Direct visualization of the three-dimensional shape of skyrmion strings in a noncentrosymmetric magnet

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Magnetic skyrmions are topologically stable swirling spin textures that appear as particle-like objects in two-dimensional (2D) systems. Here, utilizing scalar magnetic X-ray tomography under applied magnetic fields, we report the direct visualization of the three-dimensional (3D) shape of individual skyrmion strings in the room-temperature skyrmion-hosting non-centrosymmetric compound Mn1.4Pt0.9Pd0.1Sn. Through the tomographic reconstruction of the 3D distribution of the [001] magnetization component on the basis of transmission images taken at various angles, we identify a skyrmion string running through the entire thickness of the sample, as well as various defect structures, such as the interrupted and Y-shaped strings. The observed point defect may represent the Bloch point serving as an emergent magnetic monopole, as proposed theoretically. Our tomographic approach with a tunable magnetic field paves the way for direct visualization of the structural dynamics of individual skyrmion strings in 3D space, which will contribute to a better understanding of the creation, annihilation and transfer of these topological objects.
3D tomographic imaging with a tunable magnetic field can be a powerful tool for better understanding of the formation process and dynamics of skyrmion strings.

For simple centrosymmetric ferromagnets without a magnetic field, the easy axis of magnetization is along the [001] direction. By applying a magnetic field, which plays a key role in the present achievements, in addition to the genuine skyrmion strings running through the entire thickness of the sample, various defect structures, such as interrupted and Y-shaped strings, have been identified, the latter of which can be accompanied by the monopole-dipole interaction.

Thus, 3D imaging of the skyrmion string, which is stabilized in special non-centrosymmetric materials under an external magnetic field, remains an important challenge.

In this study, we have successfully visualized the 3D shape of individual skyrmion strings by employing the recently discovered room-temperature skyrmion-hosting non-centrosymmetric material Mn$_{1.4}$Pt$_{0.9}$Pd$_{0.1}$Sn (ref. 22). For this purpose, we have developed a scalar magnetic tomography measurement system that can apply a scalar magnetic field, which is proportional to the sample thickness. In Supplementary Note 4 and Supplementary Fig. 4 more detailed information on the thickness gradient of the sample is provided.

Our target compound Mn$_{1.4}$Pt$_{0.9}$Pd$_{0.1}$Sn is known as a rare example of a room-temperature skyrmion-hosting compound, and is characterized by the inverse Heusler crystal structure with non-centrosymmetric tetragonal $D_{4h}$ symmetry (space group $I4_{2d}$). The magnetic ordering temperature is around 400 K, and the easy axis of magnetization is along the [001] direction. By applying a magnetic field, the skyrmion spin texture with antivortex-type arrangement of in-plane magnetization component (often called an antiskyrmion) is stabilized at room temperature, where the skyrmion diameter depends on the sample thickness according to previous reports.

The experimental set-up for the scalar magnetic X-ray tomography and the associated scanning X-ray magnetic circular dichroism (XMCD) measurements is shown in Fig. 1c,d (ref. 25). Here, the direction of the incident X-ray beam is defined as the Y axis. X-ray energy was tuned at 11.572 keV, in resonance with the L$_3$ absorption edge of Pt (Supplementary Fig. 1). The wedge-shaped single crystal of Mn$_{1.4}$Pt$_{0.9}$Pd$_{0.1}$Sn (Fig. 1e,f) was placed at the focal point of the X-ray beam with the spot size of 150×150 nm$^2$ in full polarization-averaged absorption intensity.

