Asymmetric spin-wave dispersion on Fe(110): Direct evidence of Dzyaloshinskii–Moriya interaction

K. Zakeri, Y. Zhang, J. Prokop, T.-H. Chuang, and W. X. Tang

In 1928, Heisenberg formulated a model to describe the interaction between neighboring atoms, which leads to long range magnetic order in magnetic solids [1]. This interaction, called exchange interaction, accounts only for the interaction of electrons in neighboring atoms and could not explain the weak ferromagnetism observed in some materials, e.g. $\alpha-Fe_2O_3$ (hematite). In 1957, Dzyaloshinskii proposed an antisymmetric exchange interaction, based on symmetry arguments, to explain the weak ferromagnetism in this class of materials [2]. Three years later it was shown by Moriya that this interaction originates from the spin-orbit coupling [3]. The spin-orbit coupling connects the spin of the electrons to their orbital motion. This interaction, called Dzyaloshinskii–Moriya (DM) interaction, became very important to understand many phenomena observed in various systems.

In an ideal Heisenberg ferromagnet all spins are parallel and a deviation of one spin creates collective spin excitations, known as spin waves (SWs). The SWs with the same wavelength possess the same energy, when propagating along two equivalent directions.

By investigating the spin-wave excitations in a two atomic layer thick iron film grown on tungsten (110) using spin-polarized electron energy loss spectroscopy (SPEELS) we demonstrated that the SWs propagating along two opposite (but equivalent) directions have different energies, which is evidence for the DM interaction in this system.

In the SPEELS experiment the surface spin waves are excited in an exchange scattering process [4]. A schematic representation of the scattering geometry is given in the inset of Fig. 1(a). The conservation of the angular momentum during the scattering prohibits spin-wave excitations for incoming electrons with a spin polarization antiparallel to the sample magnetization ($I_\uparrow$). Hence, only electrons having minority spin character ($I_\downarrow$) can create SWs. The electrons with majority spin character ($I_\uparrow$) annihilate the thermally excited SWs while gaining energy [4]. These facts lead to a peak in the minority spin channel in the energy loss region and a peak in the majority spin channel in the energy gain region. Figure 1(a) shows typical SPEEL spectra measured at the wave vector transfer of $\Delta K^{\parallel} = 0.5$ Å^{-1} on a 2 ML Fe film. The spin-wave creation and annihilation processes give rise to a large peak in the energy loss region and a small dip in the energy gain region of the difference spectra at the energies marked by big triangles in Fig. 1(b). The

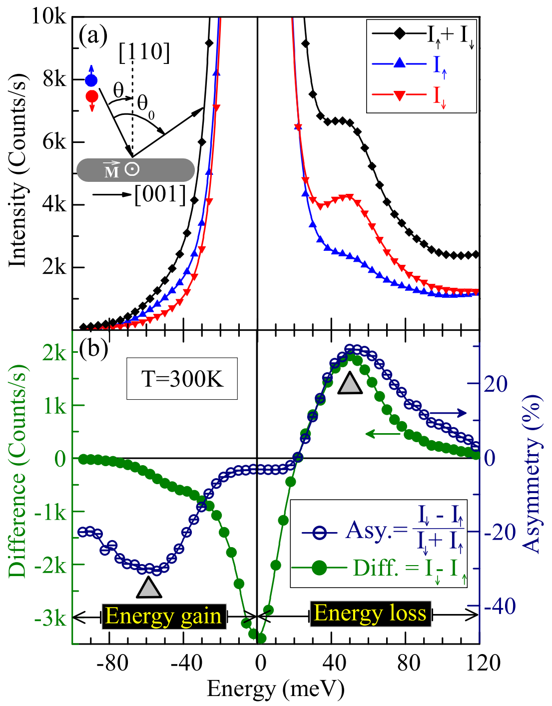

Fig. 1: (a) Spin-polarized electron energy loss spectra measured on a two atomic layer thick iron film grown on W(110) at a momentum transfer of $\Delta K^{\parallel} = 0.5$ Å^{-1}. (b) Difference and asymmetry spectra. Big triangles show the peak position due to spin-wave creation and annihilation, taking place in energy loss and gain, respectively.

features can be clearly seen in the asymmetry curve, where the asymmetry, $Asy. = \frac{I_\downarrow - I_\uparrow}{I_\downarrow + I_\uparrow}$, is plotted as a function of energy (Fig. 1(b)).

