Chapter 6

Conclusion and Outlook

In this work, a clear proof was given that spin waves with high energy and momentum can be studied by spin-polarized electron energy loss spectroscopy. In the SPEEL-spectra, the spin waves appear as pronounced loss features. These losses showed a strong dispersion as expected for an acoustic spin wave branch. The SPEELS-measurements allowed the investigation of the spin wave dispersion up to the surface Brillouin zone boundary. The thinnest film under investigation in these studies was only 2.5 atomic layers thick. Therefore, by SPEELS one has access to the "terra incognita" of high wave vector spin waves in thin films. Using SPEELS, we were able investigate spin waves at wave vector transfers about two orders of magnitude higher than what has been accessible by established techniques for thin film studies. Compared to inelastic neutron scattering, several orders of magnitude less magnetic material is required for a detectable spin wave signal. From the good signal to noise ratio observed in the SPEELS-measurements, the detection of high wave vector spin waves in one ML of magnetic material seems possible.

Up to now, different crystalline phases of Co and Fe have been studied by SPEELS, but in this work we concentrated on fcc and hcp Co. The two different phases have been stabilized by the substrates Cu(001) and W(110), respectively. In general, in both systems similar properties of the measured spin wave excitations were found.

High spin wave intensities were measured under certain conditions. A rough estimation of the upper limit shows that about $1\times10^4$ incoming electrons leaves the crystal after the excitation of a spin wave. The probability to excite spin waves by inelastic electron scattering was found to be strongly dependent on the primary energy of the incoming electrons. High spin wave intensities were measured only for primary energies below about 10 eV. The increased probability to scatter via the creation of a magnetic excitation at these low energies can be explained by the dependence of the exchange processes on the primary energy. The results of calculations that examine the energy dependence of exchange processes in electron scattering are, however, only in qualitative agreement to the experimentally observed behavior [135, 136]. In the experiments a drop of the measured spin wave intensity was also found with increasing wave vector transfer. This drop can be explained by the scattering process, as well. In addition, the spin wave intensity was found to be depended on the scattering geometry.
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The measured spin waves are intrinsically broad. As expected from bulk measurements [59] and from non adiabatic theoretical descriptions [20, 48, 49, 54], the spin waves seem to be strongly damped by the decay into Stoner excitations.

As discussed above, the spin wave losses showed a pronounced dispersion. For wave vector transfers up to about 0.8 Å\(^{-1}\) the spin wave energies in fcc and hcp Co-films are similar. For higher wave vectors, differences in the dispersion occur due to the different crystalline structures. As a result, the dispersions at higher wave vectors become drastically different. The measured spin wave dispersions in both systems are in good agreement with the dispersion of a surface spin wave mode derived from a nearest neighbor Heisenberg model. The product of the effective exchange coupling constant and the magnetic moment is \(JS = 15 \pm 1\) eV in the case of fcc Co and \(JS = 14.8 \pm 1\) eV in the case of hcp Co. From our measurements, we conclude that the value of JS is independent of the film thickness (in the range of 2.5-8 ML) within the given accuracy. As discussed in the following, the value is similar to the bulk value of JS, too.

A comparison between our measured spin wave energies and the results obtained by other experimental techniques is possible within the nearest neighbor Heisenberg model. Presuming that the spin wave losses in the SPEEL-spectra are dominated by surface spin waves, in general a good agreement to literature values was found [59, 128, 139]. The deviations are surprisingly small considering the differences in the experiments and the different spin wave regimes probed.

All these agreements were only found assuming that the spin wave losses in the SPEEL-spectra are dominated by surface spin waves. Also the thickness dependence of the spin wave energies found for fcc Co can be explained in this context. We have introduced a phenomenological model based on simple considerations of the excitation process by including a wave vector dependent excitation probability and the surface localization of each mode. This model showed that one expects a dominating contribution of the surface modes in the SPEEL-spectra. More elaborate calculations provide similar conclusions [54].

Theoretical calculations of the spin wave dispersion typically overestimate the spin wave energies compared to our measured data. This is especially the case in calculations performed for thin film systems. Here, the theory predicts an enhancement of the exchange coupling at surfaces. In our experiments, however, we found no sign of such an enhancement. The agreement to ab initio calculations for bulk samples is fairly good considering that no adjustable parameters are included in these calculations. These models rely on the adiabatic approximation and therefore cannot describe the measured broadening of the spin wave peaks. In a recent calculation using a dynamical theory that goes beyond the adiabatic approximation, Mills and coworkers studied the spectral density of spin excitations in thin Co-films. The calculations are in good qualitative agreement to the measured data. The theoretical description is, however, based on an empirical tight binding model and it has been shown that the calculated dispersion varies drastically for small changes of the parameters [54]. Full ab initio calculations for thin Co-films that go beyond the adiabatic approximation are desirable.

From the experimental results presented in this work, several future studies seem possible. Other magnetic materials have spin wave energies that are high enough to be
studied by SPEELS, provided that the spin wave intensities are similar to Co. To make use of the spin selective excitation, one only needs a defined magnetization direction at the surface. Therefore, SPEELS-studies of spin waves can possibly be performed even on uncompensated surfaces of antiferromagnets. The study of spin waves by a "complete" SPEELS experiment, using a spin-polarized source and a spin detector, seems possible as well, because of the high spin wave intensities found. Since the feasibility to study spin waves by inelastic electron scattering is now proven, the investigation of spin waves using a "standard" EELS should be straightforward. The higher energy resolution possible in these experiments, may allow measurements of spin waves at lower energies.

In addition, we found that the excitation probability of some vibrational losses are spin depended. In most cases, the dependence is weak, however, for certain geometries it can be of the order of 10% (and possibly stronger). A systematic study of these phenomena may lead to a better understanding of both, the electronic structure of the adsorbates and the excitation process involved.

We hope that the presented work will stimulate further experimental and theoretical efforts in the field of spin waves with high energy and high momentum.