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Magnetic excitations in ultrathin magnetic films: Temperature effects

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ABSTRACT

The idea of investigating large wave-vector magnetic excitations in ultrathin films by spin-polarized electron spectroscopy is briefly reviewed. The historical background of the paper is based on the personal experience of the authors who collaborated and discussed with Douglas Mills regarding this subject. Douglas Mills' impact on the understanding of fundamental mechanisms involved in the excitation process and the development of the theory of magnetic excitations is outlined.

In addition, the temperature effects on the large wave-vector magnetic excitations in ultrathin Fe films are addressed. The experimental results of magnon excitations in the pseudomorphic Fe monolayer on W(110) are presented. The temperature dependence of the magnon dispersion relation is discussed.

1. Introduction

Magnetic excitations belong to one of the most important concepts in magnetism and have been intensively investigated over several decades, as they are the fundamental basis of understanding many phenomena in solids. Generally, in a given magnetic solid there is a large variety of magnetic excitations, depending on the wavelength of these excitations and the magnetic interactions involved. On the atomic length scales the dominating magnetic interaction describing the coupling of the neighboring moments is the magnetic exchange interaction. On these length scales the exchange dominated magnetic excitations with short wavelength (large wave-vector) are important. These types of excitations possess energies on the order of a few millielectron-volts up to a few hundred millielectron-volts and are sometimes referred to as high-energy magnetic excitations.

Experimentally, these excitations have already been investigated by means of inelastic neutron scattering in bulk magnetic materials [1–13]. The dispersion relation of elementary magnetic excitations (magnons) has been measured over a large fraction of the Brillouin zone (only a small part of the Brillouin zone, close to the zone center, has not been measured due to the limited energy resolution at that time). Nowadays one can perform inelastic neutron scattering experiments with an extremely high energy resolution, for example by using cold neutrons or the so-called neutron spin echo technique. The interaction between neutrons' spin and the magnetic moment of the unit cell leads to excitation of a magnon in the system. As this interaction is of dipolar nature, it is rather weak and hence neutron scattering cannot be employed to investigate the magnons in small size structures or ultrathin films.

Probing magnetic excitations in low-dimensional magnets has been of great fundamental importance for understanding their novel properties. For probing the uniform mode (zero wave-vector) and also short wave-vector magnetic excitations in low-dimensional magnets, techniques like ferromagnetic resonance and Brillouin light scattering have been developed [14–19]. However, still a novel experimental technique was required for probing the large wave-vector excitations. One idea was to use electrons as probe tools.

In this paper we briefly review the progress in the field of spin-polarized electron energy loss spectroscopy and its application to investigate the magnetic excitations in ultrathin magnetic films. The focus is put on Douglas Mills' impact on the development of the theory of electron scattering and its use for investigating magnetic excitations. In Section 2 the basic idea of using electrons for probing magnons is discussed. One of the main goals was to take advantage of strong electron–matter interaction to probe the magnetic excitations in an ultrathin film with the thickness of one monolayer (ML). In Section 3 the experimental results of magnon excitations in 1 ML Fe(110) pseudomorphically grown on W(110), measured at different temperatures, are presented. The influence of the temperature on the magnons' energy and lifetime is discussed.

2. Basic concepts: magnon excitations by SPEELS

Generally, when an electron is inelastically scattered from a surface, it can create elementary excitations in the system. The interaction involved in this process is of electrostatic Coulomb nature and hence it is rather strong. The process would allow probing elementary excitations

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in a monolayer (or even sub-monolayer) of a ferromagnet. The substantial developments in the field of electron energy loss spectroscopy (EELS) [20] and its combination by spin-polarized electron sources [21] made the spin-polarized version of EELS a powerful tool for the investigation of large wave-vector excitations in ferromagnetic thin films and monolayers. The main idea to follow was to use the electrons to excite and probe the magnetic excitations at a ferromagnetic surface, similar to surface phonons by EELS. In this case the use of a spin-polarized beam would help to unambiguously reveal the nature of excitations. As the total angular momentum of a magnon is $1\hbar$, for exciting a magnon one should be able to transfer $1\hbar$ angular momentum to the sample. This would mean that if an incoming electron with the spin state of $-1/2$ has impinged onto the sample surface, it should be scattered into an electron with the spin state of $+1/2$ by creating a magnon. However, there have been a few open questions at the early stage of this idea: (i) Is such a process allowed? (ii) What is the main physical mechanism behind it? (iii) What are the fundamental interactions involved during the scattering? (iv) What is the typical timescale of such a process? (v) Is this timescale shorter than the lifetime of magnons?

To answer these questions, a series of experiments were performed in the 80s [23–27]. One of the experiments which shed light on these questions was performed in 1985 in which the intensity of the scattered beam was measured for different spin configurations of the incoming and scattered beam in a so-called “complete experiment”. In that experiment, which was performed on an Fe(100) surface, a spin-polarized source was used and the spin polarization vector of the scattered beam was measured [25]. It turned out that the so-called “spin-flip” excitations, which lead to the change of the total angular momentum of the sample by $\pm 1\hbar$, can indeed take place. In addition, it was observed that the intensity of the processes in which the incoming spin state is of minority character ($-1/2$) and the scattered one of majority character ($+1/2$) is dominating the others. The theory of the inelastic scattering of spin-polarized electrons from a magnetic surface was developed by Douglas Mills and co-workers [28]. It was proposed that, in principle, electrons can efficiently contribute to the creation of magnetic excitations when they are scattered from a magnetic surface. The development of the theory of magnetic excitations in model ferromagnets was also done almost at the same time [29]. These two aspects were combined to understand the mechanisms involved in magnon excitations by spin-polarized electron energy loss spectroscopy (SPEELS) [30–33].

