Observation of domain wall bimerons in chiral magnets

Tomoki Nagase1, Yeong-Gi So2, Hayata Yasui2, Takafulmi Ishida3,4, Hiroyuki K. Yoshida5, Yukio Tanaka4, Koh Saitoh3,4, Nobuyuki Ikarashi1,6, Yuki Kawaguchi4, Makoto Kuwahara3,4, & Masahiro Nagao1,6

Topological defects embedded in or combined with domain walls have been proposed in various systems, some of which are referred to as domain wall skyrmions or domain wall bimerons. However, the experimental observation of such topological defects remains an ongoing challenge. Here, using Lorentz transmission electron microscopy, we report the experimental discovery of domain wall bimerons in chiral magnet Co-Zn-Mn(110) thin films. By applying a magnetic field, multidomain structures develop, and simultaneously, chained or isolated bimerons arise as the localized state between the domains with the opposite in-plane components of net magnetization. The multidomain formation is attributed to magnetic anisotropy and dipolar interaction, and domain wall bimerons are stabilized by the Dzyaloshinskii-Moriya interaction. In addition, micromagnetic simulations show that domain wall bimerons appear for a wide range of conditions in chiral magnets with cubic magnetic anisotropy. Our results promote further study in various fields of physics.

1 Department of Electronics, Graduate School of Engineering, Nagoya University, Nagoya, Japan. 2 Department of Materials Science, Graduate School of Engineering Science, Akita University, Akita, Japan. 3 Advanced Measurement Technology Center, Institute of Materials and Systems for Sustainability, Nagoya University, Nagoya, Japan. 4 Department of Applied Physics, Graduate School of Engineering, Nagoya University, Nagoya, Japan. 5 Department of Physics, Faculty of Science, Hokkaido University, Sapporo, Japan. 6 Center for Integrated Research of Future Electronics, Institute of Materials and Systems for Sustainability, Nagoya University, Nagoya, Japan.

Email: nagase.tomoki@k.nagoya-u.jp; kuwahara@imass.nagoya-u.ac.jp; nagao.masahiro@imass.nagoya-u.ac.jp
Topological defects arise when symmetry is spontaneously broken. They have long been studied because of playing key roles in understanding of diverse systems ranging from cosmological length scales to condensed matter\textsuperscript{1,2}. A domain wall (DW) is a type of topological defect, which is the boundary between domains with different signs of order parameters in a conventional sense. DWs are interesting not only for understanding nature but also for applications. For example, in ferromagnets, multiferroics, and magnetic topological insulators where an order parameter is the magnetization, the manipulation of magnetic DWs could potentially enable the realization of devices such as high-performance memory devices\textsuperscript{3}, energy conversion devices\textsuperscript{4}, and quantum information processing\textsuperscript{5}.

A skyrmion is another type of topological defect which can occur in two or three dimensions and was first introduced in the field of nuclear physics. Skyrmions are now widespread and realized in various systems\textsuperscript{6–8}. Among them, although two-dimensional magnetic skyrmions have only a short history since the discovery in a chiral magnet\textsuperscript{9}, they are gaining attention as a platform for studying emergent electromagnetic fields and related physical properties owing to the real-space topology of their spin textures\textsuperscript{10}. In particular, their electric current-driven motion at ultralow current density is expected to be exploited in modern efficient spintronic devices.

Meanwhile, topological defects embedded in or combined with DWs have been proposed in various systems so far. Malozemoff and Slonczewski have discussed the effect of such topological defects on magnetic DW mobility, where the topological defects are Bloch lines that exist as line defects in two-dimensional DWs\textsuperscript{11}. Usually, Bloch lines are formed by accidental excitation. Subsequently, Fal’ko and Iordanskii have first predicted pairs of stable Bloch lines in DWs in quantum Hall ferromagnet at the filling factor $\nu = 1$ (ref. 12). Such topological defects are then called DW skyrmions. It is noted, however, that skyrmions are mathematically classified by the second homotopy group $\pi_2(S^2)$, whereas merons are classified by the relative second homotopy group $\pi_2(S^2, S^1)$ (refs. 13,14). The difference is the boundary condition on a circle surrounding the object: The magnetization direction around a skyrmion is fixed, meanwhile that around a meron winds with nonzero winding number $\pi_1(S^1)$. Thus, the topological defect that can exist inside a DW is not a skyrmion but a meron, and we refer it to as not a DW skyrmion but a DW bimeron. Ever since then, DW bimerons have been independently proposed using various theoretical models in $\nu = 2$ quantum Hall ferromagnet\textsuperscript{15}, liquid crystals\textsuperscript{16}, and similar topological defects in various systems\textsuperscript{17–23}. In addition, more recently, magnetic DW bimerons have also been predicted\textsuperscript{24,25}. Although DW bimerons have attracted considerable interest because of involving a wide-ranging field of physics described above, no clear observation has been achieved so far\textsuperscript{26,27}.

