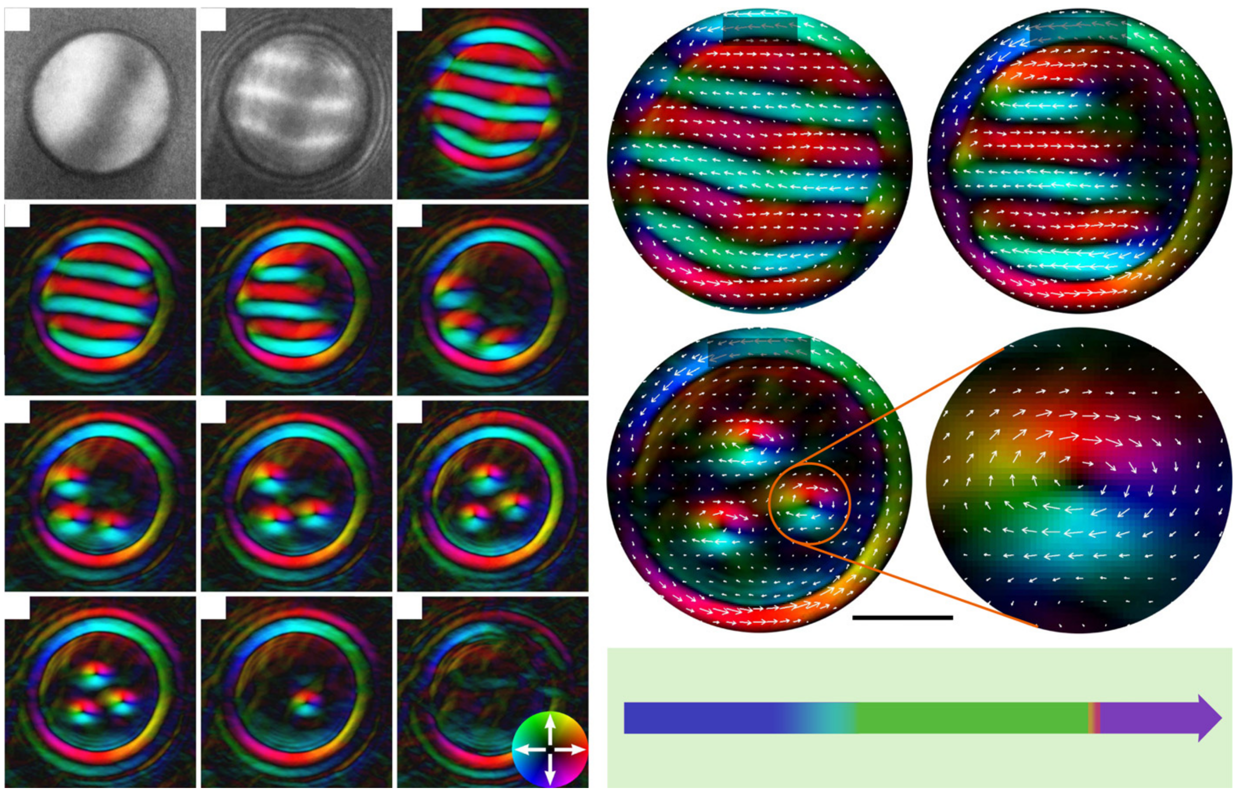

Fig. 1. Variations of spin texture with magnetic field in a 270-nm FeGe nanodisk at T = 100 K. (*A*) TEM image of the FeGe nanostripe surrounded by an amorphous PtC_x layer. (*B*) The intact magnetic contrast in ground state under underfocused conditions of Lorentz TEM with a defocus value of −192 μm. The magnetic field is applied perpendicular to the stripe plane. (*C*–*L*) Magnetic-field dependence of the spin texture at (*C*) 0 kOe, (*D*) 1.42 kOe, (E) 1.62 kOe, (*F*) 1.96 kOe, (*G*) 2.76 kOe, (*H*) 3.04 kOe, (*I*) 3.40 kOe, (*J*) 3.70 kOe, (*K*) 3.91 kOe,

