

# 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  $\hat{V}(\mathbf{r}, t) = \hat{V}_N(\mathbf{r}, t) + \hat{\mu} \cdot \hat{B}(\mathbf{r}, t)$ , where  $\hat{V}_N(\mathbf{r}, t)$  is the nuclear scattering potential,  $\hat{B}(\mathbf{r}, t)$  is the microscopic magnetic field,  $\hat{\mu} = \mu \hat{\sigma}$ ,  $\mu$  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  $\alpha_i$  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  $\lambda$ ). 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  $\rho$  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  $\mathbf{K}$  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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# Specular Offspecular Reflection Of Polarized Neutrons From Magnetic Thin Films Multilayers

**Marco Cascella**

A decorative graphic element consisting of a light blue horizontal bar with a rounded right end, and a red circular gradient shape partially visible behind it.

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Gupta, Sanjay R. Mishra, Tuan Anh Nguyen, 2022-08-29 A low dimensional magnet is a key to the next generation of electronic devices In some respects low dimensional magnets refer to nanomagnets nanostructured magnets or single molecule magnets molecular nanomagnets They also include the group of magnetic nanoparticles which have been widely used in biomedicine technology industries and environmental remediation Low dimensional magnetic materials can be used effectively in the future in powerful computers hard drives magnetic random access memory ultra low power consumption switches etc The properties of these materials largely depend on the doping level phase defects and morphology This book covers various nanomagnets and magnetic materials The basic concepts various synthetic approaches characterizations and mathematical understanding of nanomaterials are provided Some fundamental applications of 1D 2D and 3D materials are covered This book provides the fundamentals of low dimensional magnets along with synthesis theories structure property relations and applications of ferromagnetic nanomaterials This book broadens our fundamental understanding of ferromagnetism and mechanisms for realization and advancement in devices with improved energy efficiency and high storage capacity      **Neutron Scattering** Thomas Brückel, 2007      **Handbook of Magnetism and Advanced Magnetic**

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*X-ray and Neutron Reflectivity* Jean Daillant, Alain Gibaud, 2008-11-21 ways in which the magnetic interaction between neutrons and magnetic moments can yield information on the magnetization densities of thin films and multilayers I commend the organizers for having organized a group of expert lecturers to present this subject in a detailed but clear fashion as the importance of the subject deserves

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3 3 From Dynamical to Kinematical Theory 107 3 4 Influence of the Roughness on the Matrix Coefficients 111 3 A Appendix The Treatment of Roughness in Specular Reflectivity 113 3 B Appendix Inversion of reflectivity data *The Science Reports of the Tohoku University*, 2001 Includes Annual reports for the Physics and Astronomy Departments **Chemical Abstracts**, 2002 **Neutron Optics** James L. Wood, Ian S. Anderson, 2001 Metals Abstracts, 1996 **Advances in Neutron Scattering Research**, 2001 **Communicated Abstracts**, 1996 *Journal of the Physical Society of Japan*, 2001 *Digests of Intermag*, 1998 *Physics Briefs*, 1993 **Hungarian R&D Articles**, 2003 Neutron Reflectometry International Atomic Energy Agency, 2006 Thin films and multilayers have applications in the development of sensors neutron guides and beam deflectors Adsorption of surfactants and polymers is important in technological and industrial applications and characterization of these thin films is essential for their use in appliances The special features of neutron interaction with matter make neutron reflectometry a powerful tool for probing these surfaces and multilayers It is also useful in surface studies of corrosion of metals The additional advantage of the method is that it can also be effectively used with medium flux reactors This publication gives an introduction into the theory underlying this method its potential applications and a description of existing facilities It will be useful as a guide to the neutron beam user groups interested in developing a neutron reflectometer and enhance reactor utilization *Low-Angle Polarized Neutron and X-Ray Scattering from Magnetic Nanolayers and Nanostructures* Amitesh Paul, 2017-08-12 This research monograph presents the latest results related to the characterization of low dimensional systems Low angle polarized neutron scattering and X ray scattering at grazing incidence are used as the two main techniques to explore various physical phenomena of these systems Special focus is put on systems like thin film transition metal and rare earth layers oxide heterostructures hybrid systems self assembled nanostructures and self diffusion Readers will gain in depth knowledge about the usage of specular scattering and off specular scattering techniques Investigation of in plane and out of plane structures and magnetism with vector magnetometric information is illustrated comprehensively The book caters to a wide audience working in the field of nano dimensional magnetic systems and the neutron and X ray reflectometry community in particular

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