The effect of in-plane pulsed magnetic fields on antiferromagnetically-coupled bubble skyrmion pairs

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Introduction

Magnetic skyrmions, topologically protected chiral spin textures, have attracted growing research interests not only due to their rich physics as topological phases of matter but also their potential applications in data storage and Spintronics [1]. However, the recently discovered Skyrmion Hall Effect (SkHE), where ferromagnetic skyrmions will be driven towards the edge of the device[2], can lead to technical issues in skyrmion-based spintronic devices. To suppress the SkHE, we have designed and fabricated antiferromagnetically-coupled (AFM-coupled) bubble skyrmion pairs, as illustrated in Fig. 1. The top skyrmion in Fig. 1 (a), corresponding to a skyrmion in the Gd layer in Fig. 1(b), is AFM-coupled to the bottom skyrmion in Fig. 1 (a) located in Co layer in Fig. 1(b).

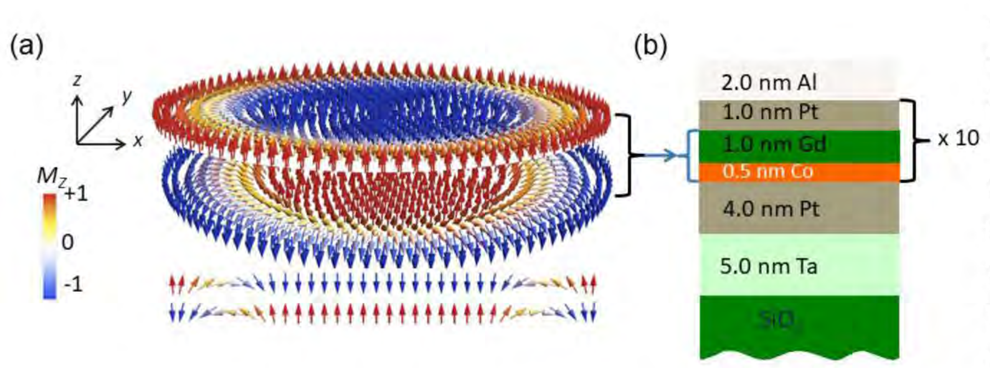

Fig. 1: (a) Illustration of an AFM-coupled bubble skyrmion pair with the spin configuration in a cross section along the radial direction depicted below. The arrows represent the atomic spins and their color corresponds to different magnetization along the z axis shown by the color scale bar to the right. (b) Structure of the multilayer sample Si/SiO_2 (300 nm)/Ta (5 nm)/Pt (4 nm)/[Co (0.5 nm)/Gd (1 nm)/Pt (1 nm)]$_{10}$/Al (2 nm).

Here we report our direct imaging study on the magnetic-field excited motion of the chiral domain walls located at the boundary of the AFM-coupled bubble skyrmions using element specific x-ray photoemission electron microscopy (PEEM). Our results can provide crucial information for applications of skyrmions in Spintronic data storage devices.

Experimental methods: PEEM imaging with pulsed magnetic fields

The PEEM imaging was performed at the Advanced Light Source of Lawrence Berkeley National Laboratory. A specifically designed sample holder with a built-in electromagnet was used to provide the excitation field *in-situ*, as shown in Fig. 2. The electromagnet can generate 1.5-second pulses of in-plane fields with magnitudes up to ~162 Oe, across the sample. After the application of each pulsed field, PEEM images were taken to investigate the effect of this applied pulsed field on the domain walls. Each final PEEM image was constructed by taking the difference of two images, acquired with left circularly polarized (LCP) or right circularly polarized (RCP) x-ray beams, to obtain magnetic contrast originated from the x-ray magnetic circular dichroism (XMCD), as shown in Fig. 3. The unique element specificity allows us to resolve the skyrmions in the Co and Gd layers, instead of only imaging the overall net magnetization.

