

Experimental report

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Proposal: DIR-272

Council: 10/2022

Title: Novel angular anisotropy in polarized SANS

Research area: Physics

This proposal is a new proposal

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Samples: (Fe_{0.7}Ni_{0.3})₈₆B₁₄

Instrument	Requested days	Allocated days	From	To
D33	4	4	19/05/2023	23/05/2023

Abstract:

The aim of this proposal is to experimentally observe a hitherto unseen angular anisotropy in the polarized SANS cross section of a magnetically strongly inhomogeneous material. Based on a theoretical prediction, the difference between the spin-up and spin-down SANS cross sections is expected to show a clover-leaf-type angular anisotropy with maxima roughly along the diagonals of the detector. The effect is particularly pronounced in inhomogeneous magnetic materials such as nanoporous ferromagnets or nanocomposites, which exhibit large nanoscale jumps in the saturation magnetization at internal particle-matrix interfaces. We aim to carry out the experiment on the two-phase nanocrystalline soft magnetic alloy Nanoperm, a material that finds widespread application as magnetic core in high-frequency power transformers. The present proposal addresses a fundamental question related to the angular anisotropy of the polarized SANS cross section.

Experimental report

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Motivation

Polarized SANS is one of the most important methods for microstructure determination in magnetism and magnetic materials research [1]. This is because it provides access to the volume of materials and to the relevant mesoscopic length scale (roughly 1-300 nm). The present experiment addresses a fundamental question related to the angular anisotropy of the polarized SANS cross section. When the externally applied magnetic field \mathbf{H} is perpendicular to the incoming neutron beam ($\mathbf{H} \perp \mathbf{k}$), the *difference* $\Delta\Sigma$ between the two half-polarized [spin-up (–) and spin-down (+)] SANS cross sections (also sometimes denoted as SANSPOL) contains three terms, and can be expressed as [1]:

$$\Delta\Sigma = \frac{d\Sigma^-}{d\Omega} - \frac{d\Sigma^+}{d\Omega} \sim [\tilde{N}\tilde{M}_z^* + \tilde{N}^*\tilde{M}_z] \sin^2\theta + [\tilde{N}\tilde{M}_y^* + \tilde{N}^*\tilde{M}_y] \sin\theta\cos\theta + \chi \quad (1),$$

where $\tilde{N}(\mathbf{q})$ is the nuclear scattering amplitude, $\tilde{M}_z(\mathbf{q})$ denotes the longitudinal (parallel to \mathbf{H}) Fourier component of the magnetization vector field of the sample, $\tilde{M}_y(\mathbf{q})$ is one of the two transversal Fourier components, θ is the angle between the scattering vector \mathbf{q} on the 2D detector and the $\mathbf{H} \parallel \mathbf{e}_z$ direction, $\chi(\mathbf{q})$ is the chiral function, and “*” denotes the complex conjugate. For statistically isotropic polycrystalline samples, as are studied in the present proposal, the chiral term does not contribute to $\Delta\Sigma$, so that one expects to observe an angular anisotropy of the scattering pattern on the detector corresponding to the two remaining terms. The $[\tilde{N}\tilde{M}_z^* + \tilde{N}^*\tilde{M}_z] \sin^2\theta$ term has been observed countless times in polarized SANS experiments, while we are not aware that the $[\tilde{N}\tilde{M}_y^* + \tilde{N}^*\tilde{M}_y] \sin\theta\cos\theta$ contribution has ever been reported. The reason why the $[\tilde{N}\tilde{M}_y^* + \tilde{N}^*\tilde{M}_y] \sin\theta\cos\theta$ term has not been reported yet in polarized SANS is (probably) related to the fact that it vanishes for a polycrystalline statistically-isotropic ferromagnet with vanishing fluctuations of the saturation magnetization. However, in the case of a two-phase system with significant spatial variations of the saturation magnetization, it can be shown that

$$\Delta\Sigma \sim 2NM_z\sin^2\theta + \frac{2pNM_z\sin^2\theta\cos^2\theta}{1+p\sin^2\theta} \quad (2),$$

where $p(q,H)$ is a dimensionless function of the material parameters (saturation magnetization, exchange-stiffness constant) [2]. Finally, the following field-dependent SANSPOL difference ratio R can be introduced:

$$R(q, \theta) = \frac{\Delta\Sigma(H_0)}{\Delta\Sigma(H_{\text{sat}})} = \frac{\tilde{M}_z}{\tilde{M}_s} \left[1 + \frac{2p\cos^2\theta}{1+p\sin^2\theta} \right] \simeq \left[1 + \frac{2p\cos^2\theta}{1+p\sin^2\theta} \right] \quad (3).$$

This ratio is dependent only on the dimensionless function p and thus on the material parameters and the applied field. A 2D theoretical simulation for the ratio R is shown in Fig.1(a). The goal of this experiment was to observe R as a signature of the presence of the $[NM_y^* + N^*M_y]$ $\sin\theta\cos\theta$ term in the polarized SANS cross section.

