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Real-Space Observation of a Transformation from Antiskyrmion to Skyrmion by Lorentz TEM

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Lorentz transmission electron microscopy (TEM) is extensively used to investigate nanometer-scale magnetic textures owing to its high spatial resolution. A conventional Lorentz TEM at the Fresnel mode can effectively obtain the information about in-plane magnetizations as well as their changes under various external stimuli. Recently, magnetic skyrmions [1] and antiskyrmions [2] have drawn particular attention due to their nanometer size and topological stability, and hence have potential applications as information carriers in magnetic storages. Skyrmions and antiskyrmions are vortex-like topological particles and anti-particles with topological charges −1 and +1 [3], respectively. To apply skyrmions and antiskyrmions to spintronics, we need to understand and control them.

Here we report the realization of the antiskyrmion and the skyrmion in a non-centrosymmetric Heusler magnet by using the Lorentz TEM (JEOL 2100F). With applications of in-plane fields, we have directly observed that the antiskyrmion can transform into the elliptic-form skyrmion via the chiral bubble.

Figs. 1a-c show the Fresnel Lorentz TEM (under-, in- and over-focus) images of the antiskyrmion taken at a normal field of 340 mT and room temperature. The under- (Fig. 1a) and over-focus (Fig. 1c) images show reversed contrasts due to the interaction between incident electrons and local magnetizations, and the in-focus image (Fig. 1b) shows a uniform contrast. The corresponding magnetization textures in Fig. 1d, deduced by using the transport-of-intensity equation [4], describe the antiskyrmion spin texture with four Bloch lines as signed by the yellow arrows, which are schematically drawn in Fig. 1e. The magnetic moments in the core of the antiskyrmion point upwards, while those at the perimeter point downwards. It should be noted that the shape of the antiskyrmion is close to a square, which is different from the circle as reported in ref. [2].

Interestingly, the topological transformation from the antiskyrmion to the skyrmion has been directly observed with varying the in-plane magnetic field as shown in Fig. 2. The antiskyrmion with a topological charge $N = +1$ in Fig. 2a, generated at a normal field of 335 mT, transforms into the chiral bubble with $N = 0$ in Fig. 2b at an in-plane field of 6 mT. To compare their Lorentz TEM images, we have observed that the left-side contrast of the antiskyrmion (Fig. 2a) is reversed, indicating that the magnetizations there are flipped, and thus the chiral bubble is generated (Fig. 2b). In addition, when the in-plane field is decreased back to almost zero, the elliptic-form skyrmion with $N = -1$ (Fig. 2c) is generated from the chiral bubble (Fig. 2b) since the right-side magnetizations of the chiral bubble are flipped deduced by the reversal of the contrast there. The *in-situ* observation exhibits a transformation from the antiskyrmion to the skyrmion together with the change of the topological charge from +1 to −1 due to the change of Zeeman energy. The transformation observed here is reversible with varying the in-plane field.

In conclusion, the above Lorentz TEM observations have clearly uncovered a variety of topological spin textures, antiskyrmion, skyrmion and chiral bubble in a non-centrosymmetric magnet. We have directly observed their magnetic structure transition with applications of in-plane fields, which is accompanied by a change of the topological charge. These results may provide a way to control various topological configurations, and may enhance the possibilities for applying them into spintronics [5].

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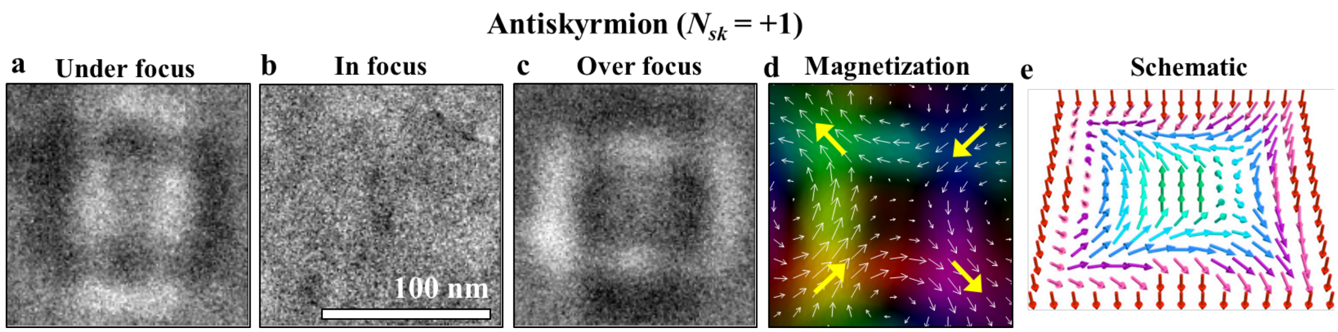

Figure 1. Lorentz TEM observation of the antiskyrmion. **a-c**, Under-, in- and over-focus Lorentz TEM images of the antiskyrmion at a normal field of 340 mT and room temperature. **d-e**, Corresponding magnetization textures (d) and schematic drawing (e) of the antiskyrmion, respectively.

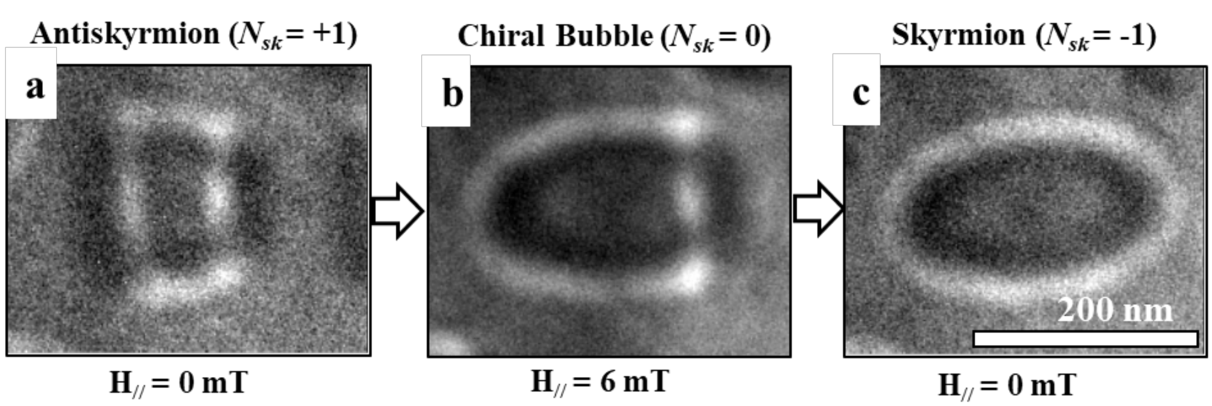

Figure 2. Transformation from the antiskyrmion to the skyrmion. **a**, Antiskyrmion with a topological charge N = +1 at a normal field of 335 mT. **b**, Chiral bubble with N_{sk} = 0 at an in-plane field of 6 mT. **c**, Elliptic-form skyrmion with N_{sk} = −1 when the in-plane field is deduced back to zero.