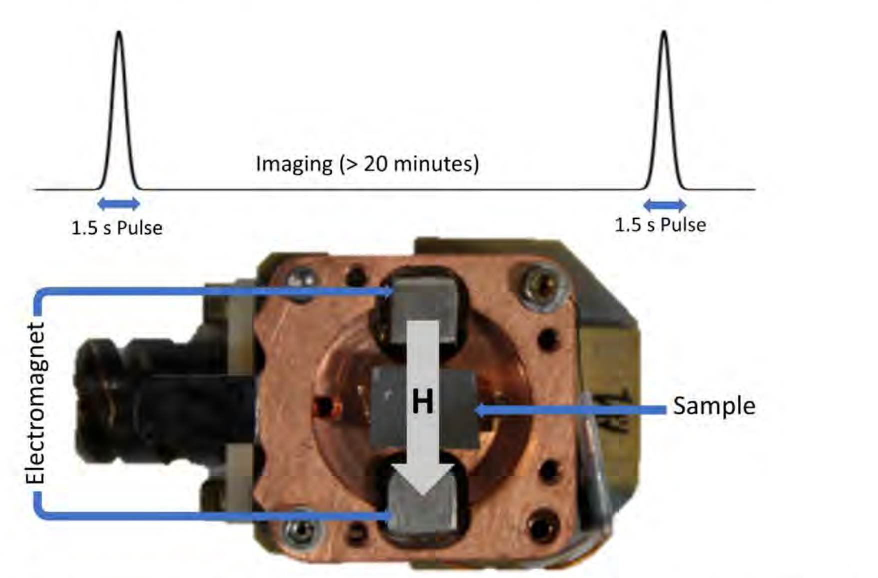

Fig. 2: Specifically designed sample holder that allows for the application of an in plane magnetic field via an electromagnet. PEEM images were taken between the 1.5 second pulsed fields of varied magnitudes.