The first signature of large wave-vector magnon excitations in SPEELS was observed in the experiments performed in Halle [22]. The observation was explained based on the theory developed in the group of Douglas Mills. Fig. 1 shows the first experimental observation of magnetic excitations in spin-polarized energy loss spectra. A comparison to the calculated intensity spectra indicates that the observed excitation is of spin-flip nature. The experiment was performed using a primary beam with an energy of $E_i = 29$ eV and at a wave-vector transfer of $\Delta K = 0.68$ Å^{-1} ($|\Delta K| = |q|$, where, q is the wave-vector of the excited magnon). The spin-dependent excitation observed at a loss energy of about 100 meV was attributed to the magnetic excitations, in line with the theoretical calculations (see Fig. 1(b)). The total energy resolution was about 100 meV and hence it was rather difficult to resolve the magnon peak. The large drop in the asymmetry curve observed below 200 meV is caused by the tail of the quasielastic peak. The small negative value of the asymmetry in the region of quasielastic peak is due to the fact that electrons with different spin orientations experience a different scattering potential when they are quasielastically scattered from the sample surface. The nature of this asymmetry is different from the one in the loss region, where the magnon peak exists. The value and the sign of the asymmetry in the region of the quasielastic peak depend strongly on the energy of the primary beam and also the scattering angles. The sign of the spin asymmetry cased by magnon excitations in the energy loss region is always positive. This is due to the exchange process of minority electrons with majority ones which leads to the creation of magnons. It was hoped that with an improved energy resolution the effect caused by quasielastic scattering shall be suppressed, allowing a precise determination of the excitation energy. The degree of the spin polarization of the incoming beam for this experiment was about 30%. It was hoped that an improved spin resolution would substantially increase the value of the spin asymmetry.

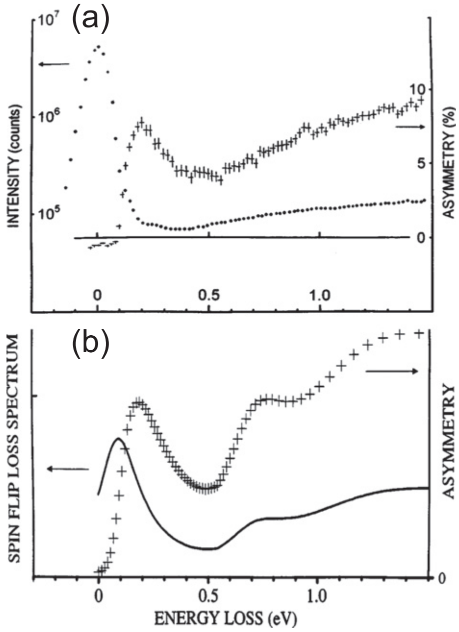

Fig. 1. The first experimental observation of magnetic excitations in spin-polarized energy loss spectra. (a) The experimental spin averaged intensity ($I_{\mathrm{Av.}} = I_\downarrow + I_\uparrow/2$) and asymmetry ($\mathrm{Asy.} = I_\downarrow - I_\uparrow/I_\downarrow + I_\uparrow$) spectra measured by SPEELS on an ultrathin Fe(110) film grown on W(110). (b) The calculated spin-flip loss and asymmetry spectra.
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This successful experiment was a strong motivation to build up a SPEELS set-up with a better energy and spin resolution [34]. The new set-up allowed the measurement of the magnon dispersion relation over the entire surface Brillouin zone for ultrathin Co(001) [35–38] and Co(0001) [39] films. The technique was successfully employed to investigate the magnetic excitations in ultrathin Fe(110) [40–45], Fe(111) [46], Fe(001) [47] and very recently in FeCo(001) films (with an out-of-plane easy axis) [48]. In addition to the magnons' energy, the lifetime of excitations could also be studied [49–51]. The technique is also capable of probing magnons and phonons, simultaneously [52]. Recently, an EELS set-up (without spin resolution) is used to investigate the magnetic excitations in Co(001) films [53–55]. The observed loss features in the spectra are attributed to the magnetic excitations. This interpretation is based on the knowledge of spin-resolved measurements obtained earlier by SPEELS [35].

3. Magnons in 1 ML Fe(110)/W(110)

One of the main goals of SPEELS experiments was to investigate the magnons in a ferromagnetic film with the thickness of 1 ML. Probing the magnon dispersion relation in a ferromagnetic monolayer would help for a better understanding of magnetism in ultrathin ferromagnetic films. The successful experiment was performed in 2009 on a pseudomorphic Fe(110) film on W(110) [41]. It is well-known that an Fe(110) monolayer grown on W(110) shows rather good structural and morphological properties and a high thermodynamic and chemical stability. Hence it can be regarded as a prototype ferromagnetic monolayer. The system is ferromagnetic at temperatures bellow 223 K [56].