Real-space imaging offers direct evidence for the presence of DW bimerons. We show the simulated Lorentz transmission electron microscopy (LTEM) images of magnetic skyrmions and conventional DWs as an example. DW bimerons would be identified as an LTEM image where the contrasts at DWs have similar to that of skyrmions. In magnets, LTEM can image both DWs and skyrmions, as illustrated in Fig. 1. The imaging principle is as follows. The incident electron beam is deflected by the Lorentz force and simultaneously its phase of the wavefunction is shifted by the in-plane component of the magnetization when passing through a magnetic thin film, and then the defocused interference image is seen on the screen. Qualitatively, the bright (dark) contrast of the LTEM images can be understood as the convergent (divergent) of the electron beam. The bright and dark contrasts reverse for the underfocused and overfocused images. In the case of Bloch DWs (Fig. 1a), the contrast pairs of the bright and dark lines are observed (Fig. 1b, c). In the case of Bloch skyrmions (Fig. 1d), either bright or dark dot contrasts are observed (Fig. 1e, f).

In this study, using LTEM, we report the direct observation of DW bimerons in cubic $\beta$-Mn-type chiral magnet Co–Zn–Mn(110) thin films. As magnetic fields are applied perpendicular to the planes, we observe the development of multidomain structures and two types of DWs, where one is a chain of DW bimerons and the other is a conventional DW. Bimeron chains and conventional DWs alternatively appear. The formation of the multidomains and paired DW structures are attributed to the combination of magnetic anisotropy, dipolar interaction, and the Dzyaloshinskii–Moriya interaction (DMI). In addition, the numerical simulations incorporating the well-known cubic magnetic anisotropy provide that DW bimerons can appear for a wide range of conditions in chiral magnet thin films.

**Results**

**Imaging magnetic structures with LTEM.** We investigate Co$_8$Zn$_2$Mn$_{12}$ (110) thin film with a thickness of $t \sim 50$ nm (see Methods). This material has the Curie temperature of 345 K and helical spin period of ~145 nm and $\beta$-Mn-type materials have larger magnetic anisotropy than $B$-type materials hosting skyrmions and the magnetic easy axes are along the <100> directions\textsuperscript{28}. Figure 2 shows the magnetization process with increasing magnetic fields perpendicularly downward to the plane at 330 K (for further LTEM images, see Supplementary Figs. 1, 2). A black line contrast identifying as a DW exists at a zero magnetic field (Fig. 2a). With increasing magnetic field, the additional black lines (conventional DWs) develop along the <110> direction, whereas the chains of the bright elliptical dots also develop (Fig. 2b). The individual bright dots are similar to the skyrmion contrasts. The conventional DWs and chains are always paired. By further increasing magnetic fields, the conventional DWs and chains develop further and show an increase in number up to 170 m$^{-1}$ (Fig. 2c, d), and then turn to a decrease in number (Fig. 2e). Finally, the conventional DWs and chains almost disappear (Fig. 2f).

In DW bimerons, bimerons play the role of the domain boundaries, in contrast to the conventional magnetic skyrmions in the uniform conical or field-polarized background\textsuperscript{9,29}. Our LTEM images (Fig. 2) imply that the chains of the bright elliptical dots are DW bimerons. However, the LTEM images alone are not clear: it is necessary to clarify whether there are domains with different magnetization directions on both sides of the chains. We
analyse the LTEM images to reveal the magnetic distributions. Figure 3a, b are the underfocused and overfocused LTEM images, respectively. We have used the transport of intensity equation based on Fig. 3a, b (see Methods). Figure 3c shows the in-plane magnetic flux density map. We note that Fig. 3c almost shows magnetization texture because the effects of leakage flux and demagnetizing field are small enough (see Methods). In addition to the Bloch magnetic texture of each vortex and DW, the domains with the opposite magnetizations along <110> directions are definitely formed on both sides of the vortex chains. Thus, our data provide direct evidence of magnetic DW bimerons. (The termination of the chains such as in the upper right in Fig. 3a, b, c may not have a topological charge of 1/2 and may have that of zero.) Furthermore, at 324 K, we found isolated bimerons bound to DWs, as presented in Fig. 3f. (The enlarged image within the blue dotted box in Fig. 3f is shown in Fig. 3g.) Since the number of observed bimerons decreases away from the Curie temperature, the formation is likely to be assisted by thermal fluctuations, as in the case of skyrmions. Further details of the temperature variation of magnetic structures are shown in Supplementary Fig. 3. In the following, bimerons playing a role of and bound to DWs are referred to as DW bimerons for convenience.