Fig. 1 | Experimental set-up for the scalar magnetic X-ray tomography measurements. a, Schematic illustration of skyrmion string, where two-dimensional skyrmion spin texture is uniformly stacked along the direction of external magnetic field $B$. The small arrows indicate the direction of local magnetic moment $\mathbf{m}(r)$. b, The corresponding spatial distribution of $\mathbf{m}(r)$, obtained by the micromagnetic simulation (see Supplementary Note 4 for details). The hue and brightness of the background colour represent the in-plane ($m^\parallel$ and $m^\perp$) and out-of-plane ($m^\perp$) component of $\mathbf{m}(r)$, respectively. The length of the magnetic moment is fixed to $|\mathbf{m}(r)| = 1$. c, Experimental set-up for the scalar magnetic X-ray tomography measurements. d, The top view of $\mathbf{m}$ is defined as the angle between the X-ray beam direction and the [001] axis of the Mn$_{1.4}$Pt$_{0.9}$Pd$_{0.1}$Sn single crystal. The sample and electromagnet are mounted on the same rotational stage, and the magnetic field is always applied parallel to the [001] direction (see Supplementary Note 2). e, Schematic illustration showing the shape of the Mn$_{1.4}$Pt$_{0.9}$Pd$_{0.1}$Sn sample. f, Scanning electron microscope image of the Mn$_{1.4}$Pt$_{0.9}$Pd$_{0.1}$Sn sample attached to the needle, viewed from the [001] direction. g, The corresponding X-ray absorption image taken for the boxed region in f. The colour represents the polarization-averaged absorption intensity $\mu$, which is proportional to the sample thickness. In Supplementary Note 6 and Supplementary Fig. 6 more detailed information on the thickness gradient of the sample is provided. h, Position dependence of absorption intensity taken along the red line in g.
width at half maximum (FWHM), and the absorption coefficient
\[ \mu = -\ln \left( \frac{I_t}{I_0} \right) \]
with \( I_t \) and \( I_0 \) being the intensity of the transmitted and incident X-ray beam, respectively) for the left- and right-handed circular polarized beam \( \mu^+ \) and \( \mu^- \), respectively) was measured by the silicon photodiode detector. The amplitude of XMCD \( \Delta \mu = \mu^+ - \mu^- \) reflects the Y component of local magnetization integrated over the beam path, and the polarization-averaged absorption \( \bar{\mu} = (\mu^+ + \mu^-)/2 \) is proportional to the electron density of the sample. The sample and the electromagnet are mounted on the common pulse-motor stages with a feedback control, which enables translation and rotation of the sample to keep the magnetic field applied along the [001] axis of the Mn\(_{1.4}\)Pt\(_{0.9}\)Pd\(_{0.1}\)Sn crystal (see Supplementary Note 2 for details). By scanning the sample position within the X–Z plane, the 2D XMCD image is obtained. As shown in Fig. 1d, the orientation of the sample and the magnetic field can be simultaneously rotated around the Z axis, and the angle between the incident X-ray direction (that is, the Y axis) and the [001] axis of the sample is defined as \( \theta \). On the basis of 2D XMCD images taken at various angles \( \theta \), tomographic reconstruction of the \( \mu^c \) (that is, the [001] component of the local magnetic moment) distribution has been performed (see Methods and ref. 29). All the measurements were performed at BL39XU of the SPring-8 synchrotron radiation facility.

In Fig. 1e,f, the detailed shape of the present Mn\(_{1.4}\)Pt\(_{0.9}\)Pd\(_{0.1}\)Sn sample, prepared from a bulk single crystal using the focused ion beam microfabrication technique, is indicated. The sample has a thin plate shape with a thickness gradient, and the widest face is parallel to the (001) plane. Figure 1f indicates the scanning electron microscope image of the sample viewed from the [001] orientation. The corresponding 2D X-ray absorption (\( \bar{\mu} \)) image, taken by scanning the position of the incident X-ray beam normal to the sample plane (that is, \( \theta = 0 \)), is indicated in Fig. 1g. The line-scan profile in Fig. 1h..
magnetic monopole (see Supplementary Note 4 and Supplementary Fig. 4 for details). The colour definition is the same as for Fig. 1b. The white circle represents the position of emergent a in mc based on LTEM and MFM measurements22,34,36. According to the . These results are consistent with previous reports antiparallel to for this set-up). The observed stripe pattern suggests the formation of helical magnetic order, where neighbouring spins rotate within a plane normal to the magnetic modulation vector \( q \) \( \parallel \) \( [100] \) and \( \parallel [010] \), \( q \) \parallel [100] \) and \( q \parallel [010] \), coexist. As the sample thickness increases, the magnetic modulation period is found to be longer, and reaches 1 \( \mu \)m at the thickest part of the sample. By applying the out-of-plane \( B \parallel [001] \) the helical magnetic stripes gradually turn into the circular magnetic skyrmions (Fig. 2b–g), whose cores are characterized by the negative sign of \( m^r \) antiparallel to \( B \). These results are consistent with previous reports based on LTEM and MFM measurements22,34,36. According to the theoretical analysis in ref. 34, the skyrmion diameter in this compound is affected not only by exchange and DM interactions, but also by magnetic dipole–dipole interactions (that is, the demagnetization field) and uniaxial anisotropy. In Supplementary Note 5 and Supplementary Fig. 5, the micromagnetic simulation considering these factors has been performed, which reproduces the 1- \( \mu \)m diameter skyrmion string with an antiskyrmion-type spin swirling manner. Figure 2i indicates the magnetic field dependence of the XMCD intensity taken with the larger beam spot size of \( \sim 13 \mu \)m (corresponding to bulk magnetization averaged over the sample), which confirms that the fully polarized magnetic state is obtained at 500 mT.

