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A low-temperature neutron polarimeter for magnetic texture analysis

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Abstract

A miniature sample rotation device has been realized that fits into a cryostat of only 20 mm diameter and allows to perform a new procedure of aligning the anisotropy axis of uniaxially anisotropic ferromagnets precisely along the neutron beam, so as to derive the relevant domain structure parameters from the observed neutron depolarization. Test measurements on NdFeB samples of known orientation of anisotropy show the feasibility of this new method.

Keywords: Neutron depolarization; Magnetic anisotropy; Ferromagnetism

Neutron depolarization (ND) [1], in particular its 3D extension [2], has developed into a powerful technique for the investigation of domain structures of ferromagnetic materials. Magnetic textures in ferromagnets are analyzed with respect to an anisotropy axis which must not be mistaken a mean direction of magnetization, as magnetic anisotropy does not imply net magnetization. The degree of alignment of an uniaxially anisotropic sample is essentially characterized by the parameter $\xi = \frac{1}{2}(3\overline{\cos^2 \vartheta} - 1)$, wherein ϑ denotes the angular deviation of an individual domain magnetization from the anisotropy axis. For instance, $\xi = 0$ ($\cos^2 \vartheta = \frac{1}{3}$) corresponds to an isotropic distribution of magnetic moments, whereas $\xi = 1$ assigns a fully aligned sample. However, a straightforward determination of ξ from ND data is only possible if this axis is oriented exactly parallel to the transmitted neutron beam [3].

Generally, in ND the transition of the incident polarization $\boldsymbol{P}_0$ to the outgoing one $\boldsymbol{P}$ is described in the form $\boldsymbol{P} = \boldsymbol{P}_0 + \Delta\boldsymbol{P} = \mathscr{D}\boldsymbol{P}_0$, i.e. by a depolarization vector $\Delta\boldsymbol{P}$ or a depolarization matrix $\mathscr{D}$, respectively. Whereas $\Delta\boldsymbol{P}$ is the quantity dealt with in the theoretical framework of magnetic small-angle scattering [3], it are the nine elements of $\mathscr{D}$ that are actually determined in experiment via $D_{ij} = (I^+_{ij} - I^-_{ij})/(eI^+_{ij} + I^-_{ij})$. The indices $i, j = x, y, z$ refer to the spatial orientation of $\boldsymbol{P}_0$ upon entering the sample and the respective spatial component of $\boldsymbol{P}$ to be measured upon leaving it. I^+ (I^-) are the intensities obtained with a spin-flip device switched off (on), e denoting its efficiency.

The depolarization of neutrons passing an uniaxially anisotropic ferromagnet depends on the mutual orientation of beam direction, incident polarization and anisotropy axis. Namely, if the incident neutron beam is polarized longitudinally and traverses the sample at an angle ψ from the anisotropy axis, the components of $\Delta\boldsymbol{P}$ in the chosen coordinates (Fig. 1) have been derived as [3]

$$\Delta P_x = AP_0\left[\frac{C-\xi}{2} n_x \cos\psi\right] = D_{yx}P_0,$$

$$\Delta P_y = AP_0\left[\frac{1-\xi}{3} + \frac{\xi - C}{2}\sin^2\psi\right] = (D_{yy} - 1)P_0,$$

$$\Delta P_z = AP_0\left[\frac{C-\xi}{2} n_z \cos\psi\right] = D_{yz}P_0.$$

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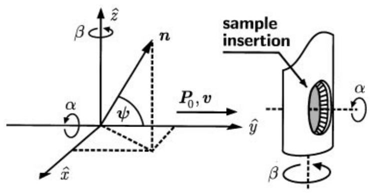

Fig. 1. Coordinate frame employed at sample position: $\boldsymbol{n}$ denotes the sample's anisotropy axis, ψ is the angle it embraces with $\hat{y}$, α and β indicate the rotational degrees of freedom.

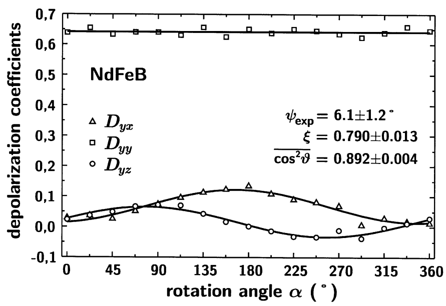

Fig. 2. Experimental test with an uniaxially anisotropic NdFeB sample at an inclination $\psi_{\text{theor}} = 5°$ of $\boldsymbol{n}$ relative to the beam direction. Rotation of the sample around the beam axis does not affect D_{yy} (i.e. ΔP_y), while the perpendicular depolarization components vary as projections of the anisotropy axis.

Here $P_0 = |\boldsymbol{P}_0|$, A and C are numeric constants and n_x, n_z denote the direction cosines of the anisotropy axis.

It is obvious from Fig. 1 that upon rotation of the sample about the $\hat{y}$-axis ψ and hence ΔP_y (or D_{yy}) remain constant, whereas ΔP_x and ΔP_z (D_{yx} and D_{yz}, respectively) will vary sinusoidally with the direction cosines n_x and n_z (Fig. 2). In particular, D_{yz} vanishes if the anisotropy axis lies within the xy-plane ($n_z = 0$). A subsequent rotation about $\hat{z}$ will change $D_{yx} \propto \sin\psi\cos\psi$, i.e. this quantity will be zero not only if the anisotropy direction is parallel to the beam ($\psi = 0°$) but also if it is oriented perpendicular to it. One way to remove this ambiguity would clearly be an additional rotation of the sample about $\hat{x}$ [4], yet this is disadvantageous for technical reasons. The rotation of the sample about three orthogonal axes imposes severe restrictions on miniaturization, which in turn is an essential prerequisite for the realization of a low-temperature facility and of efficient magnetic shielding. Therefore, it is much more favourable to tentatively tilt the incident polarization about $\hat{x}$: in case the axis of anisotropy points into $\hat{x}$, D_{yz} will vary accordingly, whereas it remains at zero value if the anisotropy is directed along the beam.

The actual feasibility of the new method was tested at the neutron polarimetry set-up at the 250 kW TRIGA reactor in Vienna that is routinely used for 3D-ND. A miniature two-axial sample orientation device has been developed which fits into a He gas-flow cryostat ($4.2 < T < 300$ K) of only 20 mm inner diameter. Details of the set-up will be published in a separate paper [5]. From a bulk sintered NdFeB block with given orientation of uniaxial magnetic anisotropy several thin samples were cut with definite tilt angles relative to the axis of anisotropy. Next, these samples were treated as if the orientation of the anisotropy axis was unknown. By employing the new method we could reproduce the original alignment within an overall accuracy of about 1.3° and consequently determine the degree of alignment ξ of all samples. However, the alignment procedure itself must be regarded considerably more precise than is indicated by the achieved accuracy. The latter is mainly determined by uncertainties of the spatial direction of the texture axis prior to cutting.

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