Experimental report

15/09/2016

Proposal: **5-54-216** **Council:** 4/2016

Title: Exchange Spring Evolution Throughout a Spin Reorientation Transition in Fe/NdCo5

Research area: Physics

This proposal is a new proposal

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Samples: Cr/NdCo5/Cr/MgO
Cr/Fe/NdCo5/Cr/MgO

Instrument	Requested days	Allocated days	From	To
D17	6	5	27/06/2016	02/07/2016

Abstract:

We propose to investigate the evolution of the exchange spring in Fe/NdCo5 with temperature using polarized neutron reflectometry (PNR). The hard magnetic NdCo5 undergoes a spin reorientation transition (SRT) near room temperature, which manifests as a change of the in-plane magnetic easy axis from c-axis to a-axis. The structural and magnetic sensitivity of PNR will be used to obtain the in-plane magnetization vectors as a function of depth with an exchange spring nucleated in the soft magnetic Fe. By studying the temperature dependence of the exchange spring throughout the SRT, we aim to conclude on the exchange coupling strength across the interface and determine the mutual influence of Fe and NdCo5 on each other. Such interfacial exchange coupling phenomena are of fundamental interest in magnetic hybrid structures.
The understanding how the SRT in NdCo5 transfers to Fe and how NdCo5 is in turn modified by Fe are prerequisites for advanced material design concepts with new functionalities. The additional degree of freedom provided by the possibility to switch the easy axis without changing external fields offers a range of applications in magnetic sensor and recording media.

Exchange Spring Evolution Throughout a Spin Reorientation Transition

Polarized Neutron Reflectometry Beam Time on D17, June-July 2016, EXP: 5-54-216

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Motivation:

Exchange spring (ES) magnets consisting of exchange-coupled high magnetization and high anisotropy materials have a range of powerful applications as strong permanent magnets or high-density recording media. High-anisotropy rare-earth alloys combined with soft magnetic transition metal materials, e.g. Fe, form a prime example of such a system, in which the hard-magnetic properties are transferred to the high-magnetization Fe layer. Within the scope of tuning the magnetic properties and exploiting advanced functionalities, the rare-earth alloy $NdCo_5$ offers additional degrees of freedom due to a spin-reorientation transition (SRT) (Figure 1).

The SRT leads to a rotation of the magnetic easy axis from the basal plane to the crystal c-axis via a transition temperature range $T_{SRT1} < T < T_{SRT2}$. The temperature range of the transition is near room temperature, which makes it feasible for applications in logic circuit, sensor and magnetic storage technologies.

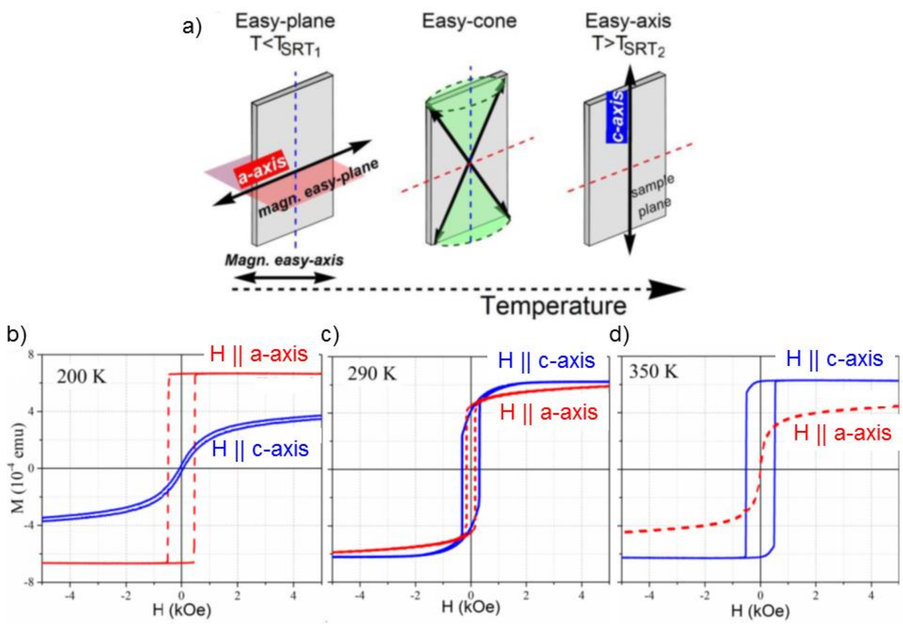

Figure 1: a) Sketch of the magnetic easy direction as a function of temperature. b) – c) Magnetic hysteresis measurements of epitaxial Fe/$NdCo_5$ bilayers at three selected temperatures.

In combination with Fe, the SRT offers the possibility to generate or annihilate the ES in Fe by changing the easy axis of $NdCo_5$. Unlike in uniaxial ES systems, a change in temperature will reversibly wind or unwind the ES without external field changes. The interfacial exchange-coupling is the decisive factor in these materials as it determines the overall anisotropy of the hybrid structure.