Next, we focused on the selected region of Fig. 2f (shown by the dashed lines) in the skyrmion phase at 437 mT, and performed the same scanning XMCD measurements for different \( \theta \) angles while keeping the \( B \parallel [001] \) unchanged. In general, a cylindrical skyrmion string (Fig. 1a) gives a circular magnetic contrast when viewed from the string direction, but will provide a more elongated one when viewed from oblique angles. Indeed, the circular XMCD pattern observed at \( \theta = 0 \) (Fig. 2h) is gradually elongated along the \( X \) direction as the tilting angle \( \theta \) increases (Fig. 2j–m), which implies the validity of the cylindrical skyrmion string picture. We performed the same measurements for \( -90° \leq \theta \leq 90° \) with steps of 5°, and the obtained XMCD images are used for the tomographic reconstruction of the magnetization distribution. (A series of XMCD images taken from various angles are summarized as an animation in Supplementary Video 1.)

In general, the isolated magnetic skyrmion is characterized by the negative sign of the core magnetization antiparallel to \( B \parallel [001] \), which is embedded in the uniform ferromagnetic (or ferrimagnetic) background with magnetization parallel to \( B \) (Fig. 1a). To identify the 3D shape of the magnetic skyrmion, we focus on the spatial distribution of the \([001] \) component of the local magnetization \( m^r(\mathbf{r}) \) and neglect the other magnetization component (see Supplementary Note 7 and Supplementary Fig. 7 for the detailed analysis on the validity of this approximation). Here, the observed XMCD image is taken with the \( X–Y–Z \) coordinates fixed to the measurement system, while magnetization distribution is defined with the coordinates \( \mathbf{r} \parallel [001] \) and \( \parallel [010] \) fixed to the crystallographic
axes of the sample (Fig. 1d). For the specific value of Z and θ, the relationship between the magnetization distribution $m'(x,y)$ and the observed XMCD contrast $\Delta \mu(X,\theta)$ is given by

$$\frac{\Delta \mu(X,\theta)}{\cos \theta} = \int m'(x,y) dY,$$

(1)

which corresponds to the Radon transform of $m'(x,y)^{29}$. Therefore, on the basis of a series of XMCD images and standard tomographic reconstruction algorithm, the 3D spatial distribution of $m'(r)$ can be straightforwardly obtained. In Supplementary Fig. 3, the experimentally measured XMCD image and the one simulated from the reconstructed $m'(r)$ and equation (1) are indicated for the selected $\theta$ values. The measured and reproduced images are in good agreement with each other, which confirms the reliability of the present tomographic reconstruction process.

Now, we discuss the detail of the experimentally reconstructed $m'(r)$ in the 3D space. Figure 3a indicates the XMCD image viewed from the [001] axis, where almost circular skyrmion cores with negative sign of $m'$ are observed. Figure 3b represents a cross-section of the reconstructed $m'(r)$ profile along the line I in Fig. 3a, cutting a well-defined skyrmion core. The negative $m'$ region is found to form a straight line along the [001] direction connecting the top and bottom surfaces. Figure 3d indicates the 3D oblique view of the reconstructed $m'(r)$ profile, which clearly visualizes the rod-shaped strings aligned along the vertical direction.

