Magnetic imaging

https://doi.org/10.1038/s41565-022-01262-6

A closer look at spin textures

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Lorentz electron ptychography, a coherent diffractive imaging method, unveils magnetization singularities in a skyrmion lattice in FeGe and captures subtle internal structures near the skyrmion cores, boundaries, and dislocations.

Topological defects are ubiquitous in nature: from screw dislocations in crystals and vortices in superconductors to ferroelectric domain walls and magnetic skyrmions[1,2]. Skyrmions are either swirling or hedgehog-like spin solitons characterized by an integer topological index, termed the skyrmion or winding number[2]. They are not only energetically favored, but also stabilized by the topology as they cannot be removed by any simple rearrangement of the spins. Consequently, they are robust to small perturbations and are expected to have a longer lifetime than their non-topological counterparts. The topological nature enables unique properties such as current-driven motion with low current densities, insensitivity to defects, topological Hall effect, skyrmion Hall effect, nontrivial spin-wave dynamics resulting from microwave perturbations and their creation and control with topological light. Writing in *Nature Nanotechnology*, Zhen Chen et al. report the development of Lorentz electron ptychography (LEP) for nanometer-resolution imaging of magnetic skyrmions using widely available electron microscopes[3]. They image magnetization singularities in a skyrmion lattice in a FeGe single crystal and observe subtle internal structures near the skyrmion cores, boundaries, and dislocations, which are crucial for a comprehensive description of skyrmion states.

Key to this advance is the combination of a sensitive and high dynamic-range pixel array detector with robust electron ptychography. Ptychography is a coherent diffractive imaging (CDI) method[4], which scans a probe beam across a sample and collects a series of diffraction patterns from partially overlapping regions[5]. An iterative algorithm is then used to reconstruct the magnitude and phase of the complex exit wave of the sample as well as the probe function from the diffraction patterns[5,6]. Compared with Lorentz transmission electron microscopy and holography[7,8], LEP has three unique advantages. First, the spatial resolution of LEP is not limited by the electron lens, but determined by the maximum electron scattering angle at which a statistically meaningful signal can be recorded. Second, by taking advantage of the state-of-the-art pixel array detector, LEP can be implemented with low electron doses, making it well-suited for exploring spin textures in radiation-sensitive materials such as organic or molecular magnets. Third, powerful iterative algorithms make it possible to quantitatively reconstruct the phase shift created by the magnetic vector potential, from which a two-dimensional (2D) lateral magnetic induction field can be derived.

Figure 1a shows the schematic layout of LEP, in which a focused electron probe of a few nanometers in diameter scans across a FeGe single-crystal sample with each probe overlapping with the previous ones. The magnetic induction field (**B**) in the sample deflects the electrons and a 2D pixel array detector collects the diffracted electrons at each scan position. The researchers reconstruct the magnitude and phase of the electron exit wave of the sample from the measured diffraction patterns by an iterative algorithm (Fig. 1b). Their quantitative analysis indicates that the precision of the phase determination by LEP is 2 ± 1 mrad, which is 2–4 times higher than electron holography and differential-phase-contrast imaging. By taking the gradient of the phase, Chen et al. obtain the lateral **B** field of a skyrmion lattice in the FeGe sample, unveiling magnetization singularities such as clockwise vortices at the intersection of three skyrmions, anti-vortex-like textures at the boundary of two skyrmions, and Bloch-type skyrmions with counterclockwise swirling approaching to the inner core of skyrmions. These experimentally observed magnetization singularities are corroborated by micromagnetic simulations by the researchers. Furthermore, Chen et al. observe an edge dislocation in the skyrmion lattice. The skyrmions near the dislocation core are significantly distorted, but their winding numbers are topologically conserved, which are the same as those in the perfect regions of the skyrmion lattice.

