

Simultaneous polarization analysis of Zeeman splitting in polarized neutron reflectometry using a polarized ^3He neutron-spin filter

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Abstract. A polarized ^3He neutron-spin filter was used to analyze polarized neutrons reflected from a 1000-Å-thick Fe film immersed in a magnetic field. The spin filter analyzed both the specularly reflected component and the off-specular component caused by the phenomenon of Zeeman splitting of surface-scattered neutrons observed by Felcher et al. and investigated in more detail in subsequent experiments. The sample of polarized ^3He was polarized by metastability-exchange optical pumping and compressed into a glass cell at the Indiana University Cyclotron Facility. The polarized gas was transported by car in a battery-powered solenoid holding field to the neutron reflectometry instrument POSY I at the Intense Pulsed Neutron Source at Argonne National Laboratory. Using the large solid angle of the polarized ^3He spin filter, we were able to simultaneously analyze both components to the scattering and verify (as expected) that the polarization of the specular component was unchanged upon reflection and that the polarization of the off-specular component was reversed. To our knowledge this work represents the second experiment to employ a polarized ^3He neutron-spin filter in polarized neutron reflectometry.

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Polarized neutron reflectometry is an experimental technique that can be used to obtain information on surface and sub-surface magnetization of various types of thin-film magnetic materials [1, 2]. Recently, a number of measurements using this technique have shown evidence for an interesting neutron spin-flip process. The magnetic interaction between polarized neutrons incident at glancing angles on a magnetic substrate, which possesses local fields that are not aligned with the external magnetic guide field, leads to adiabatic spin-flip scattering events. No energy is exchanged between the neutron and the sample, and therefore the change in potential energy of the neutron in the external field is com-

pensated by a change in the kinetic energy of the neutron. This changes the exit angle of the neutron relative to the surface. In this case the coherent scattering from the target possesses two components. One component, which corresponds to events in which the neutron spin is unchanged, possesses the usual relation between the angles of incidence and reflection: $\theta_i = \theta_r$. The other component, corresponding to the adiabatic spin-flip events, reflects at an angle that is different from the angle of incidence. This effect was observed by Felcher et al. [3], who referred to the effect as Zeeman splitting of surface-scattered neutrons, and this and related effects were investigated in more detail in later experiments [4–7, 9].

These later experiments showed explicitly by neutron-polarization analysis that the specular ($\theta_i = \theta_r$) and off-specular ($\theta_i \neq \theta_r$) scattered beams corresponded to non-spin-flip and spin-flip scattering, respectively. In the experiments described in Fredrikze et al. [7], a stack of slightly bent supermirrors was used to simultaneously analyze the entire reflected neutron beam. However, since this mirror is bent, there is concern that the image might be distorted after reflection. In another experiment, Krist et al. [5] successfully scanned a standard supermirror in transmission mode. One can imagine future experiments which exploit the phenomenon of Zeeman splitting in neutron reflectometry, in which it would be valuable to have the capability to simultaneously analyze the polarization of both reflected components in addition to the diffuse scattering without distorting the beam [8]. This would be possible using a polarized ^3He -based neutron-polarization analyzer as opposed to a reflection-based analyzer.

In the remainder of this paper we describe the use of a polarized ^3He neutron-polarization analyzer to simultaneously analyze the polarization of both components of the reflected beam generated by the Zeeman-splitting phenomenon. As expected, our results are in agreement with previous work and the physical mechanism proposed by Felcher et al. in their original paper. This experiment represents one of the first uses of a polarized ^3He analyzer in neutron reflectometry (for an application in diffuse reflectometry see [10]).

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1 Neutron-polarization analyzer based on polarized ^3He

Polarized ^3He is a transmission neutron spin polarizer and analyzer. It exploits the three orders of magnitude difference in the total cross section of neutron spins parallel and antiparallel to the polarized ^3He at thermal neutron energies. The solid angle that can be subtended is larger than typical reflection-based analyzers in this neutron-energy range. These attributes make ^3He useful for neutron-polarization analysis of a divergent neutron beam.