In Fig. 4, we provide a more quantitative analysis of the 3D shape of individual the skyrmion strings. Figure 4a,e indicates the top-view XMCD image (extracted from Fig. 3a) and the corresponding reconstructed 3D shape of a selected skyrmion string. Here, we define the skyrmion core as the region with negative $m'$, and the contour surface for $m'=0$ is plotted. In h, yellow and green surfaces represent the ones obtained at 437 mT and 392 mT, respectively. For these plots, the higher frequency component (with the period shorter than the X-ray beam spot size) is removed to suppress the possible noise contribution (see Supplementary Note 8 and Supplementary Fig. 8 for the discussion on the noise and spatial resolution in the reconstructed 3D profiles). i-i, The depth (that is, position along the [001] direction) dependence of effective skyrmion diameter $\lambda_{\text{eff}}$ and relative core centre position $r_c$, which are deduced from the data sets for e-h, respectively. Here, we define $A_c = \pi(\lambda_{\text{eff}}/2)^2$ and $r_c$ as the area and centroid of the skyrmion core, respectively. The red (blue) data in the right panels represent the relative position of the skyrmion core centre along the [001] (010) direction.

**Fig. 4** Reconstructed 3D shape of magnetic skyrmion strings. a-d, Top-view XMCD image of four skyrmion strings measured at $\theta=0$ at 437 mT, which is extracted from different positions in Fig. 3a. e-h, The three-dimensional shape of skyrmion strings reconstructed from the scalar magnetic X-ray tomography measurements, which correspond to the ones in a-d, respectively. We defined the skyrmion core as the region with negative $m'$ and the contour surface for $m'=0$ is plotted. In h, yellow and green surfaces represent the ones obtained at 437 mT and 392 mT, respectively. For these plots, the higher frequency component (with the period shorter than the X-ray beam spot size) is removed to suppress the possible noise contribution (see Supplementary Note 8 and Supplementary Fig. 8 for the discussion on the noise and spatial resolution in the reconstructed 3D profiles).
the surface of the skyrmion string core) is frequently pinned by the crystallographic defects. In the corresponding XMCD image (Fig. 4a), the non-monotonic depth dependence of the cross-sectional outline of the skyrmion string leads to the blurred and distorted manner of the magnetic contrast. As shown in Fig. 3a, the manner of the distortion of the skyrmion core shape is random, which probably reflects the random pinning of the skyrmion wall region. In Fig. 4b,h, the magnetic field dependence of the skyrmion string shape is also indicated. It demonstrates that the effective diameter of the skyrmion string is gradually enhanced by reducing magnetic field strength at any depth. Supplementary Videos 2 and 3 provide the 360° view and slice animation, respectively, of reconstructed \( m'(r) \) profiles at 437 mT, which reveal the 3D shape of individual skyrmion strings in more detail.

According to the latest theories, skyrmion strings are also predicted to host several different types of defect structures\(^{15,28,31}\). In Fig. 3c, another cross-sectional image along the line II in Fig. 3a is presented. On the left side, the skyrmion string with negative \( m' \) forms a straight line starting from the top surface, while it is terminated at the middle of the sample. This interrupted skyrmion string is characterized by weaker magnetic contrast than the genuine one in the top-view XMCD image (Fig. 3a), reflecting its limited string length. On the other hand, on the right side of Fig. 3c, two parallel skyrmion strings starting from the top surface are found to merge into a single string connected to the bottom surface. Such interrupted or Y-shaped string structures have recently been proposed\(^{14,32} \), the former of which is often referred to as the chiral bobber and considered as another candidate for an information carrier\(^{16,33} \). For these interrupted skyrmion strings, more quantitative analysis of their 3D shape has been performed in Fig. 4b,c,f,g,j,k. The results here provide direct experimental evidence to prove the existence of these predicted defect structures in 3D space.