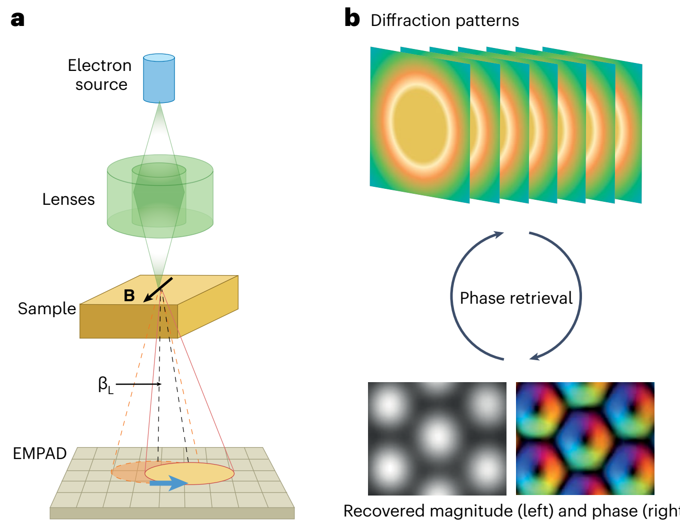

Fig. 1 | Lorentz electron ptychography and the phase retrieval algorithm. **a**, Schematic of LEP, in which a focused electron probe scans across the magnetic sample. The electrons are deflected by the **B** field in the sample with β_L as the deflection angle. The diffracted electrons are collected by an electron microscope pixel array detector (EMPAD) at each scan position. **b**, The phase retrieval is implemented by a computational algorithm that iterates between real and reciprocal space. In each iteration, the overlapping regions and the measured diffraction patterns are used as constraints in real and reciprocal space, respectively. Usually, after tens to hundreds of iterations, the magnitude and phase of the complex exit wave of the sample as well as the probe function can be simultaneously reconstructed from the diffraction patterns.

Although LEP is a sensitive, high-resolution method to image nanoscale spin textures, there is still room for improvement. First, to extract the lateral **B** field, the researchers assume a wedge-shaped FeGe sample with smooth surfaces in local regions to remove the effect of the electrostatic potential. However, the **B** field is intrinsically three-dimensional and it would be even more meaningful to image 3D magnetic textures in magnetic materials[7]. Through a combination of ptychography and x-ray magnetic circular dichroism, hard x-ray vector tomography can image the 3D spin textures in the vicinity of magnetic singularities (Bloch points) with 100 nm resolution[9]. More recently, soft x-ray vector ptycho-tomography enabled the observation of the interaction of topological magnetic monopoles with a 3D resolution of 10 nm[10]. Thus, the combination of LEP and powerful tomography algorithms[11] should in principle allow for imaging the 3D spin textures in magnetic materials with sub-nanometer resolution. Second, as a CDI method, LEP uses the coherent interference of the diffracted electron waves to extract the phase information. But presently most electron microscopes utilize only partially coherent electron sources. With the development of more coherent electron sources, LEP can in principle achieve higher spatial resolution with less electron doses. Finally, phase retrieval from diffraction patterns is still an active research field, which requires practitioners to get algorithmic training to optimize the parameters and obtain good results. To make LEP more accessible to a broad user community, it is important to develop standard phase retrieval software packages that require minimal user intervention.

With all these developments, we expect that LEP will become a powerful tool to image the topology and singularities of different spin textures in a wide range of magnetic materials with sub-nanometer resolution. When implemented with fast electron sources, LEP could also be used to capture dynamics in spintronic devices.

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Published online: 23 November 2022

References

1. Mermin, N. D. *Rev. Mod. Phys.* **51**, 591–648 (1979).
2. Nagaosa, N. & Tokura, Y. *Nat. Nanotechnol.* **8**, 899–911 (2013).
3. Chen, Z. et al. *Nat. Nanotechnol*. https://doi.org/10.1038/s41565-022-01224-y (2022).
4. Miao, J., Charalambous, P., Kirz, J. & Sayre, D. *Nature* **400**, 342 (1999).
5. Rodenburg, J. M. et al. *Phys. Rev. Lett.* **98**, 34801 (2007).
6. Thibault, P. et al. *Science* **321**, 379–382 (2008).
7. Phatak, C., Petford-Long, A. K. & De Graef, M. *Curr. Opin. Solid State Mater. Sci.* **20**, 107–114 (2016).
8. Lichte, H. *Ultramicroscopy* **108**, 256–262 (2008).
9. Donnelly, C. et al. *Nature* **547**, 328–331 (2017).
10. Rana, A. et al. Preprint at https://arxiv.org/abs/2104.12933 (2021).
11. Yang, Y. et al. *Nature* **592**, 60–64 (2021).

Competing interests

The authors declare no competing interests.