Direct visualization of three-dimensional shape of magnetic skyrmion string

In recent years, the swirling texture of electron spins, called “magnetic skyrmions”, that appear in magnetic materials has attracted considerable attention. Because of their geometrical stability, extremely small size, and efficient electrical controllability, they are expected to be a promising candidate for information carriers for next-generation ultrahigh density and ultralow power consumption magnetic storage and computation devices [1,2].

Skyrmion is known to have particle-like properties in an ideal two-dimensional system (Fig. 1(a)), and has been experimentally identified using two-dimensional imaging techniques such as Lorentz transmission electron microscopy [1]. On the other hand, recent theoretical studies predict that skyrmions in real three-dimensional systems have the properties of “strings” with spins aligned in a tornado shape (Fig. 1(b)). However, their experimental observation has been considered difficult, because the information along the depth direction is usually lost in the traditional two-dimensional imaging methods. In this context, the development of a novel experimental method to directly visualize three-dimensional shape of skyrmion strings is highly anticipated.

In this study, we focused on a technique called X-ray tomography (which is used in computed tomography (CT) scans for the inspection of the human body), in order to clarify the three-dimensional shape of the skyrmion strings. This approach enables precise reconstruction of the three-dimensional shape of the target object based on two-dimensional transmission images taken from various angles. For this purpose, we constructed an appropriate measurement environment at SPring-8 **BL39XU** (Fig. 1(c)). Here, we employed a circularly polarized X-ray beam to identify the local spin orientation from the X-ray magnetic circular dichroism (XMCD). X-ray energy was tuned at 11.572 keV, in resonance with the L_3 absorption edge of Pt. The X-ray beam was focused to a width of 150 nm for a high spatial resolution, and the sample position was scanned to obtain two-dimensional transmission images. By simultaneously rotating the sample and external magnetic field, such two-dimensional transmission images are taken from various angles, enabling the reconstruction of the three-dimensional distribution of the scalar magnetization component. We applied this technique to a tiny plate-shaped single crystal of non-centrosymmetric magnet $\mathrm{Mn_{1.4}Pt_{0.9}Pd_{0.1}Sn}$, which has been reported to produce skyrmions with a diameter of 135 nm at room temperature [3]. As a result, three-dimensional shape of a skyrmion string has been successfully visualized for the first time. This observation experimentally proved the existence of a nearly straight skyrmion string in the sample and also revealed the existence of various defect structures such as interrupted and Y-shaped strings (Fig. 2) [4].

The above results establish a brand new method for the direct observation of the three-dimensional shape of a skyrmion string, which is expected to make a significant contribution to a

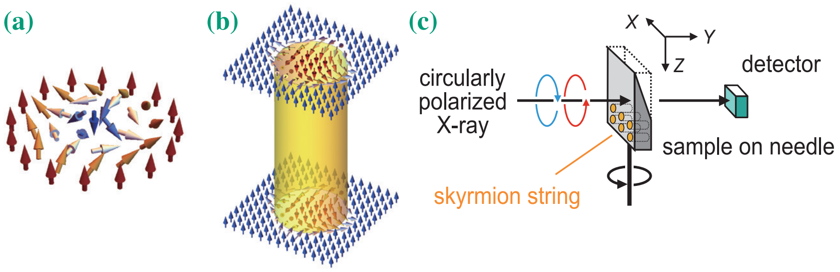

Fig. 1. Schematic illustration of **(a)** a skyrmion particle in a two-dimensional system and **(b)** a skyrmion string in a three-dimensional system, which is characterized by a uniform stacking of two-dimensional skyrmions in the string direction. Arrows indicate the direction of spin. **(c)** Measurement arrangement of the X-ray tomography experiment in this study. Using the two-dimensional XMCD transmission images observed from various angles, we reconstructed the three-dimensional shape of the skyrmion string as shown in Fig. 2.

better understanding of the properties of skyrmions as information carriers. In particular, it is important to understand how a skyrmion string is deformed or pinned in the presence of crystallographic defects in the material when it is driven by an external stimulus such as electric current. The detailed investigation of this process will lead to the elucidation of new guidelines for a more efficient control of skyrmions. According to recent studies, it is also possible to transfer information via the vibration of a skyrmion string, like a tin-can telephone [5]. Since the vibration of such a string does not cause energy loss due to Joule heating (proportional to the square of the current) unlike the current in an electric circuit, skyrmion strings have the potential to be utilized as a rewritable information transmission channel with low power consumption. 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.

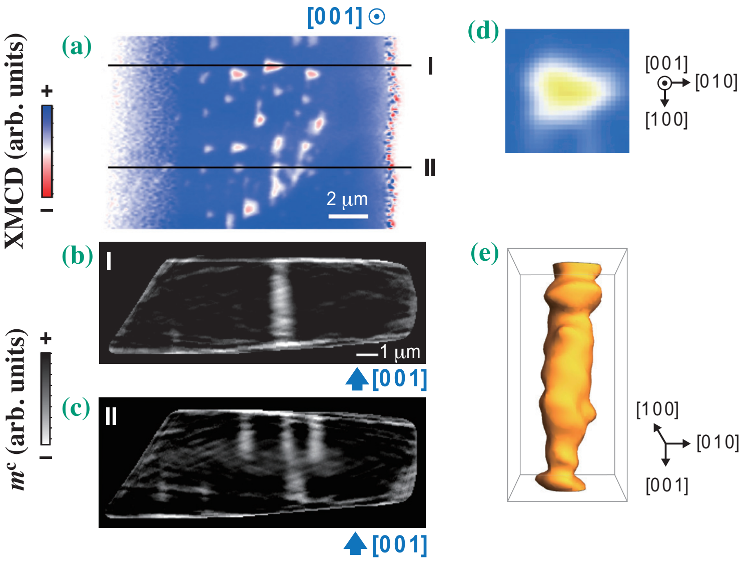

Fig. 2. **(a)** Two-dimensional XMCD transmission image of skyrmion strings in a $Mn_{1.4}Pt_{0.9}Pd_{0.1}Sn$ alloy, observed from the string direction. The background color represents the XMCD intensity and reflects the spin component along the out-of-plane direction. **(b, c)** Cross sections of the three-dimensional spatial distribution of the [001] spin component (m^c) reconstructed from tomographic measurements. In **(b)**, the skyrmion string penetrates from one end of the sample to the other, whereas in **(c)**, the interrupted or Y-shaped skyrmion strings are identified. **(d)** Expanded view of two-dimensional XMCD transmission image of a skyrmion string observed from the string direction. **(e)** Three-dimensional shape of the corresponding skyrmion string obtained from tomographic measurements.

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