Theoretically, conduction electrons interacting with such spin textures should feel the emergent magnetic field \( b_{\text{em}}(r) \) associated with the quantum Berry phase\(^1 \). In the case of a genuine skyrmion string, the individual skyrmion string carries a quantized emergent magnetic flux along the direction of the string. On the other hand, for the interrupted or Y-shaped skyrmion strings, the divergence of the emergent magnetic flux \( \nabla \cdot b_{\text{em}} \neq 0 \) must appear at the termination or merging point of skyrmion strings. These singular point defects are referred to as emergent magnetic monopoles (or anti-monopoles)\(^ {14,32} \), and they are topologically equivalent to the Bloch point magnetic singularity observed in different contexts\(^ {10,41,42} \). Here, we performed the micromagnetic simulation by assuming the \( D_{\text{sym}} \), symmetry of the DM interaction, and estimated the local magnetization distribution \( m(r) \) for the genuine, interrupted and Y-shaped skyrmion strings, as shown in Figs. 1b and 3e,f, respectively. The calculation of the corresponding emergent magnetic field distribution \( b_{\text{em}}(r) \) supports the existence of emergent magnetic monopoles at the termination or merging points of strings, whose positions are highlighted by the white circles in Fig. 3e,f (see Supplementary Fig. 4 and Supplementary Note 4 for details). Recently, the dynamics of such emergent magnetic monopoles have been considered as the key to interpreting the non-trivial electron transport properties in topological magnetic phases\(^ {14,32} \). The present approach provides a unique experimental method to track the 3D position of individual emergent magnetic monopoles under an external magnetic field, which will contribute to deeper analysis of the various exotic phenomena associated with emergent electromagnetic fields.

In this study, by developing a scalar magnetic X-ray tomography measurement system with tunable magnetic field, we have successfully visualized the 3D shape of individual skyrmion strings and their defect structures at room temperature for a non-centrosymmetric Heusler compound. The present results pave the way for direct 3D imaging of the creation and annihilation, as well as the transfer process, of individual skyrmion strings driven by external stimuli, and will contribute to a better understanding of their intricate dynamics for potential device applications. The above experiments also expand the reach of magnetic X-ray tomography in terms of both methodology (that is, additional magnetic field environments) and target material systems, and will promote further advancement in this emerging 3D magnetic imaging technique. In principle, because of the short wavelength of X-rays, the spatial resolution can be further improved. The full reconstruction of the vector magnetization distribution (that is, vector magnetic tomography, which is possible by two-axis rotation of the target object but currently successful only under zero magnetic field\(^ {23,36,47} \)) and the direct experimental confirmation of the winding number will be another important future challenge (for a detailed discussion of the in-plane magnetization component, see Supplementary Note 9). Previously, the stability and dynamics of skyrmions have been studied mainly on the basis of 2D imaging and associated theoretical simulations. The present 3D visualization approach allows us to access the unexplored third dimension of skyrmions, which may signal a new phase in the development of skyrmionics.