and (*L*) 3.98 kOe. The color wheel in *L* indicates the direction and strength of inplane magnetization at each point. For clarity, some typical spin textures in *C*, *D*, and *I* are zoomed in *M*, *N*, and *O*, respectively. (*P*) A single skyrmion. The white arrows represent the in-plane magnetization at each point. (*Q*) The phase diagram in H space. N_s, skyrmion numbers. Credit: Xuebing Zhao, et al. (2016) Direct imaging of magnetic field-driven transitions of skyrmion cluster states in FeGe nanodisks. *Proc Natl Acad Sci USA* 113 (18) 4918-4923.

Magnetic skyrmions, or noncoplanar swirling spin textures, are particle-like spin configurations with an integer topological charge that promise faster, denser memory storage. The hurdle to overcome in creating such devices is being able to understand single skyrmions in patterned nanoelements – but despite theoretical progress, real-world experimental studies of these entities have remained elusive. Recently, however, scientists at Chinese Academy of Science, Hefei, Fudan University, Shanghai, Nanjing University, Nanjing, and University of New Hampshire, Durham have demonstrated the direct visualization of skyrmion cluster states having different geometrical configurations in iron-germanium nanodisks. (Iron-germanium, or FeGe, is a complex alloy whose magnetic properties can vary considerably at nanoscale dimensions.) The researchers conclude that their results have an immediate implication for designing future skyrmion-based devices.

Prof. Mingliang Tian (Chinese Academy of Science) and Prof. Renchao Che (Fudan University) discussed the paper that they and their colleagues published in *Proceedings of the National Academy of Sciences*. One of the main challenges the team encountered, Tian tells *Phys.org*, was demonstrating the direct visualization of skyrmion cluster states of in nanodisks fabricated from iron-germanium. The scientists accomplished this, he adds, by using high-resolution Lorentz transmission electron microscopy to report the magnetic field-driven dynamics of individual skyrmions in nanodisks with diameters on the order of several skyrmions. "Real-space imaging of skyrmions is essential for addressing the dynamic behaviors of individual skyrmions," he explains. "However, the real implementation is highly challenging because of limitations in spatial resolution, sensitivity and the edge effect of the nanostructure on the recorded contrast of Lorentz transmission electron microscopy." Lorentz transmission electron microscopy (LTEM) is used to study a material's magnetic domains by imaging the deflection of electrons caused by the Lorentz force in magnetic fields. "The latter issue seriously affects the visualization of individual skyrmions in nanostructures with sizes below 200 nm due to the presence of Fresnel fringes, formed at the edge of the nanostructure," adds Prof. Renchao Che, director of Fudan University's LTEM lab. "This is because LTEM imaging requires an out-of-focus condition that causes the Fresnel fringes to smear out the recorded magnetic signal in the vacuum/sample interface."

As described in the paper, Tian's team members and co-authors, Dr. Haifeng Du and doctoral student Chiming Jin, developed a technique to reduce the interfacial Fresnel fringes in the Lorentz TEM images by using a focused ion beam (FIB) to encircle the outer size-tunable nanodisks with a layer of amorphous platinum-carbon alloy (PtC_x). "This significantly reduced the size range of the artificial magnetic contrast," Tian explains, "thus leading to the direct image of the skyrmion cluster states in 100 nm scale disks."