The transmission of neutrons with spin parallel (antiparallel), $T_{+(-)}$, to the polarized ^3He is given by

$$T_{\pm} = T_e e^{-nl\sigma(1\mp P)}, \quad (1)$$

with T_e the neutron transmission through the analyzer cell devoid of ^3He , n and l the number density and the length of the ^3He , σ the average cross section for spin-up and spin-down neutrons, and P the polarization of the ^3He . The analyzing power and flipping ratio of the spin analyzer are then

$$A = \frac{T_+ - T_-}{T_+ + T_-}, \quad (2)$$

$$F = \frac{T_+}{T_-}. \quad (3)$$

One can measure the polarization of the ^3He while installed on the beam line by taking the natural logarithm of the ratio of T_+ to T_- . Since in practice the polarization of the ^3He decreases slowly during a measurement due to spin relaxation from magnetic field gradients and collisions with the cell walls, it is necessary to use the average polarization during the length of a particular run to analyze the data.

2 Experiment

The sample of polarized ^3He was produced at the Indiana University Cyclotron Facility (IUCF) using a mixture of $^3\text{He} : ^4\text{He}$ (1 : 3) by metastability-exchange optical pumping, followed by a two-stage compression sequence to achieve a final pressure in the spin-analyzing cell of 1.45 bar and a polarization of 25%. The analyzing cell, which was a Corning 1720 cylinder with 3-mm-thick GE180 windows, was 10-cm long with a radius of 3 cm, which yields a ^3He thickness, $nl = 8.71 \times 10^{23} \text{ m}^{-2}$. After filling, the cell was placed in a solenoidal holding field powered by a battery and then driven 402 km by car in a 4-h trip from Bloomington, Indiana to the Intense Pulsed Neutron Source (IPNS) at Argonne National Laboratory near Chicago, Illinois.

As mentioned in Sect. 1, we could determine the parameters of the spin analyzer by measuring the neutron transmission through the polarized ^3He for both states of the neutron-spin flipper. From the relative transmissions of the spin states, the measured spin-relaxation rate was $\Gamma = 13 \pm 3 \text{ h}$, and the time-averaged polarization during the spin-analyzed run was $P = 0.15 \pm 0.02$. This gives average transmissions $T_+ = 0.151 \pm 0.006$ and $T_- = 0.086 \pm 0.006$, analyzing power $A = 0.274$, and flipping ratio $F = 1.76 \pm 0.01$ over the wavelength range 7–8 Å during the spin-analyzed run discussed below. There is a discrepancy in the relaxation time measured via neutron transmission and what was measured on

the compression system at Indiana (30 h). This was probably due to unexpected magnetic field gradients along the POSY beam path, and we are currently constructing a magnetic shield for the holding field to overcome the problem in future measurements.

This measurement was performed on the POSY I polarized neutron reflectometer at the Intense Pulsed Neutron Source at Argonne National Laboratory. The sample, a 1000-Å-thick Fe thin film, was placed on POSY I in a magnetic field oriented normal to the surface at a value below saturation, as in the original experiments, so that the film possessed components of the magnetization at right angles to the external field. The neutron beam was incident to the thin film at an angle of $\theta_i = 0.5^\circ$ to the thin film's surface, and the direction of the beam's polarization was flipped with each neutron pulse. In the presence of the Zeeman phenomenon, this leads to four possible reflected beam intensities, two for each incident spin state, labeled R_{++} , R_{+-} , R_{--} , R_{-+} , where the first (second) index is the initial (final) neutron-spin state. However, since there was no spin flipper after the Fe thin film, we expect R_{+-} to be more difficult to measure than R_{-+} as $T_- < T_+$. This was in fact the case, and so we present only the data for spin down initially.