Formation mechanism. The formation mechanism of observed DW bimerons is different from that of theoretical predictions24,25 and our previous study30. Our achievement is attributed to the combination of the thin film thickness with $t \sim 50$ nm, magnetic anisotropy, dipolar interaction, and DMI. Our previous experiment on the same material Co$_{8.5}$Zn$_{2.5}$Mn$_4$(110) thin films with $t \sim 100$ nm reported that an applied magnetic field perpendicular to the plane induces a transition from a stripe phase to a smectic liquid-crystalline phase of skyrmions without any multidomains, due to magnetic anisotropy and partially modulated spin structures30. In the smectic phase, skyrmions exist within the uniform conical domain or field-polarized background30 as with conventional skyrmions. On the other hand, in the present study, in-plane helical spin orders with propagation vector perpendicular to the plane stabilize at a zero magnetic field, which has often been observed in the thin films of β-Mn-type Co–Zn–Mn (refs. 31,32), and the sample thickness (~50 nm) is about a third of the helical spin period (~145 nm). As a result, propagating in-plane helical spin orders are truncated before going around once in the present thin film. Truncated in-plane helical spin orders lead to a finite in-plane net magnetization, which is the magnetic structure of the domains. Figure 2a indeed shows two domains having different initial phases of spin at the sample surface (bottom) which are separated by the DW, due to dipolar interaction and wedge-shaped sample geometry effect. In conventional ferromagnet thin films, when a magnetic field is applied perpendicular to the plane, the volume fraction of domains only changes and the number of domains does not increase, but, in our thin film, multidomains accompanied by DWs and DW bimerons develop (Fig. 2b, c, d). Considering the combined effects of magnetic anisotropy and dipolar interaction can explain the formation and development of multidomains. In our thin film, one magnetic easy axis is parallel to the in-plane direction, and the other two are at an angle of 45° to the in-plane direction. The latter two have the components parallel to both the <110> directions within the plane and the direction of the applied magnetic field. By a magnetic field is applied perpendicular to the plane, magnetostatic energy and Zeeman energy mainly compete. In particular, due to magnetic induction, the increase in magnetostatic energy becomes quite large in the present thin film, whose thickness is ~50 nm, which is much thinner than that of the previous study30. Here, to reduce magnetostatic energy by dipolar interaction, the initial phase of spins on the sample surface (bottom) chooses between two equivalent magnetic easy axes in the <110> directions, resulting in truncated in-plane conical spin orders with a finite in-plane net magnetization, as shown in Fig. 3d, e where the arrows depict perpendicularly averaged magnetization to the plane. Therefore, multidomains composed of truncated conical spin orders with different initial phases of spins on the sample surface (bottom) develop. It is noted that LTEM detects the average value in the film thickness direction of the in-plane component of magnetic flux, therefore, DWs between truncated conical domains are imaged similarly as with
DWs in conventional ferromagnets. Of particular importance to form DW bimerons is the DMI that restricts the magnetic chirality of DWs. By applying a magnetic field perpendicular downward to the plane, DWs with the downward spin rotation are unstable, and instead, bimerons are stabilized at the boundaries between the domains (Fig. 3e). The formation of DW bimerons, which differ dramatically from that of smectic skyrmions at different film thicknesses, is due to the combination as above described, which has been not predicted.