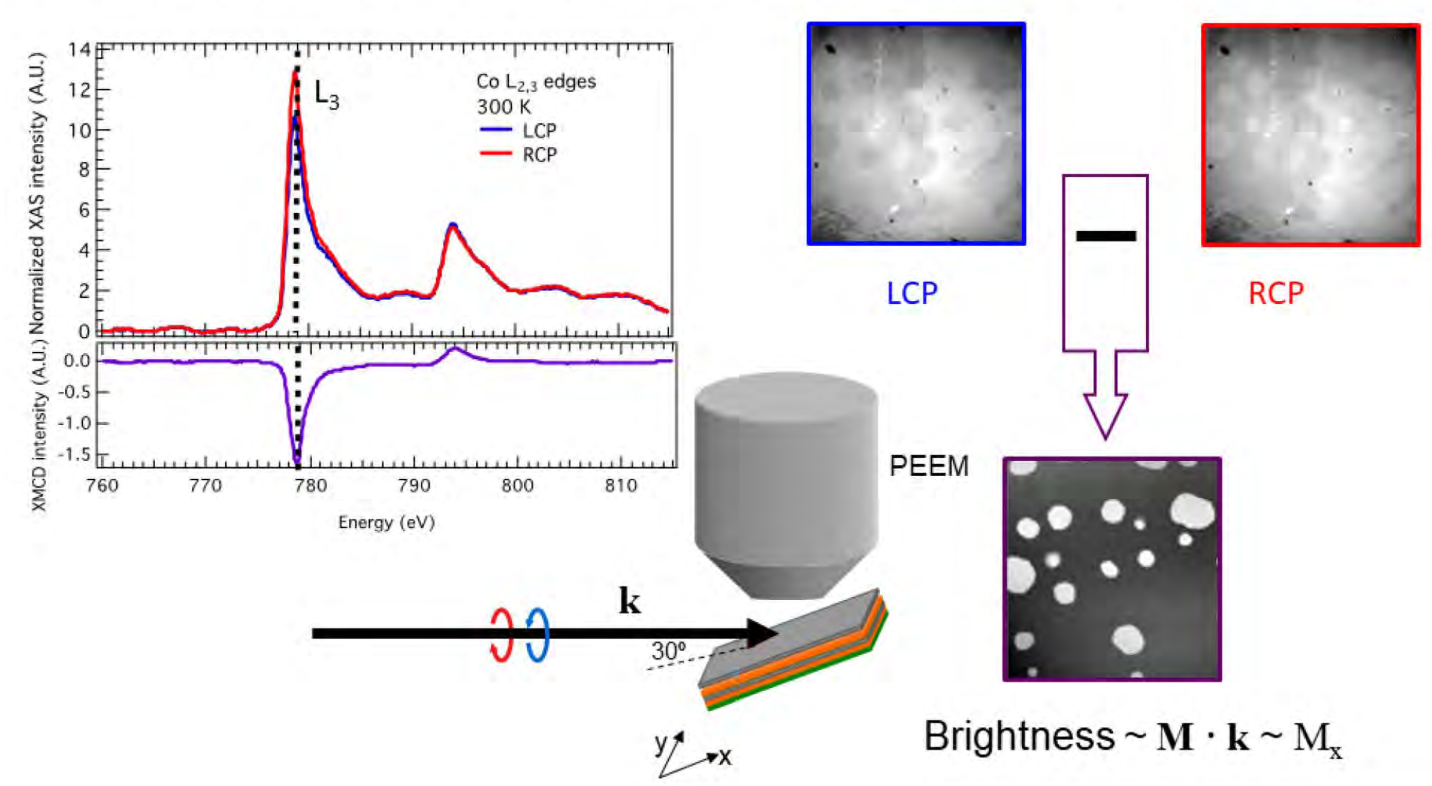

Fig. 3: Illustration of the experimental set-up and mechanism for PEEM imaging. The left panel shows the x-ray absorption spectra excited by x-rays of different circular polarizations as well as the resultant XMCD spectrum of Co $L_{2,3}$ edges. PEEM images were obtained by taking the difference of images taken with a LCP or RCP x-ray beam. The x-ray beam incident angle is 30°.

Domain wall motion excited by pulsed in-plane magnetic fields

An obvious increase in the size of the skyrmions, due to the motion of domain walls, was observed after different magnitudes of pulsed in-plane fields were applied, as shown in Fig. 4. The white areas show the regions of growth and the black areas indicate regions of shrinkage with respect to the original state. This movement of the domain walls results from the competition between the various magnetic interactions present in the skyrmion system. In order to quantify the domain wall (DW) motion, the PEEM image corresponding to the previously applied field was subtracted from the current image. The maximum distance along the radial directions of these difference areas from the subsequent images was measured and then divided by the duration of the magnetic field pulse to obtain the maximum speed of the DW motion. Afterwards, the maximum speed for the entire image versus the magnetic field was graphed, shown in Fig. 5. It can be seen from both Fig. 4 and Fig. 5 that, for the majority of skyrmions, as the strength of the in-plane field was increased the speed of DW growth tends to increase as well.

The domain wall motion at different regions of skyrmions were compared by calculating the area of growth and shrinkage of four regions which are illustrated through the inset included in Fig. 6. At low fields (< 50 Oe) there is almost no motion for all the regions; however, when the field is above 140 Oe an obvious difference between the growth of the L and R regions can be seen. This asymmetric DW motion could be a result of the opposite domain wall directions in the L and R regions with respect to the direction of the pulsed in-plane field. Specifically, the spin orientations of the domain walls in the L(R) region are almost antiparallel(parallel) to the applied in-plane pulsed field, giving rise to very different Zeeman energy, which is minimized(maximized) when the spin is parallel (antiparallel) to the field.