Using specular polarized neutron reflectometry (PNR) we aim at the investigation of the magnetic depth profile, i.e. magnetization directions and characteristics of the ES, as a function of temperature and external magnetic field. Of special interest is the magnetic profile across the interfacial region in comparison to the structural sharpness. From this we will derive the coupling energies throughout the SRT and the extension of the ES beyond the interface, which in the transition region is likely influenced by disorder.

Experimental details:

A $NdCo_5$(40nm)/Fe(20nm) bilayer sample grown on Cr buffered MgO single crystal and capped with Cr was measured in different orientations and temperatures. Unfortunately, the sample had been cut several times before the beamtime for angle resolved MOKE measurements and further complimentary magnetometry and only 5×6 mm^2 remained for the experiment. In addition, the sample was grown on very thin MgO (160μm) to facilitate the magnetic characterization with volume averaging techniques. This led to a substantial bending of the sample and therefore strongly diffuse reflectivities. We nevertheless conducted the experiment to establish feasibility and procedures for future experiments. The sample was heated in the cryomagnet to 320 K and saturated in 0.2 T along the magnetically easy c-axis. This reference measurement represents the collinear state of all magnetizations. Subsequently, the sample was rotated by 90° without removal from the cryomagnet, such that the field is now applied along the magnetically hard a-axis. This measurement shows the winding of the ES in the high-temperature state. Subsequent to the measurement in this configuration, the sample is cooled to 200 K, where the a-axis becomes magnetically easy and the ES unwinds. This represents the reference measurement for the 200 K configuration along the a-axis. An additional turning back to the initial configuration again leads to a winding of the ES, this time in direction of the magnetically hard c-axis.

Results:

Figure 3 shows two measurements at 320 K with the field applied along the crystallographic c- and a-axis. A clear increase of spin-flip signal is observed beyond the critical edge in the a-axis configuration. The spin-flip observed in the c-axis measurement is a result of the not 100% spin polarization of the instrument, but a precise polarization-efficiency correction has become impossible due to the diffuse nature of the reflected neutron beam from a curved sample surface. In addition to the enhanced spin-flip, we observe changes in the non-spin flip channels, which further indicate the magnetic reconfiguration.

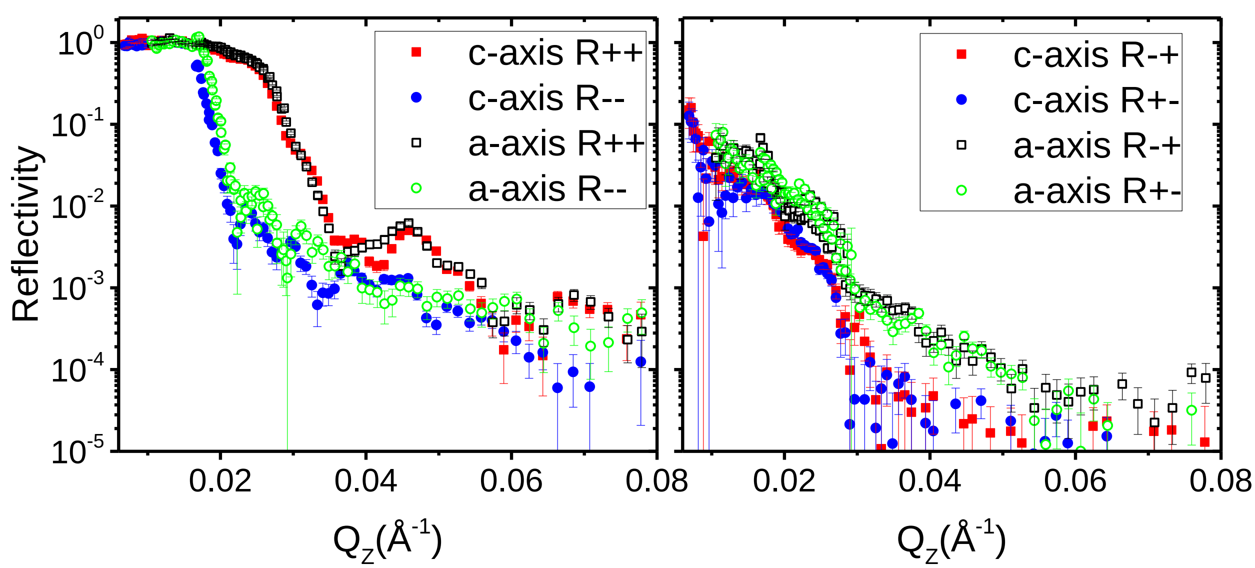

***Figure 2:** Non-spin flip (left panel) and spin-flip (right panel) specular reflectivities obtained along the c- and a-axis at 320 K. The changes in the reflectivity indicate the magnetic reconfiguration due to a winding of the magnetic directions in depth through the Fe and $NdCo_5$ film.*

In order to shorten the acquisition time and enable a more reliable data reduction, we restricted most acquisitions to specular reflectivity without spin analysis. In these measurements, the exact amount of spin-flip processes in the layers over a reduction of magnetization remains somewhat ambiguous, but changes in the magnetic configuration become obvious nevertheless.