**Micromagnetic simulations.** To verify the above surmise, the micromagnetic simulation seems to be an effective method. In fact, despite using the simple micromagnetic model expressed only by terms describing the ferromagnetic exchange interaction, DMI, Zeeman, and dipole interaction energies, it can well reproduce the microscopic internal spin textures of skyrmions and their array in chiral magnets such as B20-type FeGe (ref. 33). However, it is known that it is difficult to completely reproduce the magnetic structure of β-Mn-type Co–Zn–Mn by the micromagnetic simulation (ref. 30). The reason may be due to the atomic-scale complexities of the Co–Zn–Mn. This material has the two crystallographic sites randomly occupied by the two or three elements and the coexistence of the ferromagnetic coupling between Co–Co, Co–Mn, and the antiferromagnetic coupling between Mn–Mn (ref. 34). Due to these specific material properties, it is regrettably difficult for the Co–Zn–Mn to fully reproduce the magnetic structures, and therefore in future, more complex simulations should be developed.

Here, apart from the complex Co–Zn–Mn, we numerically propose that DW bimerons appear for a wide range of conditions in cubic magnets that have magnetic anisotropy. We have performed the micromagnetic simulation using the simple model described above with the addition of the cubic magnetocrystalline anisotropy (see Methods). The term of the magnetocrystalline anisotropy is described by $K_c[(m·C_1)^2(m·C_2)^2+(m·C_3)^2(m·C_3)^2]$, where $K_c$ is an anisotropy constant, $m$ is the unit magnetization vector, and $C_1$, $C_2$, $C_3$ are the unit vectors along the $<100>$ directions. $K_c$ in our simulations is the same in order of magnitude as that of other works (ref. 30). The magnetic easy axes are the $<100>$ directions ($K_c > 0$) (ref. 33) and the magnetic field ($B$) is applied perpendicularly downward to the ($110$) thin film plane with $t = 50$ nm. The simulated magnetic structures are summarized in Fig. 4a where the colors indicate the orientation and magnitude of perpendicularly averaged in-plane components of magnetization to the plane. At zero and small $K_c$ (lower left area), the conventional triangular skyrmion lattice is stabilized. At large $K_c$ (right area), on the other hand, triangular skyrmion lattice is unstable, and instead, domains with the opposite net magnetization as that of other works (ref. 30) are stabilized into strips along the ($110$) directions. Accordingly, the Bloch DWs and the vortex chains are...
formed alternately as the domain boundaries. To confirm that the vortex chains are DW bimerons, in Fig. 4c, we profile the topological charge density (TCD) for the simulation result (Fig. 4b). In the TCD map, there are peaks at each vortex, while no peaks at the Bloch DWs. The integration value of the TCD, which is the sum of half the regions of the two adjacent vortices, is +1, indicating the bimeron spin texture. Furthermore, the simulated underfocused and overfocused LTEM images for the magnetic distributions (see Methods) are almost in agreement with the experimental LTEM images (Fig. 3a, b). There is a little difference between the simulation and experimental results due to the complexities of the Co–Zn–Mn. In our experiment, DW bimerons along the <100> directions actually appear in Co–Zn–Mn thin films when the above conditions are satisfied. It is expected that bimerons are formed as DWs in the vicinity of the Curie temperature of $T_C \approx 60$ K due to thermal fluctuations and bound to DWs in temperatures away from $T_C$ as well as the present study of the Co–Zn–Mn(110) thin films.

**Discussion**

In the field of physics related to topology such as field theory and Bose–Einstein condensates, bimerons and merons/antimeron have long been paid much attention. For example, the bound states of fractional vortices are discussed in terms of quark confinement, where baryons and mesons are considered to be bimerons and pairs of meron–antimeron, respectively (refs. 38,39). In magnetism, merons/antimeron and bimerons have currently attracted considerable interest in spintronic applications utilizing topological properties as well as fundamental physics, and their lattice forms and isolations have proposed to be formed by in-plane magnetic anisotropy. In a chiral magnet thin film supposedly with in-plane magnetic anisotropy, a recent experiment showed a square lattice form of merons/antimerons, which stimulate further investigation of emergent electromagnetic properties as well as skyrmions. On the other hand, in our chiral magnet thin films, we show chained and isolated bimerons.
playing a role of and bound to DWs, respectively, which are realized by not only in-plane magnetic anisotropy component but also the combination of DMI, out-of-plane magnetic anisotropy, dipolar interaction, and Zeeman effect. These unique bimeron states and their formation mechanism have not been predicted in previous studies and our findings provide a new platform of discussion for topology in condensed matter as well as for field theory and Bose–Einstein condensates. It is noted that an isolated bimeron bound to a DW is a defect within a defect. Such kinds of defects have been discussed so far in various systems. In magnets, Bloch lines are randomly formed defects due to dipolar interaction. However, in chiral magnets that we studied here, isolated bimerons are selectively formed in one side of DWs only due to the above mechanism. They are found for the first time in this study, and in an application, expected to be driven along DWs which could avoid a phenomenon similar to the Hall effect that impedes device realization.