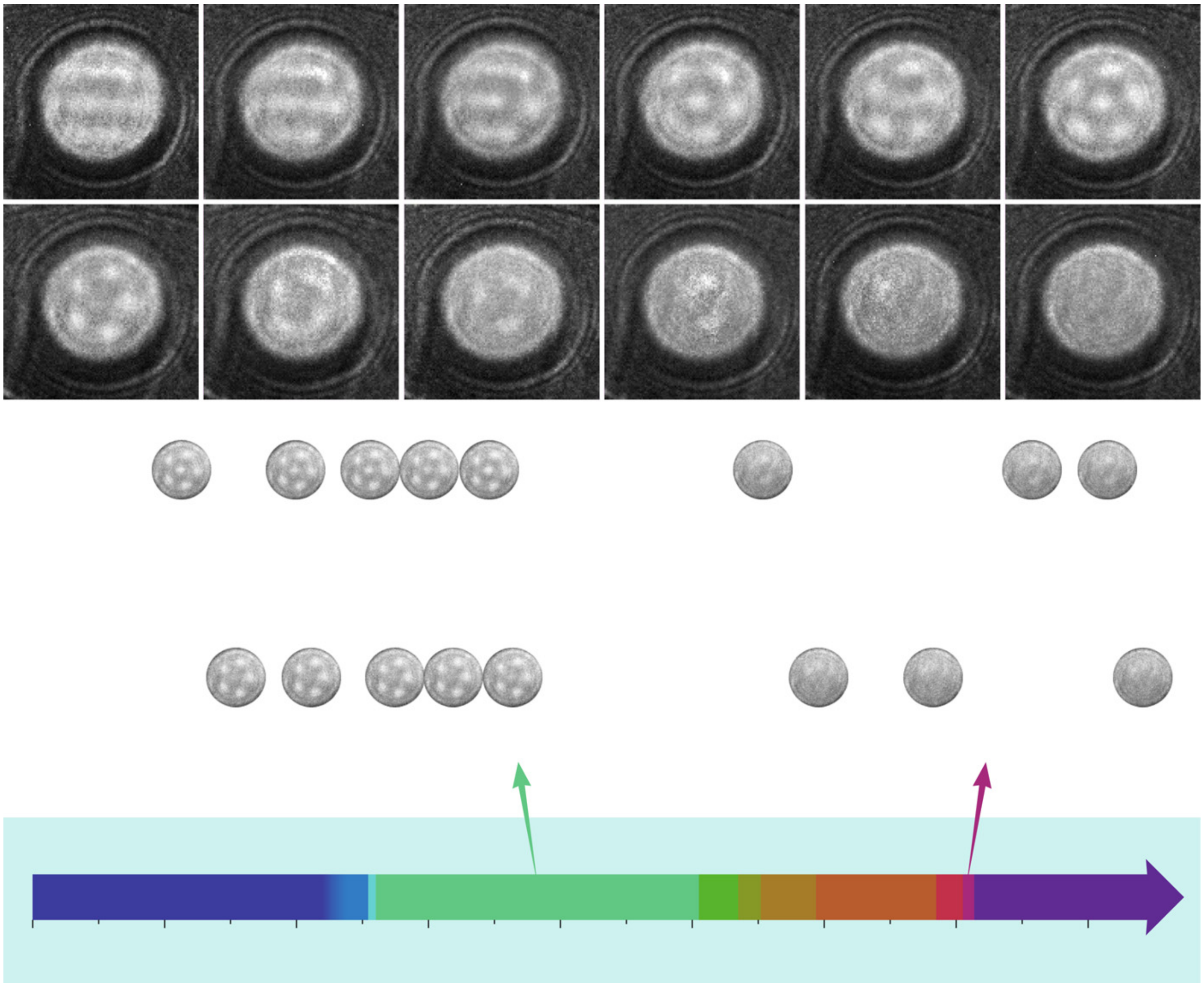

Fig. 2. Evolution of spin texture with magnetic field in a 270-nm FeGe nanodisk at temperature $T = 220$ K. (*A–L*) Magnetic-field dependence of the spin texture for (*A*) 0 kOe, (*B*) 0.44 kOe, (*C*) 0.47 kOe, (*D*) 0.51 kOe, (*E*) 0.52 kOe, (*F*) 0.56 kOe, (*G*) 1.01 kOe, (*H*) 1.11 kOe, (*I*) 1.37 kOe, (*J*) 1.41 kOe ($N_s = 2$), (*K*) 1.41 kOe ($N_s = 1$), and (*L*) 1.43 kOe. The bright spots represent skyrmions obtained by direct Lorentz TEM imaging, and dotted circles in *J* and *K* are used to guide the eye. (*M*) The quantized phase transitions between $N_s = 6$ and $N_s = 5$ cluster states. (*N*) The transitions between $N_s = 2$ and $N_s = 1$ cluster states. (*O*) The phase diagram in *H* space. The indicator "$N_s = 6/5$" represents the jumping state between $N_s = 6$ and $N_s = 5$ states, and so forth. Credit: Xuebing Zhao, et al. (2016) Direct imaging of magnetic field-driven transitions of skyrmion cluster states in FeGe nanodisks. *Proc Natl Acad Sci USA* 113 (18) 4918-4923.

Another issue the researchers encountered was determining the relationship between temperature, magnetic field, and disk size. "The real challenge in building this relationship comes from nanofabricating small disk samples," Tian notes. "We address this by using a top-down method to directly and controllably fabricate varied-size nanodisks." He adds that their results contrast significantly with the current expectations in bulk or two-dimensional films, where the skyrmions form closely-packed lattice arrangements. "We found that, at low temperatures – below ~200 Kelvin for FeGe nanodisks – the skyrmions form cluster states with maximum skyrmion number proportional to the disk diameter. This differs from skyrmion