**Online content**

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**References**

1. Mühlbauer, S. et al. Skyrmion lattice in a chiral magnet. Science 323, 915–919 (2009).
2. Yu, X. Z. et al. Real-space observation of a two-dimensional skyrmion crystal. Nature 465, 901–904 (2010).
3. Rößler, U. K. et al. Spontaneous skyrmion ground states in magnetic metals. Nature 442, 797–801 (2006).
4. Fert, A., Reyren, N. & Cros, V. Magnetic skyrmions: advances in physics and potential applications. Nat. Rev. Mater. 2, 17031 (2017).
5. Nagaosa, N. & Tokura, Y. Topological properties and dynamics of magnetic skyrmions. Nat. Nanotechnol. 8, 899–911 (2013).
6. Jonietz, F. et al. Spin transfer torques in MnSi at ultralow current densities. Science 330, 1648–1651 (2010).
7. Yu, X. Z. et al. Skyrmion flow near room temperature in an ultralow current density. Nat. Commun. 3, 988 (2012).
8. Jiang, W. et al. Blowing magnetic skyrmion bubbles. Science 349, 283–286 (2015).
9. Woo, S. et al. Observation of room-temperature magnetic skyrmions and their current-driven dynamics in ultrathin metallic ferromagnets. Nat. Mater. 15, 501–506 (2016).
10. Neubauer, A. et al. Topological Hall effect in the A phase of MnSi. Phys. Rev. Lett. 102, 186602 (2009).
11. Schulz, T. et al. Emergent electrodynamics of skyrmions in a chiral magnet. Nat. Phys. 8, 301–304 (2012).
12. Zhang, X. et al. Magnetic skyrmion logic gates: conversion, duplication and merging of skyrmions. Sci. Rep. 5, 9400 (2015).
13. Song, K. M. et al. Skyrmion-based artificial synapses for neuromorphic computing. Nat. Electron. 3, 148–155 (2020).
14. Milde, P. et al. Unwinding of a skyrmion lattice by magnetic monopoles. Science 340, 1076–1080 (2013).
15. Kagawa, F. et al. Current-induced viscoelastic topological unwinding of metastable skyrmion strings. Nat. Commun. 8, 1332 (2017).
16. Yokouchi, T. et al. Current-induced dynamics of skyrmion strings. Sci. Adv. 4, eaat1115 (2018).
17. Koshihara, W. & Nagaosa, N. Dynamics of skyrmion in disordered chiral magnet of thin film form. Sci. Rep. 9, 5111 (2019).
18. Seki, S. et al. Propagation dynamics of spin excitations along skyrmion strings. Nat. Commun. 11, 256 (2020).
19. Seki, S., Yu, X. Z., Ishiwata, S. & Tokura, Y. Observation of skyrmions in a multiferroic material. Science 336, 198–201 (2012).
20. Tokunaga, Y. et al. A new class of chiral materials hosting magnetic skyrmions beyond room temperature. Nat. Commun. 6, 7638 (2015).
21. Kézsmárki, I. et al. Néel-type skyrmion lattice with confined orientation in the polar magnetic semiconductor GaV$_4$S$_8$. Nat. Mater. 14, 1116–1122 (2015).
22. Nayak, A. K. et al. Magnetic antiskyrmions above room temperature in tetragonal Heusler materials. Nature 548, 561–566 (2017).
23. Zhang, S. et al. Reciprocal space tomography of 3D skyrmion lattice order in a chiral magnet. Proc. Natl Acad. Sci. USA 115, 6386–6391 (2018).
24. Park, H. S. et al. Observation of the magnetic flux and three-dimensional structure of skyrmion lattices by electron holography. Nat. Nanotechnol. 9, 337–342 (2014).
25. Moreau-Luchaire, C. et al. Additive interfacial chiral interaction in multilayers for stabilization of small individual skyrmions at room temperature. Nat. Nanotechnol. 11, 444–448 (2016).
26. Birch, M. T. et al. Real-space imaging of confined magnetic skyrmion tubes. Nat. Commun. 11, 1726 (2020).
27. Yu, X. Z. et al. Real-space observation of topological defects in extended skyrmion-strings. Nano Lett. 20, 7313–7320 (2020).
28. Donnelly, C. et al. Three-dimensional magnetization structures revealed with X-ray vector nanotomography. Nature 547, 328–331 (2017).
29. Suzuki, M. et al. Three-dimensional visualization of magnetic domain structure with strong uniaxial anisotropy via scanning hard X-ray microtomography. Appl. Phys. Exp. 11, 036601 (2018).
30. Hierro-Rodriguez, A. et al. Revealing 3D magnetization of thin films with soft X-ray tomography: magnetic singularities and topological charges. Nat. Commun. 11, 6382 (2020).
31. Donnelly, C. et al. Imaging three-dimensional magnetic systems with X-rays. J. Phys. Condens. Matter 32, 213001 (2020).
32. Schütte, C. & Rosch, A. Dynamics and energetics of emergent magnetic monopoles in chiral magnets. Phys. Rev. B 90, 174432 (2014).
33. Vir, P. et al. Anisotropic topological Hall effect with real and momentum space Berry curvature in the antiskyrmion-hosting Heusler compound Mn$_{13}$PtSn. Phys. Rev. B 99, 140406(R) (2019).
34. Ma, T. et al. Tunable magnetic antiskyrmion size and helical period from nanometers to micrometers in a D$_{1n}$ Heusler compound. Adv. Mater. 32, 2002043 (2020).
35. Jena, J. et al. Elliptical Bloch skyrmion chiral twins in an antiskyrmion system. Nat. Commun. 11, 1115 (2020).
36. Srivastava, A. K. et al. Observation of robust Néel skyrmions in metallic PtMnGa. Adv. Mater. 32, 1904327 (2020).
37. Radon, J. On the determination of functions from their integral values along certain manifolds. IEEE Trans. Med. Imaging 5, 170–176 (1986).
38. Gordon, R., Bender, R. & Herman, G. T. Algebraic reconstruction techniques (ART) for three-dimensional electron microscopy and X-ray photography. J. Theor. Biol. 29, 471–476 (1970).
39. Rybakov, F. N. et al. New type of stable particlelike states in chiral magnets. Phys. Rev. Lett. 115, 117201 (2015).
40. Zheng, F. et al. Experimental observation of chiral magnetic bobbers in B20-type FeGe. Nat. Nanotechnol. 13, 451–455 (2018).
41. Feldkeller, E. Mikromagnetisch stetige und unstetige Magnetisierungs konfigurationen. Z. Angew. Phys. 19, 530–536 (1965).
42. DaCol, S. et al. Observation of Bloch-point domain walls in cylindrical. Phys. Rev. B 89, 180405(R) (2011).
43. Kanazawa, N. et al. Critical phenomena of emergent magnetic monopoles in a chiral magnet. Nat. Commun. 7, 11622 (2016).
44. Fujishiro, Y. et al. Large magneto-thermopower in MnGe with topological spin texture. Nat. Commun. 9, 408 (2018).
45. Donnelly, C. et al. Experimental observation of vortex rings in a bulk magnet. Nat. Phys. 17, 316–321 (2020).
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Methods
Sample preparation and characterization. A polycrystalline sample of Mn$_{75}$Pt$_{15}$Pd$_{10}$Sn was prepared by arc-melting stoichiometric amounts of pure Mn, Pt, Pd and Sn pieces under an Ar atmosphere. Bulk single crystals were grown by slow cooling of melted polycrystalline samples sealed into a silica tube under vacuum. Crystal orientations were determined using the back-reflection X-ray Laue photography method, and the purity of the sample was confirmed by powder X-ray diffraction. The wedge-shaped single-crystal sample for the scalar X-ray tomography measurements was prepared using the focused ion beam microfabrication technique, which was attached to a needle on the sample holder by tungsten bonding.