Experiment description

We have measured the spin-up and spin-down SANS signals of a nanocrystalline inert-gas condensed (IGC) iron sample as a function of an applied magnetic field $\mathbf{H} \perp \mathbf{k}$ at the D33 instrument. The IGC sample (with an average grain size of about 20 nm) contains a volume fraction of about 10 % of nanopores [3]. It can therefore be seen as a two-phase nanocrystalline system that exhibits large nanoscale variations in the saturation magnetization, i.e, $M_s = M_s(\mathbf{r})$. The room-temperature measurements were carried out for three applied fields (3T, 0.1 T, 0.07 T) using incident neutrons with a mean wavelength of $\lambda = 4.65 \text{ \AA}$, $\Delta\lambda/\lambda \sim 10\%$ (FWHM), and at three sample-to-detector distances, covering a total q -range of about $0.035 \text{ nm}^{-1} \leq q \leq 1.5 \text{ nm}^{-1}$. The subsequent SANS data reduction and correction (correction for background scattering, transmission, detector efficiency, spin-leakage) was carried out using the GRASP software package.

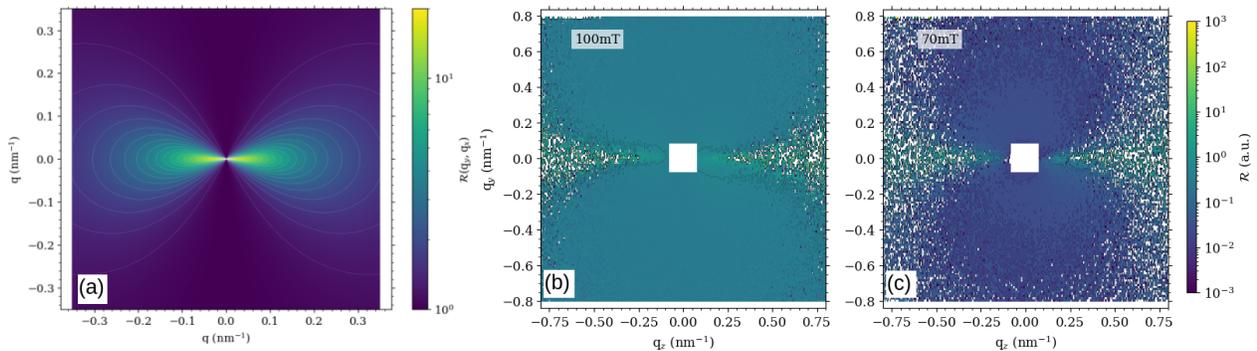


Fig. 1: (a) Theoretical prediction for the field-dependent SANSPOL difference ratio R [Eq. (3)]. Experimental 2D patterns for the ratio R at (b) 0.1 T and (c) 0.07 T (logarithmic color scales).

Results

The experimental SANSPOL cross section ratio R at 0.1 T and 0.07 T is shown in Fig.1(b) and (c), respectively. Here, we used the data at 3 T as the saturation field H_{sat} . The theoretical prediction for R is shown in Fig.1(a) and can be used as a reference for the expected shape and intensity of

the anisotropy. The key feature of the anisotropy, i.e., a higher intensity along the q_z direction is clearly observed for both fields, and we note that the anisotropy becomes more pronounced with decreasing field.

In a continuation experiment, we intend to observe the predicted angular anisotropy at lower applied fields (e.g., at 50 mT and below) and at lower temperatures to increase the relative magnitude of the magnetic scattering contribution. Additionally, we aim to verify the existence of the $[\tilde{N}\tilde{M}_y^* + \tilde{N}^*\tilde{M}_y] \sin\theta\cos\theta$ scattering term for another inhomogeneous material – a two-phase nanocrystalline material from the Nanoperm family of alloys.

References

- [1] A. Michels, *Magnetic Small-Angle Neutron Scattering: A Probe for Mesoscale Magnetism Analysis*, Oxford University Press, Oxford, 2021.
- [2] D. Honecker and A. Michels, *Phys. Rev. B* **87**, 224426 (2013).
- [3] A. Michels et al., *EPL* **85**, 47003 (2009).