

Off-specular polarized neutron scattering from magnetic fluctuations in thin films and multilayers

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Abstract. Polarized neutron off-specular scattering from magnetic fluctuations (magnetic domains, roughnesses, and dynamical spin correlations) in thin films and multilayers is theoretically considered within the super-matrix approach of the distorted wave Born approximation. General equations relating the scattering cross section with the pair spin correlation function, the correlator of the nuclear scattering potential fluctuations, and the magnetic-nuclear cross correlator are derived and brought into a form easy for applications.

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One of the greatest advantages of neutron scattering for a wide range of problems in magnetism is the transparency of the data interpretation and the reliability of the quantitative analysis. Relatively weak interactions with matter often guarantee a single-event scattering process, which can be described within the framework of the Born approximation (BA). Then, the magnetic scattering cross section is simply proportional to the Fourier transform of a known combination of the pair spin correlation tensor (related to the dynamical susceptibility) components. Explicit equations derived in the BA [1–4] for the neutron polarization at magnetic scattering have allowed the invention of the vector or 3D polarization analysis [5, 6], widely employed [7] not only to separate nuclear scattering from magnetic scattering and from their interference, but also to determine different components of the susceptibility tensor, as well as to distinguish between static and dynamical correlations. In thick crystals the BA may not be valid [8], and then one needs to develop a dynamical scattering theory of polarized neutrons [9], which appears to be cumbersome and quite difficult in practical use. For scattering at grazing incidence on a flat surface the BA also breaks down, but the situation is handled much more easily. In this case interaction with the mean potential averaged over the lateral projection of the neutron coherence length is strong and leads to the optical effects: specular reflection and refraction,

which are exactly accounted for. According to the neutron spin states the exact solution incorporates birefringence [10–12] of the neutron wave refracted into the homogeneous magnetic media. Lateral inhomogeneities of the interaction potential giving rise to off-specular scattering are considered as a perturbation and described within the distorted wave Born approximation (DWBA) [13]. Examples of these inhomogeneities can include interfacial roughnesses [14], magnetic domains [15], inclusions [16], thermal spin fluctuations, or even lateral crystalline structure [10]. Each violates the translational invariance of the system with respect to the lateral shift and causes off-specular scattering, which in magnetic materials may be associated with spin-flip processes. This paper is devoted to the derivation of the explicit equations for (spin-flip and non-spin-flip) scattering cross sections. It generalizes earlier results [11, 12, 17, 18] used in [10, 15, 16, 19–23] to treat various experimental situations.

1 Refraction, transmission, and reflection

The neutron interaction with a magnetic material is formally described by the operator $\hat{V}(\mathbf{r}, t) = \hat{V}_N(\mathbf{r}, t) + \hat{\mu} \cdot \mathbf{B}(\mathbf{r}, t)$, where $\hat{V}_N(\mathbf{r}, t)$ is the nuclear scattering potential, $\mathbf{B}(\mathbf{r}, t)$ is the microscopic magnetic field, $\hat{\mu} = \mu \hat{\sigma}$, μ is the neutron magnetic moment, $\hat{\sigma}$ is the vector of the Pauli matrices, and $\hat{1}$ is a unit matrix in the neutron spin, $s = \hat{\sigma}/2$, space. A neutron wave impinging onto a surface at the angle α_i of grazing incidence averages out most of the microscopic details of the interaction potential $\hat{V}(\mathbf{r}, t)$ over the lateral projection $l_\perp \sim l_c / \sin \alpha_i$ of the coherence length $l_c \sim \lambda / \delta \theta$, which is mostly related to the primary divergence $\delta \theta$ of the beam (with the wavelength λ). As far as the mean value $\langle \hat{V}(\mathbf{r}, t) \rangle_\perp = \bar{V}(z)$ is a function of the coordinate z normal to the surface and independent of the lateral projection ρ of the neutron coordinate $\mathbf{r}$, the solution of the Schrödinger equation with $\bar{V}(z)$ is factorized into the product $\langle \Psi(\mathbf{r}, t) \rangle = e^{-2i\phi} e^{i\mathbf{K} \cdot \mathbf{P}} \langle \phi(z) \rangle$, where $\mathbf{e}$ is the lateral projection of the wave vector $\mathbf{k}$, $2mE = \hbar^2 k^2$, m is the neutron mass, and $\langle \phi(z) \rangle$ is the two-component vector in the neutron spin

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