Our LTEM images have demonstrated the experimental observation of magnetic DW bimerons, pairing up with the conventional DWs in chiral magnets. Co–Zn–Mn (110) thin films. In addition, our micromagnetic simulations propose that DW bimerons can appear for a wide range of conditions in cubic chiral magnet (110) thin films with large magnetocrystalline anisotropy. Our results provide a guide to realize DW bimerons and promote further study in diverse fields of physics.

Methods

Sample preparation and LTEM observations. The bulk polycrystalline samples of β-Mn-type Co–Zn–Mn were prepared from highly pure Co (99.99%), Zn (99.99%), and Mn (99.99%) by a conventional melting process. The constituents of the alloys sealed in an evacuated quartz tube were heated at 1273 K for 12 h, then slowly cooled to 1198 K at a cooling rate of 1 K/h, and kept at the temperature for 72 h, followed by water-quenching. The magnetization measurement was performed using the superconducting quantum interference device. The magnetic structures are simulated by full energy minimization approach. Micromagnetic simulations were performed using Mumax3 (ref. 44). Magnetic structures are simulated by only magnetization. The electron disturbance is calculated by

\[ \psi(k_x, k_y) = \frac{i}{\hbar} \int \left( \frac{\partial \mathbf{r}}{\partial x} \right) \exp \left( -2\pi i (k_x x + k_y y) \right) dx dy. \]

By considering transfer function

\[ t(k_x, k_y) = A \left( k_x, k_y \right) \exp \left( -2\pi i \left( k_x x + k_y y \right) \right) \]

The LTEM image intensity is calculated as

\[ I(x, y) = \left( \int \left| \psi(k_x, k_y) \right|^2 E(k_x, k_y) \exp \left( -2\pi i \left( k_x x + k_y y \right) \right) dk_x dk_y \right)^2. \]

Data availability

The data that support the results of this study are available from the corresponding authors upon reasonable request.

Code availability

The micromagnetic simulation code (Mumax3) is available at https://mumax.github.io/ and the LTEM image simulation code is available from the corresponding authors upon reasonable request.

Received: 22 March 2021; Accepted: 19 May 2021;
Published online: 09 June 2021

References

1. Chuang, I. et al. Cosmology in the laboratory: defect dynamics in liquid crystals. Science 251, 1336 (1991).
2. Lahiri, J. et al. An extended defect in graphene as a metallic wire. Nat. Nanotechnol. 5, 326–329 (2010).
3. Parkin, S. S. P. et al. Magnetic domain-wall racetrack memory. *Science* **320**, 190–193 (2008).

4. Catalán, G. et al. Domain wall nanoelectronics. *Rev. Mod. Phys.* **84**, 119 (2012).

5. Yasuda, K. et al. Quantized chiral edge conduction on domain walls of a magnetic topological insulator. *Science* **358**, 1311–1314 (2017).

6. Sondhi, S. L. et al. Skyrmions and the crossover from the integer to fractional quantum Hall effect at small Fermi energies. *Phys. Rev. B* **57**, 16419 (1993).

7. Choi, J. et al. Observation of topologically stable 2D skyrmions in an antiferromagnetic spinor Bose-Einstein condensate. *Phys. Rev. Lett.* **108**, 035301 (2012).

8. Dass, S. et al. Observation of room-temperature polar skyrmions. *Nature* **568**, 368–372 (2019).

9. Mühbauer, S. et al. Skyrmion lattice in a chiral magnet. *Science* **323**, 915–919 (2009).

10. Nagaosa, N. & Tokura, Y. Topological properties and dynamics of magnetic skyrmions. *Nat. Nanotechnol.* **8**, 899–911 (2013).

11. Malozemoff, A. P. & Sliozberg, J. C. Effect of Bloch lines on magnetic domain-wall mobility. *Phys. Rev. Lett.* **29**, 952 (1972).

12. Fallani, V. I. & Iordanskii, S. V. Topological defects and Goldstone excitations in domain walls between ferromagnetic quantum Hall liquids. *Phys. Rev. Lett.* **82**, 402 (1999).

