Towards a Tomographic Reconstruction of Neutron Depolarization Data

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Abstract. In this paper we show a first approach to the three dimensional reconstruction of spatially resolved neutron depolarization data. We will show measurements with a position sensitive CCD detector on a longitudinal polarization analysis setup using ³He polarizers and analyzers installed at the radiography beamline ANTARES at FRM II, Munich. A tomographic reconstruction of data acquired with an inhomogeneous Pd₁₋ₓNiₓ sample shows that this method is a powerful tool to identify regions of different magnetic properties inside the sample.

1. Introduction
The combination of neutron imaging with polarization analysis is a new and powerful method which has proven to be useful in the investigation of magnetic field distributions in complex solenoids [1]. It may additionally be used for visualisation of effects like flux-pinning in superconductors [1], variations of the magnetisation in thin magnetic films [2] or even visualisation of domain walls for samples with very large domains [3]. Another very promising field of application is the investigation of inhomogeneous ferromagnets [4]. In particular, the depolarization of the neutron beam may be used to map out variations of ferromagnetic properties as a function of external parameters such as stress, pressure, applied magnetic and electric field or temperature as well as internal characteristics such as chemical composition, defects and strain.

The possibility of reconstructing the orientation of magnetic domains from tomographic measurements has been extensively discussed (see [5] and references therein). However this is only possible for the subsequent transmission of very few domains. A further prerequisite for this technique is a spatial resolution, which must be better than the domain size. Since typical domain sizes are of the order of a few µm this method can currently not be used on standard neutron radiography setups.

In this paper we will present a 3D reconstruction of neutron depolarization data, which yields a volume model of the sample and its magnetic properties on a macroscopic scale. Depolarization tomography is based on the spatially resolved measurement of the polarisation of a neutron beam.
after transmission of a sample under different projection angles. The data are then reconstructed using a standard filtered backprojection algorithm.

2. Experiments

The setup used for the experiments described in this paper is shown in Fig. 1. It was installed at the radiography beam line ANTARES at FRM II and consists of a $^3$He polarizer and analyzer, a precession coil spin flipper, a closed-cycle cryostat with a base temperature of $3.5$ K, which holds the sample and a position sensitive CCD detector that records the image on a LiF/ZnS scintillator with a thickness of $200 \mu$m. The sample was mounted in a container filled with He exchange gas reducing the temperature gradient to less than $0.1$ K along the sample. A monochromatic neutron beam of $3.2$ Å was obtained with a double crystal monochromator [6]. To minimize the effect of stray fields around the sample, a pair of Helmholtz coils was placed around the cryostat, which produced a field of $80$ G parallel to the guide field. For the tomography, the cryostat was mounted on a rotary stage with its axis of rotation parallel to the magnetic field at the sample position.

![Figure 1. Schematic drawing of the setup used for the experiments described in this paper. The $^3$He polarizer and analyzer are indicated with the magnetostatic cavities surrounding them. The sample was mounted in a closed-cycle cryostat around which a pair of Helmholtz coils was mounted. The detector is a position sensitive CCD with $2048 \times 2048$ pixels.](image)

In order to increase the relaxation time of the polarised $^3$He, it has to be kept in a very homogeneous magnetic field [7] with field gradients less than $10^{-4}$. Thus, a bulky magnetostatic cavity containing the $^3$He cell had to be placed between sample and detector and consequently limited the minimum sample to detector distance to $d_{SD} \approx 300$ mm, resulting in a spatial resolution of $0.75$ mm. The initial polarisation of the $^3$He gas was about $70\%$ yielding a beam polarisation of $\approx 80\%$ with a relaxation time of the order of $150$ h.

The sample we investigated was a Pd$_{1-x}$Ni$_x$ polycrystal, which was grown with the Czochalski technique and has a nominal Ni concentration of $x = 2.67\%$. The sample has a cylindrical shape with a diameter of $11$ mm and a length of $26$ mm. Pd$_{1-x}$Ni$_x$ is a weak itinerant ferromagnet with a strong dependence of the Curie-temperature $T_C$ on the Ni concentration $x$ [8].

First, a radiographic temperature scan of the neutron depolarisation was made in a temperature range from $5$ K to $40$ K to find an appropriate temperature at which to record the tomography. Here, one has to avoid the condition of total depolarization of the beam after transmission of the sample, which is equivalent to non-penetration in absorption radiography leading to artifacts in the reconstruction. This can be done by setting a sufficiently high sample temperature, where the ordered moment $M_s$ and consequently the depolarisation is lower. The Curie temperatures found for this sample range from below $5$ K to $26$ K. Based on the results of this measurement, a tomography of the sample was recorded at a temperature of $8$ K. During
the experiment, the sample was rotated over 180° with angular steps of 1°. At each angular position 5 spin-up and spin-down images were recorded with an exposure time of 60 s each and later summed up to obtain better neutron counting statistics. The total measurement time for the tomography was approx. 30 h.