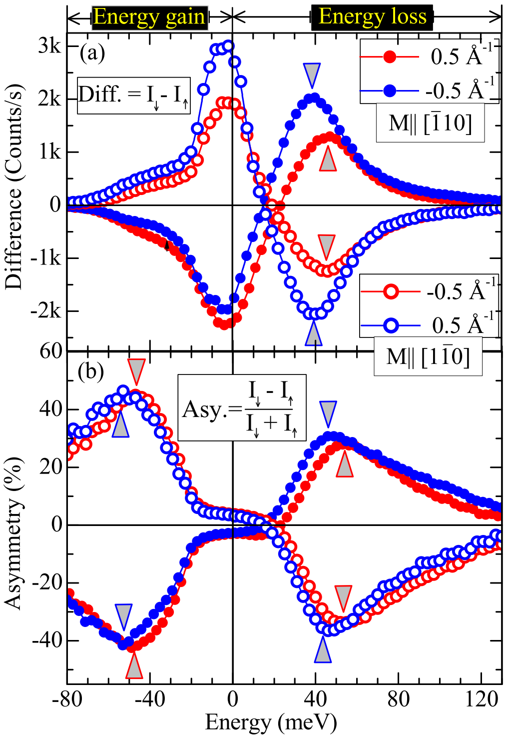

Fig. 2: Series of (a) difference and (b) asymmetry spectra measured for $\Delta K^{\|} = \pm 0.5$ Å^{-1} on a two atomic layer thick Fe film on W(110). The filled symbols are for $\vec{M} \parallel [\bar{1}10]$ and the open ones are for $\vec{M} \parallel [1\bar{1}0]$. Big triangles mark the peak positions of spin-wave creations and annihilations, taking place at energy loss and gain, respectively.

Figure 2 shows a series of difference and asymmetry curves measured on two atomic layers of Fe on W(110) at room temperature. The full symbols are the results of measurements when the magnetization is pointing along the $[\bar{1}10]$-direction. One clearly sees that for $\Delta K^{\|} = 0.5$ Å^{-1} the spin-wave creation peak (energy loss) is at higher energies, whereas the SW annihilation peak (energy gain) is at lower ones (it can be seen better in the asymmetry curves). The situation is totally reversed for negative wave vector transfers i.e. $\Delta K^{\|} = -0.5$ Å^{-1}; the spin-wave annihilation peak is at higher energies and spin-wave creation peak is at lower energies now. If this effect is caused by an uncertainty in the wave vector transfer, due to the stray field induced bending of the electron beam in two different experiments, one would expect the same effect in the gain and loss regions (increase or decrease in both energies). The reversed phenomena in energy gain and loss regions indicate that this effect cannot be due to a slightly different electron trajectory in two different experiments.

Another argument which clarifies that this is an intrinsic property of the system comes from measuring the same spectra for opposite magnetization directions. In magnetism, reversing the sample magnetization is equivalent to time inversion. The data for magnetization along the $[1\bar{1}0]$-direction are shown by open symbols in Fig. 2. In the case of reversed magnetization the spin-wave excitation peak for $\Delta K^{\|} = -0.5$ Å^{-1} is at higher energies with respect to the one for $\Delta K^{\|} = 0.5$ Å^{-1}. This clearly indicates that having a slightly different energy for the spin waves propagating along the [001]-direction with respect to the ones propagating along the $[00\bar{1}]$-direction is an intrinsic property of the spin waves in this particular system. Based on spin-wave theory, the symmetric exchange interaction cannot lead to different excitation energy for spin waves, with the same momentum but propagating along opposite directions. Hence, we conclude that this effect is caused by the DM interaction [5].

In summary, we demonstrated that in a two atomic layer Fe film on W(110) the spin waves propagating along two opposite directions possess different energies, evidencing the presence of the DM interaction in the system. Our results, which reveal the importance of the antisymmetric exchange interaction, provide a new insight into the spin dynamics in magnetic nanostructures.

References

[1] W. Heisenberg, Z. Physik **38**, 441 (1926).

[2] I. E. Dzyaloshinskii, Sov. Phys. JETP **5**, 1259 (1957).

[3] T. Moriya, Phys. Rev. **120**, 91 (1960).

[4] M. Plihal, D. L. Mills, and J. Kirschner, Phys. Rev. Lett. **82**, 2579 (1999).

[5] K. Zakeri, Y. Zhang, J. Prokop, T.-H. Chuang, N. Sakr, W. X. Tang, and J. Kirschner, Phys. Rev. Lett. **104**, 137203 (2010).