lattices at higher temperatures with the maximum skyrmion numbers proportional to the square of the disk diameter." Moreover, he adds, the magnetic field transition interval of skyrmion cluster states decreases with ascending temperature. "I was very excited when I directly observed, for the first time, the cascading transition and the fluctuations of skyrmion cluster states driven by the magnetic fields."

While LTEM is a powerful tool for imaging magnetic structures with nanometer-scale resolution, and has been used to image skyrmions by Dr. Xiuzhen Yu[1], Tian notes that direct imaging of individual skyrmions in nanodisks with a size on the order of ~ 100 nm is still challenging due to the influence of Fresnel fringes at the sample edge. "By utilizing a top-to-down method with FIB technique, we fabricated nanodisks of various diameters from bulk FeGe enclosed with amorphous PtC_x composite in order to enhance the mechanical strength and thereby precise manipulation of the nanodisk. "We're very lucky that edge coating with conducting PtC_x composites was found to greatly weaken the Fresnel fringes near the edge boundary, and that by so doing enables us to extract the magnetic information in nanodisks smaller than 180 nm."

The scientists state that the team's results have immediate implication for designing future skyrmion-based devices, such as multibit memory cells.

"We give the direct proof that single skyrmion can exist in nanostructured elements," Tian says. "Given the similarity between the skyrmions and magnetic vortices in soft magnetic nanodisks, the observed individual skyrmions will provide a viable alternative to spin-torque vortex-oscillator devices, and be a potential candidates for microwave signal-processing applications."