3. Results and Discussion

With a spin flipper the beam polarisation after transmission of the sample can be determined as 

\[ P = \frac{1}{(pp_0)} \frac{(I_\uparrow - I_\downarrow)}{(I_\uparrow + I_\downarrow)} \]

and the absorption is calculated as 

\[ A = \frac{(I_\uparrow + I_\downarrow)}{I_0} \]

where \( I_\uparrow \) and \( I_\downarrow \) are the spin-up and spin-down intensities, respectively and \( I_0 \) is the sum of these intensities measured without the sample in place. The term \( pp_0 \) is the product of the polarising and analysing efficiency, which can be measured outside of the sample region during the experiment and thus allows to correct for the relaxation of the \(^3\text{He} \) polarisation with time. In the case of a random orientation of the magnetic domains, the beam polarisation after transmission of the sample follows an exponential decay [9] 

\[ P = P_0 e^{-\rho d} \]

with the sample thickness \( d \). Here \( \rho = \frac{1}{3} \frac{\gamma \delta B^2}{v^2} \) can be interpreted as a neutron depolarisation density, where \( \gamma \) is the neutron’s gyromagnetic ratio, \( \delta \) is the average domain size, \( B \) is the average magnetic field inside a domain and \( v \) is the neutron velocity. This law resembles the exponential attenuation law and the neutron depolarisation density can therefore be reconstructed with exactly the same filtered back projection algorithm [10]. Only the magnetic field and the domain size are variable in this expression and consequently \( \rho \), which can also be interpreted as a spin-flip probability, contains information about the product of the domain size and the magnetisation of the domains. Further details on the reconstruction procedure will be discussed elsewhere [11].

![Figure 2](image_url)

**Figure 2.** 3D Reconstruction of the ND data. a) View of the crystal; b) through f) Paramagnetic regions of the sample are shown in light grey. Ferromagnetic regions are displayed in blue. Several cuts through the sample are shown from c) to f).

Both the polarisation and the absorption data were reconstructed separately and then visualised with the volume rendering software VGStudio Max [12] as shown in Fig. 2. Here, the paramagnetic regions of the sample are displayed in grey, whereas the ferromagnetic regions are shown in blue. In order to reduce the noise in the reconstruction, the 3D data were median filtered. Fig. a) shows an outside view of the absorption data of the crystal as an overview. At the bottom of the sample the glue which was used to fix the sample on the sample holder is visible. Furthermore at the top of the sample one can clearly see an edge which was cut off the crystal for bulk measurements. For images b) through f) the paramagnetic regions of the sample were rendered more transparently to visualize the ferromagnetic parts inside the sample. Furthermore images c) through f) show horizontal cuts through the absorption data for better visibility of the depolarisation data. For all images the orientation of the 3D object was the same.
One can readily see that the sample is extremely inhomogeneous and has vast paramagnetic regions. Furthermore the ferromagnetic parts of the sample tend to arrange in horizontal layers, which are however, also not perfectly homogeneous. This might be due to the crystal growth process, which was perpendicular to these planes. A change in the growth parameters (i.e. the growth velocity) could be responsible for variations in the Ni concentration and consequently in the magnetic properties of the sample. The more detailed quantitative analysis of the distribution of the amplitude of the magnetisation in the sample will be discussed elsewhere.

4. Conclusion and Outlook

The experiment described in this paper shows that in addition to the results obtained in neutron depolarization radiography one can obtain 3D information on the distribution of magnetic properties of a sample by using a tomographic method. This could help to improve the understanding of substances showing a strong dependence of the Curie temperature on the composition or phase separation. Furthermore this method allows to locate regions of desired magnetic properties from a 3D model and later cut these out of the sample for further investigation with bulk or neutron scattering measurement methods.

Several other substances such as Ni$_3$Al and Heusler alloys have already been studied with this method and it turns out that many samples, which were thought to be of very high quality show drastic variations of their magnetic properties on a macroscopic scale. [11] This observation becomes especially important if neutron scattering studies are performed on such samples, since these use an large beam which performs an implicit average over the sample volume.

We are currently as well studying the influence of different crystal growth conditions on the resulting crystal quality and will try to identify the ideal parameters for high quality crystals using radiography and tomography with polarized neutrons.

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