Scalar magnetic X-ray tomography measurements. The scanning hard-X-ray microtomography experiment was conducted at BL39XU of the SPring-8 (refs. 29, 46). X-ray radiation from the standard in-vacuum undulator was monochromatized using a Si(111) double-crystal monochromator. The X-ray energy was tuned at 11.572 keV, at which the present sample of Mn$_{75}$Pt$_{15}$Pd$_{10}$Sn showed the maximum amplitude of the XMCD spectrum at the Pt L$_3$ edge (see Supplementary Fig. 1 and Supplementary Note 1). A 1.4-mm-thick diamond X-ray phase plate was used to generate a circularly polarized X-ray beam with a degree of circular polarization of $P_c > 0.99$. The circularly polarized monochromatic X-ray beam was then focused onto a sample with a spot size of $150 \times 150 \text{nm}^2$ in FWHM using elliptical mirrors in the Kirkpatrick–Baez configuration. The depth of the focus was 200 μm, which was much greater than the sample diameter and the eccentric radius of the sample rotation stage.

A schematic illustration of the experimental set-up is shown in Fig. 1c,d. The wedge-shaped Mn$_{75}$Pt$_{15}$Pd$_{10}$Sn sample was placed on top of a projection-type electromagnet, and both were mounted on the same rotation stage ($\theta$) and two-dimensional translation ($Z$) stages. In this system, the sample and the electromagnet were rotated and moved while the relative orientation of the sample crystal axis and the magnetic field were unchanged during tomographic data acquisition. The more detailed experimental configuration around the sample and the electromagnet are provided in Supplementary Fig. 2 and Supplementary Note 2.