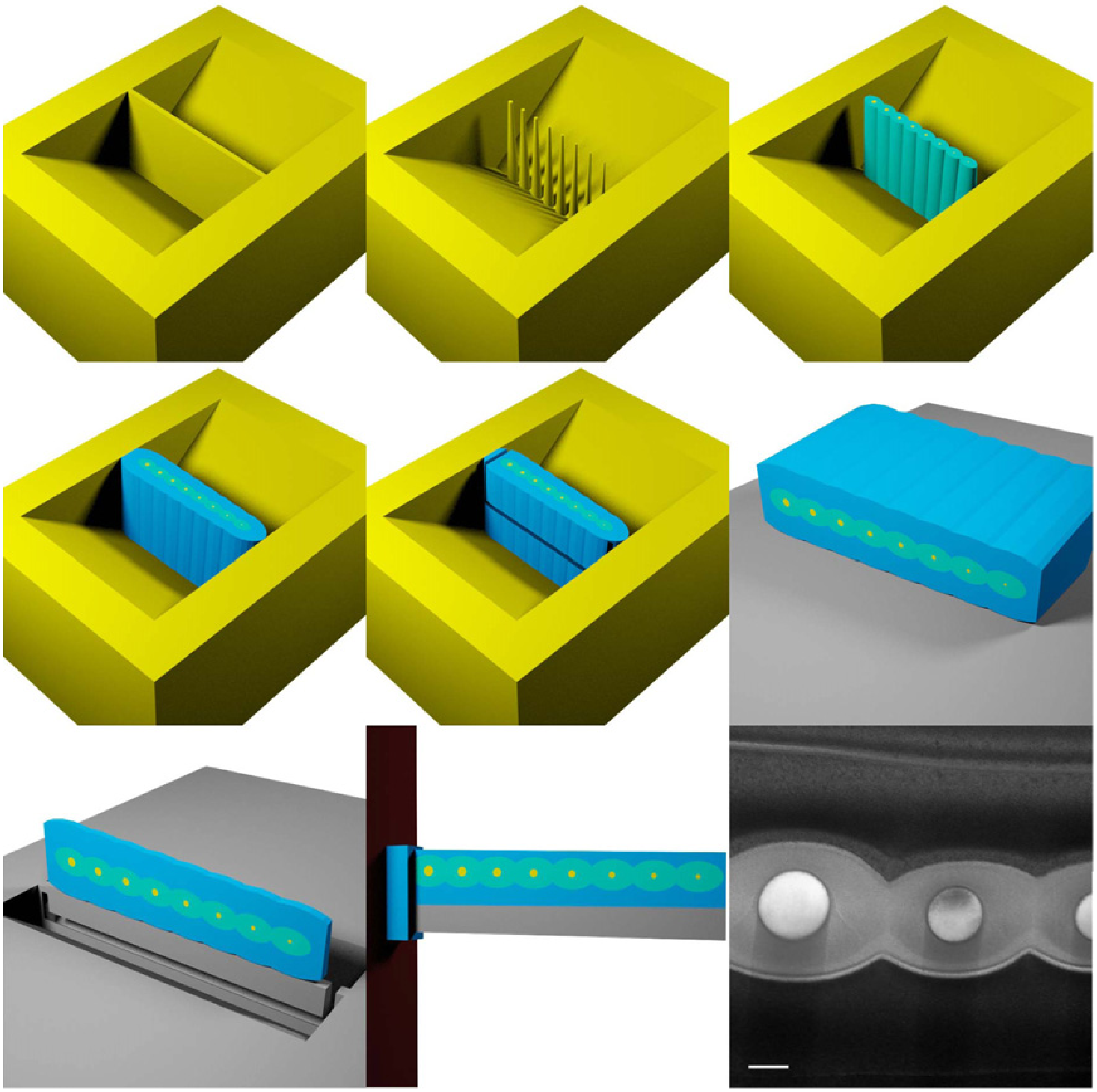

Fig. S1. Schematic procedure for fabricating FeGe nanodisks by using the FIB-SEM dual-beam system (Helios NanoLab 600i; FEI) equipped with a GIS, and Omniprobe 200+ micromanipulator. The whole process is shown schematically in eight steps for *A–I*: (*A*) Following the standard TEM specimen preparation procedure (40), a thin FeGe sheet with a thickness of ~1 μm was carved on the surface of a polycrystalline FeGe bulk using the FIB milling technique. (*B*) The FeGe sheet was cut into circular columns with different diameters by FIB using annular patterns. (*C*) Using the GIS system, a layer of amorphous PtC_x was deposited on the FeGe columns by the electron beam-assisted chemical vapor deposition technique. This PtC_x coating works as protection of the FeGe nanocolumns for nanomanipulation processes and also reduces the Fresnel fringe at the edge of the disk for the Lorentz TEM study. (*D*) Further deposition of amorphous PtC_x layer by ion beam-assisted chemical vapor deposition to fasten the samples. (*E*) A U-shaped cut was made from the sheet by FIB milling. (*F*) The sheet of FeGe nanocolumns surrounded by amorphous PtC_x was transferred to a clean surface of silicon and laid down by an Omniprobe 200+ micromanipulator. (*G*) Using the standard TEM specimen preparation procedure, a slice consisting of FeGe nanodisks in various sizes was fabricated by FIB milling. (*H*) The slice was transferred to a TEM Cu chip using the micromanipulator, and then was thinned to the desired thickness. (*I*) TEM image of the nanodisk sample depicted in the dashed box in *H*. (Scale bar, 200 nm.) Credit: Xuebing Zhao, et al. (2016) Direct imaging of magnetic field-driven transitions of skyrmion cluster states in FeGe nanodisks. *Proc Natl Acad Sci USA* 113 (18) 4918-4923.