Figure 2 (left panel) shows measurements with field along the crystallographic c-axis obtained at 320 K and 200 K, i.e. above and below the SRT in an applied field of 200 mT. The field is high enough to saturate the $NdCo_5$ along the easy axis at 320 K, but not at 200 K, where the a-axis is magnetically favored. The Fe layer is able to reorient in the external field, only constrained by the exchange coupling at the interface to $NdCo_5$. A clear change in reflectivity is observed in the spin-down channel, indicating the magnetic reconfiguration.

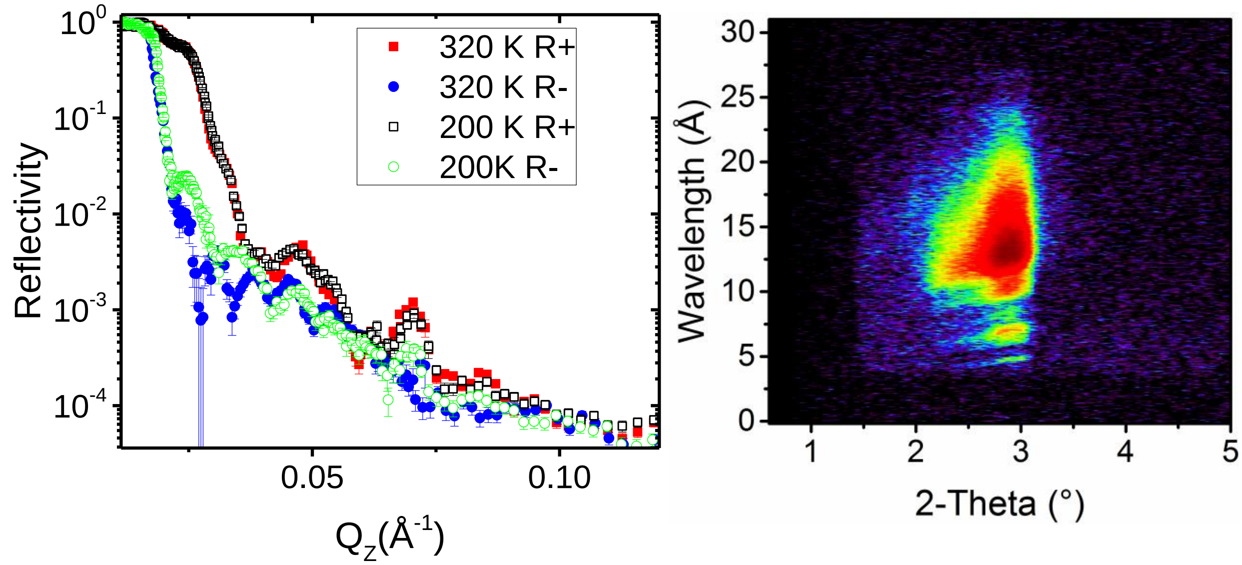

***Figure 2:** Left panel: Specular reflectivity of the $NdCo_5$ bilayer in a 200 mT applied field along the c-axis at 320 K and 200 K. Right Panel: Raw detector image of the diffuse intensity reflected from the sample at 1.5° angle of incidence.*

The analysis of the data is ongoing and first promising fits have been obtained despite the complications of small sample size and curved reflecting surface. Figure 2 (right panel) shows a raw detector image of the reflected intensity. The diffuse smearing of the data is clearly observed. Although we developed a procedure to deal with sample curvatures, which significantly improved the data and made an analysis possible at all, the precise comparison of different spin states remains impaired. Additionally, the spin-analysis becomes unreliable since the analyzer only accepts a very narrow range of angles of incidence.

The features observed in the measurements without spin-analysis agree with a full 90° rotation of the magnetization in $NdCo_5$ upon cooling of the sample, while only a part of the Fe follows. An important conclusion of the spin-analysis measurements is that the film does not appear to break into domains, which would complicate a determination of the ES due to lateral averaging. The measurement further indicates that a significant part of the Fe layer follows the external field and therefore the ES is successfully established. However the fits are not reliable and a determination of the extension of the ES or the nature of the magnetic interface will not be unambiguously determined from these measurements.

Based on these promising results we have started to fabricate a larger sample on thicker substrate just for polarized neutron reflectometry measurements. We are confident that the PNR technique will provide the desired information on the magnetic configuration with temperature in a future beamtime.