Summary and Perspectives

Within the framework of this thesis, the effects of spatial limitations and surfaces on the magnetic properties of AFM materials were studied by means of resonant magnetic soft x-ray scattering. This technique has become a powerful method to study complex ordering phenomena in thin films, but also in single crystals. In particular, it is the method of choice for studying magnetic structures of thin and ultra-thin samples and provides pronounced magnetic scattering signals even from single atomic layers close to the ordering temperature. Therefore, resonant magnetic soft x-ray scattering is one of the key techniques applied to nano-structured magnetic systems and interfaces, which are of high technological relevance in the fields of magnetic recording and spintronics.

For the demanding experiments in the soft x-ray regime, a novel scattering apparatus was developed and built. Equipped with a two-stage rotary feedthrough as a diffractometer, this apparatus is characterized by excellent vacuum conditions and a high flexibility concerning the application of complex detector designs as demonstrated in this work by a novel position sensitive detector. By virtue of the excellent performance of this diffractometer, the magnetic properties of in-situ prepared AFM holmium films and ultra-thin samples of the AFM semiconductor EuTe could be studied, with partly unprecedented data quality down to temperatures as low as 5 K.

Exploiting these advantages, it was possible to observe pronounced magnetic diffraction features, even from thin polycrystalline holmium films. Interestingly, such polycrystalline films exhibit a substantially reduced ordering temperature. While single-crystalline Ho films are already characterized by an unusually fast decrease of the ordering temperature as a consequence of a spatial limitation along the direction of the long-period AFM modulation, the present experiments on Ho films, characterized by a strong lateral confinement, revealed the thickness dependence of the ordering temperature known for simple ferromagnets. This result suggests that the modified decrease of the ordering temperature in single-crystalline Ho films is caused by limitations along the direction of the AFM modulation. Hence, in long-period antiferromagnets the thickness dependence of T_N is an anisotropic property.

While the work on Ho films demonstrated already the potential of resonant magnetic soft x-ray scattering, the following study on EuTe underlined this even stronger. By exploiting the additional gain of magnetic contrast due to magnetic Bragg reflections occuring at the Brewster angle at the Eu-M_5 resonance, magnetic Laue patterns could be measured with unprecedented quality. These data allowed a complete reconstruction of the temperature-dependent magnetization profiles normal to the surface of a 20-ML EuTe film. The derived magnetization profiles are in good qualitative and quantitative agreement with earlier theoretical predictions of Binder and Hohenberg.

The large magnetic contrast allowed to obtain pronounced magnetic signals even well above the ordering temperature. These signals, caused by the persisting short-range magnetic correlations, allowed to study the critical behavior of the EuTe samples, i.e. the decay of the critical fluctuations above T_N, from macroscopic distances down to the distance between neighboring Eu ions. Therefore, the complete temperature-dependent evolution of the critical fluctuations could be examined in samples as thin as 3 ML, which revealed a distinctly different decay of the critical fluctuation in 3 ML

compared to the behavior of all thicker films. This altered decay of the critical fluctuations with increasing temperature can be attributed to a dimensional crossover between 3 ML and 4 ML of EuTe. The characteristics of this altered temperature dependence are in good agreement with results of an earlier study on thin Ho films, where an analogous behavior was observed between 16 ML and 11 ML. These observations suggest a relation between the crossover thickness and the AFM period length.

In summary, all present studies observed deviations in the thickness-dependent modifications of magnetic behavior of antiferromagnets from the well-known changes in ferromagnets. These deviations depend on the direction and length of the antiferromagnetic modulation and have to be taken into account in future applications of comparable materials in nanoscale devices.

These results highlight the potential of the applied method. Technical improvements are on the way, e.g. more sensitive detectors that can be easily implemented in the present setup as well as improved cryostats. It will allow a more precise study of the critical properties of EuTe, which might include the quantification of several critical exponents and thus to test the validity of the surface scaling relations for magnetic phase transitions in thin films. In the critical regime, the spins are not only spatially correlated but also in time, with both phenomena being connected. A study of temporal correlations makes use of coherent x rays, which allows recording speckle patterns. From speckle patterns, the characteristic behavior in the time domain can be examined and compared with the spatial behavior. This will be particularly interesting for the 3-ML EuTe sample. Very recently, such experiments have been performed with the presented setup on thin Ho samples and the preliminary results demonstrate the feasibility of such studies. We recently also achieved temperatures well below 5 K with our setup, which opens the field for challenging experiments on several interesting materials like the metamagnet EuSe or the magnetic superconductors [Re]Ni_2B_2C, containing $3d$-metals and rare-earth (Re) elements.

Resonant soft x-ray scattering is not exclusively sensitive to magnetism, but also to other ordering phenomena like charge or orbital ordering as observed in the $3d$-transition-metal oxides. Materials exhibiting such ordering phenomena should show size and surface effects, which are comparable to the findings in this work. Despite the fact that the detailed results in this study benefitted from the special advantage of a magnetic Bragg peak occuring at the Brewster angle, such experiments are not restricted to EuTe. Application of suitable polarization analyzers, probably in combination with more sensitive detectors, will allow to extend the experiments performed to a large class of interesting materials in future studies.