We made two measurements with the reflecting thin film in place: one with and one without the spin analyzer installed on the neutron beam. This is necessary since we need to know the non-analyzed intensities in order to determine the

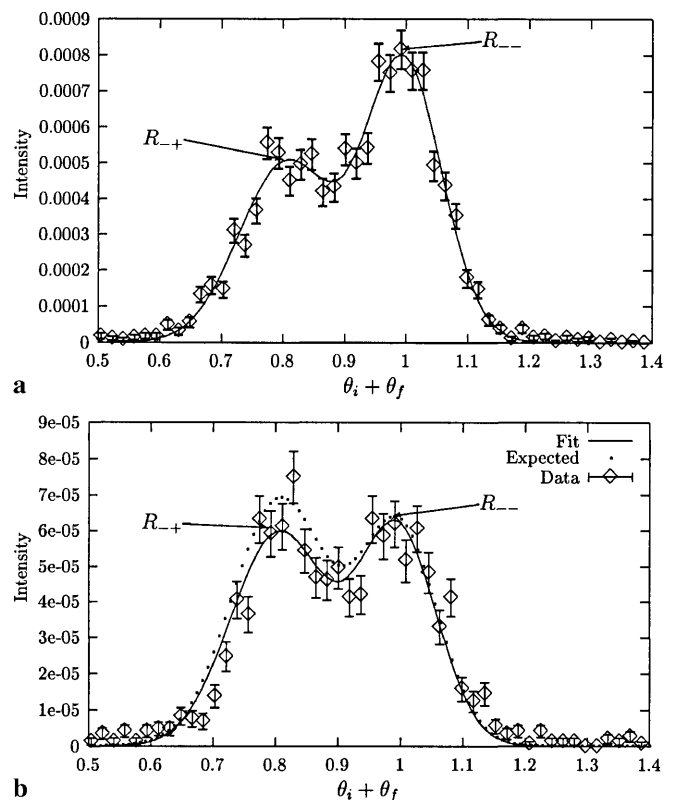


Fig. 1a,b. Normalized neutron intensity versus $\theta_i + \theta_f$ for initially spin-down neutrons in the wavelength range 7–8 Å. **a** With no spin analyzer installed. The *solid line* is a best fit of a sum of two Gaussians. **b** With the spin analyzer in place. The *solid line* is a fit to the data using the centers and shapes determined from the fit in Fig. 1 and allowing the intensities to vary. The *dotted line* corresponds to what would be expected based solely on the transmission through the analyzing cell

polarization of the two reflected peaks. Assuming that the non-specularly reflected beam undergoes a spin flip, then

$$F = \frac{R}{R'}, \quad (4)$$

where R is the ratio of the specular to the non-specular intensities, and the prime indicates the spin-analyzed case. We focused our attention on the wavelength range 7–8 Å, as the two separate peaks were clearly separable in this energy range and there was sufficient neutron-counting statistics.

Shown in Fig. 1a is the non-spin-analyzed angular spectrum. We assumed that the reflected neutron beam intensity was Gaussian-distributed in space and that the transmission through the analyzer maintains this feature. The solid curve in Fig. 1a is a best fit to the data using a sum of two Gaussian distributions. We then calculated the predicted intensity distribution using the measured flipping ratio and the measured neutron attenuation of the GE180 windows [12]. As one can see from Fig. 1b, this model of the operation of the polarization analyzer is consistent with the data. This result is consistent with the expected spin states of the two components according to the Zeeman phenomenon. If we instead infer the flipping ratio from the data themselves, we obtain $R/R' = 1.53 \pm 0.13$. Given the simplicity of the model (particularly the treatment of the scattering in the windows), this agrees well with the flipping ratio that was measured ($F = 1.76 \pm 0.01$).

3 Conclusions

We have successfully used a polarized ^3He neutron-polarization analyzer to determine the polarization of the two reflected beams from a magnetic thin film under conditions corresponding to the Zeeman-splitting phenomenon noted by Felcher et al. Our results are in complete agreement with the

interpretation of this phenomenon in terms of spin-flip scattering without energy transfer to the sample. Although the ^3He polarization used in this measurement was quite small, it nevertheless sufficed to perform the measurement successfully. In addition, we have successfully transported the polarized ^3He analyzer cell over long distances to the IPNS neutron scattering facility without significant losses in polarization. Further exploitation of neutron-polarization analyzers based on polarized ^3He in polarized neutron reflectometry requires larger ^3He polarization. This is achievable and work is in progress.

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