The paper points out that the theory-predicted target skyrmion in chiral magnets was not observed in the present experiment due to weak magnetic contrast and Fresnel fringes. "Target skyrmions, a concentric helicoidal undulation predicted previously by Dr. Du, may spontaneously exist in small size nanodisks without an external magnetic field, which is more suitable to skyrmion-based devices," Tian tells *Phys.org*. "It shows that target skyrmion stability will increase as nanodisk size decreases. However, at sizes below 100 nm, the weak artificial contrast from the edge will diffuse the real magnetic structure though the PtC_x coating, and so significantly reduce the edge effect. Therefore, to realize the observation of target skyrmions, other magnetic microscopy techniques such as electron holography should be considered to avoid Fresnel fringe interference."

Moving forward, says Tian, by cooperative research between his nanomagnet physical properties team and Che's structural characterization team, the researchers will target several important issues in future, including searching for target skyrmions by varying disk size, thickness or other conditions by using electron holography, as previously noted; studying the current-driven motion of skyrmions in confined geometries; performing manipulation and electrical detection of skyrmions; and developing new techniques to fabricate nano-sized samples that are more controllable and more efficient for large-scale production.

In closing, Tian tells *Phys.org* that other areas of might research benefit from their study. "The techniques used in our study, such as our focused ion beam patterned procedure and transport intensity equation analysis, can be applied to other micromagnetics research. Moreover, since skyrmions have many features in common with Abrikosov vortices in superconductors, our results may provide some inspirations in this field."