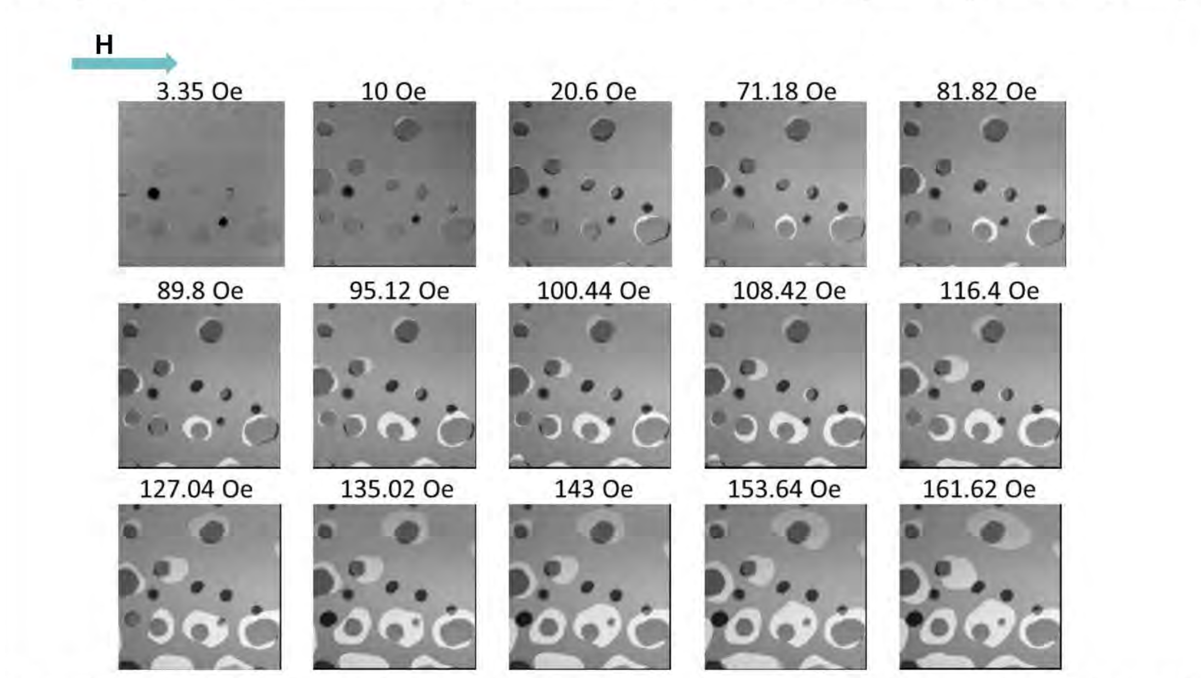

Fig. 4: PEEM images of skyrmions taken after different pulsed in-plane fields with the 0 Oe image subtracted as reference. Gray suggests no change, white indicates growth, and black shows shrinkage. As the field was increased the smaller skyrmions reversed magnetization and disappeared while the larger ones grew.

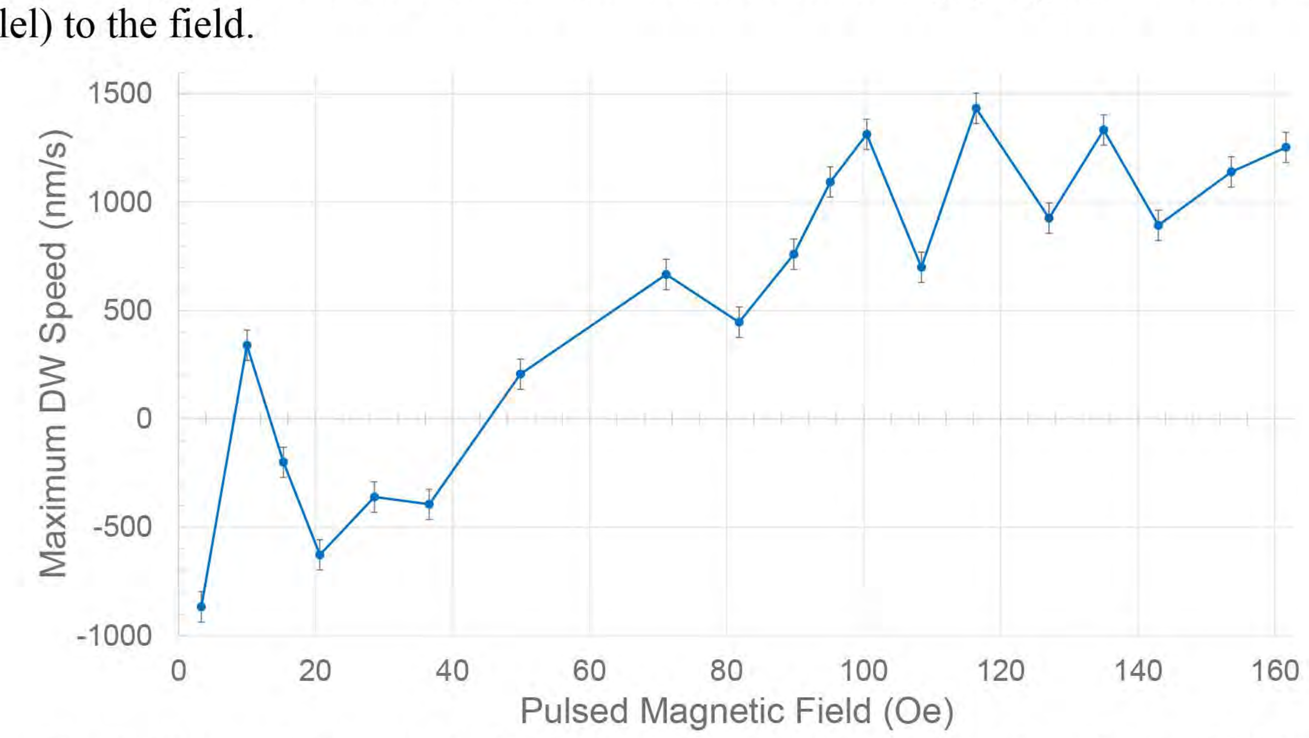

Fig. 5: The maximum speed of the domain wall motion as a function of the pulsed in-plane magnetic field with possible error originating from the misalignment of the images corresponding to adjacent fields. As the magnetic field increases the domain wall (DW) motion speed tends to increase.

