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Interferometric phase contrast tomography

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Abstract

The recently proposed implementation of the tensorial magnetic tomography concept into perfect crystal neutron interferometry is considered. The mathematical relations between the observables of neutron interference and standard depolarization experiments are given. © 2000 Elsevier Science B.V. All rights reserved.

Keywords: Neutron depolarization; Interferometry; Tomography; Magnetic order

The neutron depolarization method proposed by Halpern and Holstein [1] and extended by Rekveldt [2,3] and Maleev and Ruban [4] offers the possibility for a non-destructive investigation of the magnetic structure of bulk materials. Although the depolarization process is theoretically well understood, there exists no unique procedure for data inversion because measuring in a single direction does not provide sufficient information on the correlations between the domains. Recently, a tomographic extension of the neutron depolarization method was proposed [5] where a two-dimensional scan of a given cross section of the specimen is performed. Thus, the object is penetrated by the beam in various directions and different projections of the domain structure are obtained. However, the analysis of tomographic data is rather involved due to the tensorial character of the data. At present no analytic solution to the inverse problem is known. Hence iterative numerical methods have been developed for data analysis [6]. The results obtained are very promising and indicate that neutron magnetic tomography might be a potential tool for the visualization of magnetic domains within bulk materials.

The experimental implementation of neutron magnetic tomography by extension of the standard depolarization technique requires a high effective flux and represents a challenge for neutron physics. Therefore such experiments must be performed at high flux sources using modern neutron optical devices for focussing as well as high-resolution imaging detectors.

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Recently, we proposed an alternative method [6] based on a combination of polarized neutron interferometry with the tomographic depolarization method. The concept is similar to that of phase-contrast topography introduced by Schlenker and Baruchel [7]. We show schematically the set-up for such an experiment (Fig. 1). Obviously, the observables of the interferometric measurement are different from those of the standard depolarization technique because the former yield direct information on the amplitude while in the latter only intensities are involved.

In this contribution we consider the relations between these observables. Let us consider a beam passing through N successive magnetic domains. In the nth domain the wave function is modified by a spin rotation operator $\mathcal{U}_n = \exp(\mathrm{i}\chi_n)\exp(-\mathrm{i}\boldsymbol{\sigma}\cdot\boldsymbol{\alpha}_n)$ so that the total modification by the sample is

$$\mathcal{U}_{\mathrm{tot}} = \mathcal{U}_N \dots \mathcal{U}_2\mathcal{U}_1 = e^{\mathrm{i}\chi}(s\mathbf{1} - \mathrm{i}\boldsymbol{v}\cdot\boldsymbol{\sigma}), \tag{1}$$

where χ is the overall scalar phase shift due to nuclear interaction and $\boldsymbol{\alpha}_n$ describes the spin rotation generated by the magnetization of the nth domain. The quantity s is a real scalar and $\boldsymbol{v}$ is a real vector, satisfying $s^2 + \boldsymbol{v}^2 = 1$. A straightforward but rather lengthy calculation similar to that given in Ref. [8] reveals that the intensity I' and the polarization $\boldsymbol{P}'$ of the outcoming beam of the interferometer are given by

$$I' = \frac{I}{2}(1 + s\cos\chi + \boldsymbol{P}\cdot\boldsymbol{v}\sin\chi),$$

$$\boldsymbol{P}' = \frac{I}{2I'}[(\cos\chi + s)(s\boldsymbol{P} + \boldsymbol{v}\times\boldsymbol{P}) + (\sin\chi + \boldsymbol{P}\cdot\boldsymbol{v})\boldsymbol{v}], \tag{2}$$

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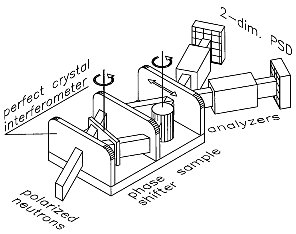

Fig. 1. Set-up for neutron interferometric phase-contrast tomography.

where I and $\boldsymbol{P}$ are the intensity and polarization of the incident beam. Using a variable phase shifter in one arm of the interferometer one can determine the quantities s and $\boldsymbol{v}$ even in the case of an unpolarized incident beam ($\boldsymbol{P}=0$).

Standard depolarization measurements determine the depolarization matrix $\mathscr{D}$ which describes the change of the polarization caused by the sample. The polarization $\boldsymbol{P}_s$ of the partial beam passing through the sample is hence given by

$$\boldsymbol{P}_s = \mathscr{D}\boldsymbol{P} = \mathrm{Trace}(\mathscr{U}_{tot}\tfrac{1}{2}(1+\boldsymbol{P}\cdot\boldsymbol{\sigma})\mathscr{U}^{\dagger}_{tot}\boldsymbol{\sigma}) \quad (3)$$

with matrix elements D_{jk} of $\mathscr{D}$,

$$D_{jk} = (s^2 - \boldsymbol{v}^2)\delta_{jk} + 2s\varepsilon_{jkm}v_m + 2v_jv_k, \quad (4)$$

completely determined by the interferometric observables s and $\boldsymbol{v}$. It is remarkable that the interferometric concept yields also the signs of s and $\boldsymbol{v}$ which cannot be extracted from the standard depolarization technique. Furthermore, the tomographic problem is reduced to matrices of rank 2 whereas $\mathscr{D}$ is of rank 3.

In summary, the realization of tensorial neutron tomography is most likely to be achieved if its concept is combined with that of perfect crystal neutron interferometry. This allows to exploit the intrinsic horizontal collimation properties of perfect crystals and overcomes the hitherto necessity for thin beams. Added to that, interferometric tomography is feasible even with unpolarized incident neutrons which implies a significant gain in intensity. The development of effective algorithms for the extraction of the magnetization distribution within the sample from the observables s and $\boldsymbol{v}$ is in progress.

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