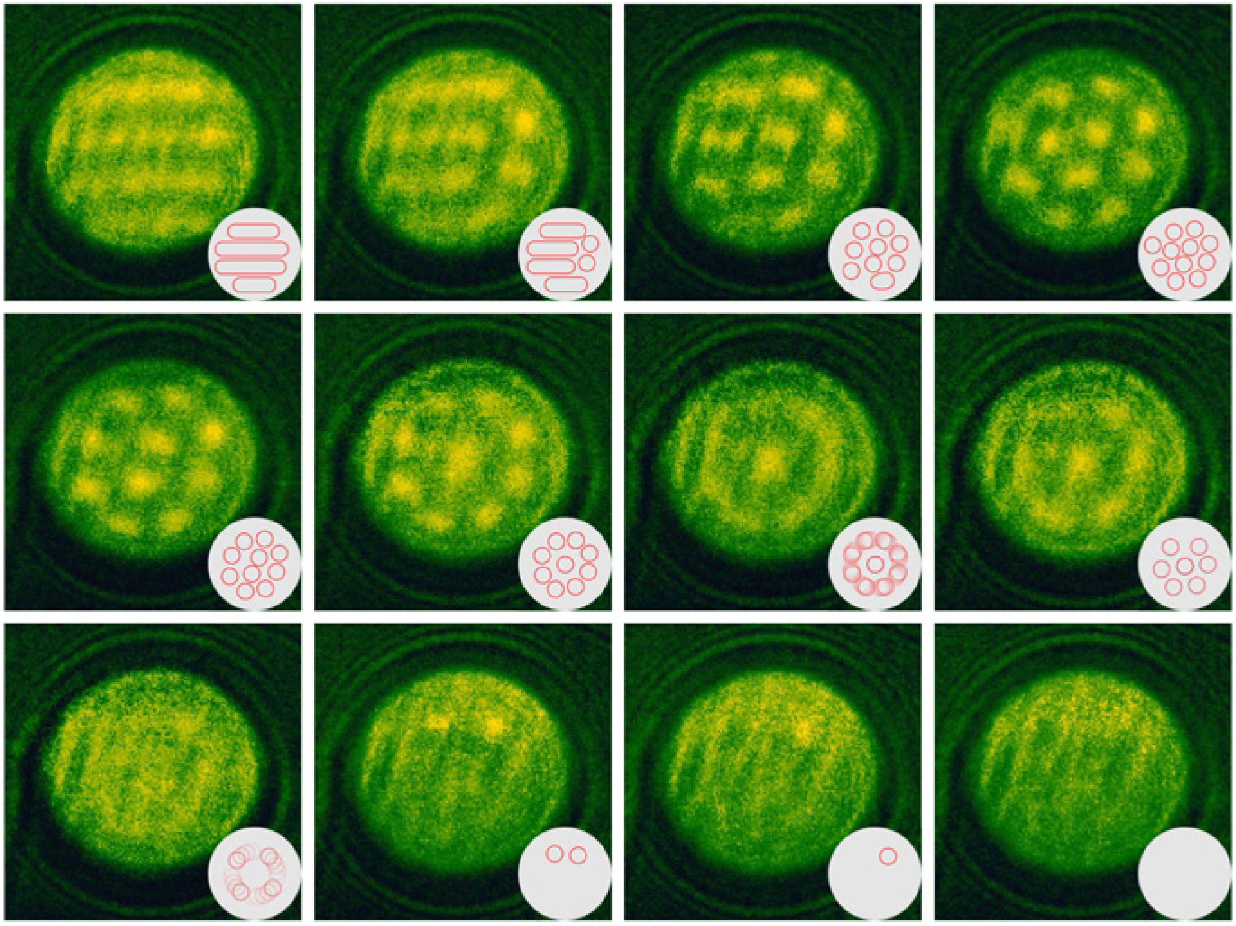

Fig. S2. Underfocused Lorentz TEM images of a 330-nm FeGe nanodisk at 220 K under an external magnetic field. At zero field, the ground state consists of four helical periods. With the increase of the external field, some skyrmions were nucleated from the helix at 0.45 kOe, and the skyrmions eventually occupied the whole disk at 0.47 kOe. After the number of skyrmions N_s reaches the maximum of 11, i.e., eight skyrmions circle around the edge of the disk, with three inside the circle. Further increasing the external field, the number of the inner skyrmions, in turn, merges to 2 at 0.81 kOe and 1 at 0.98 kOe. It's worth noting that, at 0.98 kOe, the eight circumambient skyrmions begin to rotate around the center one, leading to a ring-like structure (see Movie S3). Red circles in the white plate at the corner of each panel point out the position of skyrmions and helixes. All images are extracted from a video captured at a defocus value of −288 μm and an exposure time of 0.2 s. Credit: Xuebing Zhao, et al. (2016) Direct imaging of magnetic field-driven transitions of skyrmion cluster states in FeGe nanodisks. *Proc Natl Acad Sci USA* 113 (18) 4918-4923.

More information: Direct imaging of magnetic field-driven transitions of skyrmion cluster states in FeGe nanodisks, *PNAS* May 3, 2016, vol. 113 no. 18 4918-4923, doi:10.1073/pnas.1600197113

Related
[1] Real-space observation of a two-dimensional skyrmion crystal, *Nature* **465**, 901–904 (17 June 2010), doi:10.1038/nature09124