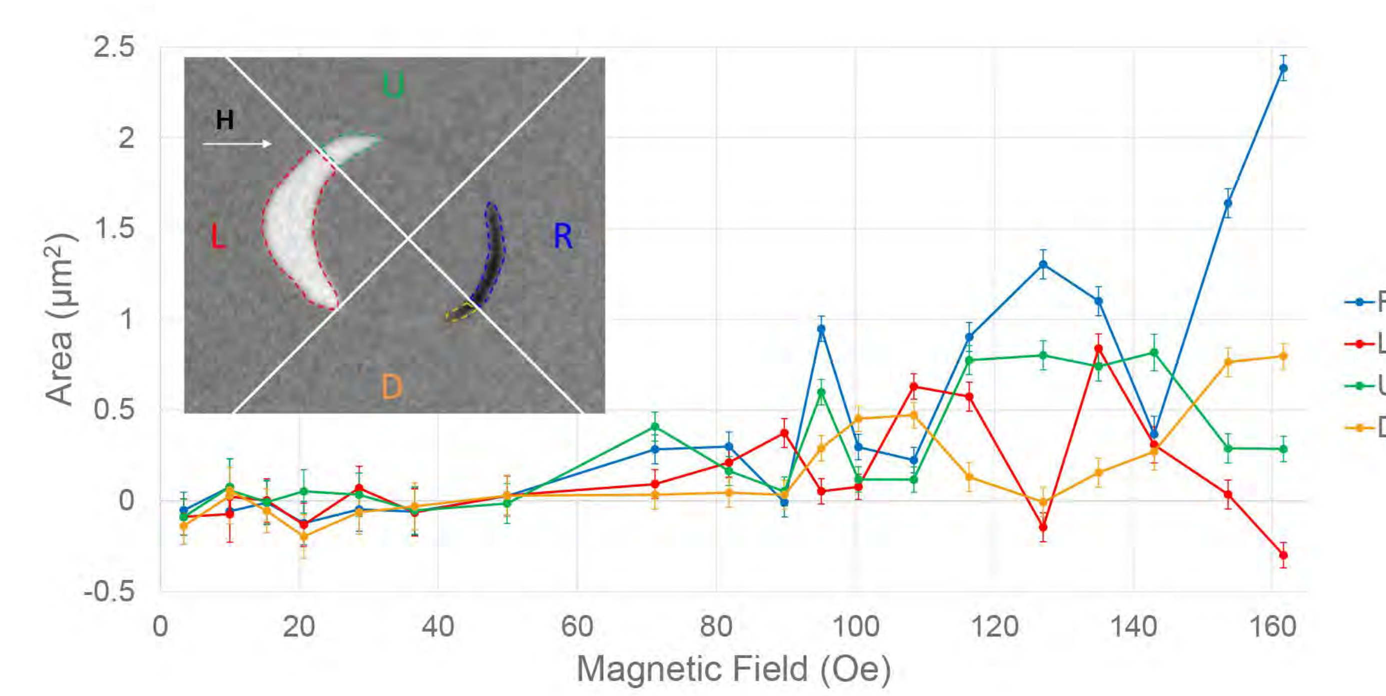

Fig. 6: The average area of the regions of growth and shrinkage for each quadrant as a function of the pulsed in-plane magnetic field. These four regions of the skyrmion behave differently from each other once the magnetic field is sufficiently large, approximately 50 Oe.

References and Acknowledgements

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Conclusions

- Element specific PEEM was utilized to study *in situ* the effect of in-plane pulsed magnetic fields on the domain walls of AFM-coupled bubble skyrmion pairs.
- The speed of the domain wall motion increases as the magnitude of the pulsed in-plane magnetic field increases.
- The observed asymmetric domain wall motion could be a result of the opposite spin reorientations with respect to the in-plane field.
- The domain wall motion of the AFM-coupled bubble skyrmions could be attributed to the competition among the dipolar interaction, Dzyaloshinskii-Moriya interaction and Zeeman energy.
- Further micromagnetic simulations will be conducted to investigate the mechanism behind the effect of in-plane pulsed fields to the domain walls of AFM-coupled skyrmion pairs.