The projected images of X-ray absorption (XAS) and magnetic (XMCD) contrast were collected by scanning the sample two-dimensionally in the $X$–$Z$ plane as a function of the rotation angle $\theta$ between $-90^\circ$ and $+90^\circ$ with a step of $3^\circ$. The helicity modulation technique with X-ray photon helicity switching at 37 Hz was used for lock-in detection of the dichroic signals with a high signal-to-noise ratio. The XAS and XMCD projections were recorded simultaneously. For reconstructing a 3D XAS image, the standard algorithm of the algebraic reconstruction technique (ART) was applied to 37 projection images collected at the angles from $-90^\circ$ to $+90^\circ$. To reconstruct a 3D magnetic image, a modified ART algorithm has been applied to XMCD projections. In the modified ART, the $001$ component of local magnetization $m_r^C$ (in accord with the easy-axis uniaxial magnetic anisotropy of the present compound) was assumed and a correction for the $\cos \theta$ dependence of the XMCD amplitudes has been included. Then we obtained the 3D distribution of the $m_r^C$ component of the magnetization vector of the sample. This reconstruction method was previously shown to reproduce the 3D structure of the internal magnetic domains in a GdFeCo disk, which has a strong uniaxial anisotropy, with a spatial resolution of 360 nm (ref. 33).

Micromagnetic simulation. Micromagnetic simulation of 3D spatial distribution of vector magnetization $\mathbf{m}(r) \equiv \mathbf{m}$ was performed on the basis of the Landau–Lifshitz–Gilbert equation with the magnetic Hamiltonian described as

$$\mathcal{H} = \mathcal{H}_0 + \mathcal{H}_D + \mathcal{H}_{K_{\text{eff}}} + \mathcal{H}_{\text{coup}}$$

$$= \sum_r \left[ \mathbf{m}_r \cdot (\mathbf{m}_{r+\mathbf{a}} + \mathbf{m}_{r+\mathbf{b}} + \mathbf{m}_{r+\mathbf{c}}) \right] + D \sum_r \left[ \mathbf{m}_r \times (\mathbf{m}_{r+\mathbf{a}} + \mathbf{m}_{r+\mathbf{b}} + \mathbf{m}_{r+\mathbf{c}}) \right] - K_{\text{eff}} \sum_r \left[ \mathbf{m}_r^C \mathbf{m}_r^C - \mathbf{m}_r^C \right]$$

$$- \mathcal{H}_{\text{coup}} \sum_{r \in \Lambda} \left[ \mathbf{m}^C_r \mathbf{m}^C_{r+\mathbf{a}} + \mathbf{m}^C_r \mathbf{m}^C_{r+\mathbf{b}} + \mathbf{m}^C_r \mathbf{m}^C_{r+\mathbf{c}} \right]$$

$$+ \mathcal{H}_{\text{imp}} \sum_r \left[ \mathbf{m}_r^C \right]$$

$$\text{with } \mathbf{a}, \mathbf{b} \text{ and } \mathbf{c} \text{ are the unit vectors along the } [100], [010] \text{ and } [001] \text{ directions, and } m_r^C \text{ is the } 001 \text{ component of } \mathbf{m}_r. J, D \text{ and } B \text{ represent the amplitude of the exchange interaction, DM interaction with } D_{\text{an}} \text{ symmetry and external magnetic field along the } 001 \text{ direction, respectively. The single-ion magnetic anisotropy } K_{\text{eff}} \text{ was introduced on the random sites } \mathbf{r} \in \Lambda \text{ to represent the disorder in the crystals}.$$

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Author contributions
S.S., M.S. and T.O. planned the project. S.S., M.S., M.I. and T.O. performed the scalar magnetic X-ray tomography measurements. R.T., N.D.K., S.S., and Y.T. prepared the samples. M.I. and Y.S. supported the sample characterization. M.S. performed the reconstruction of the scalar magnetic tomography data. S.S. and M.S. analysed the reconstructed images and performed the simulation of tomographic reconstruction. K.S., S.S. and W.K. performed the theoretical calculations. S.S. wrote the manuscript and CREST (grant no. JPMJ(CR1874)) from JST, Asahi Glass Foundation and Murata Science Foundation. The synchrotron radiation experiments were performed with the approval of the Japan Synchrotron Radiation Research Institute (JASRI) (proposal nos. 2018A2067, 2019B1173 and 2020A2057).

Competing interests
The authors declare no competing interests.

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