13. Mineyev, V. P. & Volovik, G. E. Planar and linear solitons in superfluid 3He. *Phys. Rev. B* **18**, 3197 (1978).

14. Gao, N. et al. Creation and annihilation of topological meron pairs in in-plane magnetized films. *Nat. Commun.* **10**, 5603 (2019).

15. Brey, L. & Tejedor, C. Spins, charges, and currents at domain walls in a non-abelian sandpile model. *J. Phys. D.* **40**, 196801 (2007).

16. Machon, T. & Alexander, G. P. Woven nematic defects, skyrmions, and the transport of intensity equation. *Phys. Rev. D.* **84**, 053620 (2011).

17. Xu, C. et al. Topological spin texture in Janus monolayers of the chromium trihalides Cr(I, II, III)X3. *Int. J. Mod. Phys. A* **30**, 1550006 (2015).

18. Nitta, M. et al. Creating vortons and three-dimensional skyrmions from domain-wall annihilation with stretched vortices in Bose-Einstein condensates. *Phys. Rev. A* **85**, 053639 (2012).

19. Kasamatsu, K. et al. Wall-vortex composite solitons in two-component Bose-Einstein condensates. *Phys. Rev. A* **88**, 013620 (2013).

20. Eto, M. et al. Skyrmions from instantons inside domain walls. *Phys. Rev. Lett.* **95**, 252003 (2005).

21. Kobayashi, M. & Nitta, M. Sine-Gordon kinks on a domain wall ring. *Phys. Rev. D.* **87**, 085003 (2013).

22. Gudnason, S. B. & Nitta, M. Domain wall skyrmions. *Phys. Rev. D.* **89**, 085022 (2014).

23. Bychkov, V., Kreshchuk, M. & Kurianovych, E. Strings and skyrmions on domain walls. *Int. J. Mod. Phys. A* **33**, 1850111 (2018).

24. Cheng, R. et al. Magnetic domain wall skyrmions. *Phys. Rev. B* **99**, 184412 (2019).

25. Xu, C. et al. Topological spin texture in Janus monolayers of the chromium trihalides Cr(I, II, III)X3. *Phys. Rev. B* **101**, 060404 (2020).

26. Muraki, K. et al. Charge excitations in easy-axis and easy-plane quantum Hall ferromagnets. *Phys. Rev. Lett.* **87**, 196801 (2001).

27. Yang, K. F. et al. Pump-probe nuclear spin relaxation study of the quantum Hall ferromagnet at filling factor v = 2. *N. J. Phys.* **21**, 083004 (2019).

28. Utkiev, V. et al. Element-specific soft x-ray spectroscopy, scattering, and imaging studies of the skyrmion-hosting compound Co8Zn9MnO14. *Phys. Rev. B* **99**, 144408 (2019).

29. Kim, T. et al. Mechanisms of skyrmion and skyrmion crystal formation from the conical phase. *Nano Lett.* **20**, 4731–4738 (2020).

30. Nagase, T. et al. Smectic liquid-crystalline structure of skyrmions in chiral magnet Co8Zn9MnO14 thin film. *Phys. Rev. Lett.* **123**, 137203 (2019).

31. Tokunaga, Y. et al. A new class of chiral materials hosting magnetic skyrmions beyond room temperature. *Nat. Commun.* **6**, 7638 (2015).

32. Yu, X. et al. Transformation between meron and skyrmion topological spin textures in a chiral magnet. *Nature* **564**, 95–98 (2018).

33. Shibata, K. et al. Temperature and magnetic field dependence of the internal and lattice structures of skyrmions by off-axis electron holography. *Phys. Rev. Lett.* **118**, 087202 (2017).

34. Nakajima, T. et al. Correlation between site occupancies and spin-glass transition in skyrmion host Co8Zn9MnO14. *Phys. Rev. B* **98**, 064407 (2018).

35. Preißinger M. et al. Vital role of anisotropy in cubic chiral skyrmion hosts. Preprint at https://arxiv.org/abs/2011.05967 (2020).

36. Chacon, A. et al. Observation of two independent skyrmion phases in a chiral magnetic material. *Nat. Phys.* **14**, 936–941 (2018).

37. Qian, F. J. et al. New magnetic phase of the chiral skyrmion material Co8O5Se9O9. *Sci. Adv.* **4**, eaat7323 (2018).
