

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, $\hat{\mu} = \mu \hat{\sigma}$, 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 $\langle \Psi(\mathbf{r}, t) \rangle = e^{-i\mathbf{k} \cdot \mathbf{r}} \phi(z)$, where $\mathbf{k}$ is the lateral projection of the wave vector $\mathbf{k}$, $2mE = \hbar^2 k^2$, m is the neutron mass, and $\phi(z)$ is the two-component vector in the neutron spin

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Amitesh Paul



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Specular and Off-specular Reflection of Polarized Neutrons from Magnetic Thin Films and Multilayers Robbert W. E. van de Kruijs, 2002-01-01 Fundamentals of Low Dimensional Magnets Ram K. 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 *Magnetic Characterization Techniques for Nanomaterials* Challa S.S.R. Kumar, 2017-04-24 Sixth volume of a 40 volume series on nanoscience and nanotechnology edited by the renowned scientist Challa S S R Kumar This handbook gives a comprehensive overview about Magnetic Characterization Techniques for Nanomaterials Modern applications and state of the art techniques are covered and make this volume an essential reading for research scientists in academia and industry **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 **Neutron Scattering** Thomas Brückel, 2007 **Experimental Neutron Scattering** B. T. M. Willis, C. J. Carlile, 2017-03-23 The first systematic experiments in neutron scattering were carried out in the late 1940s using fission reactors built for the nuclear power programme Crystallographers were amongst the first to exploit the new technique but they were soon followed by condensed matter physicists and chemists Engineers and biologists are the most

recent recruits to the club of neutron users The aim of the book is to provide a broad survey of the experimental activities of all these users There are many specialist monographs describing particular examples of the application of neutron scattering fifteen of such monographs have been published already in the Oxford University Press series edited by S Lovesey and E Mitchell However this book will appeal to newcomers to the field of neutron scattering who may be intimidated by the bewildering array of instruments at central facilities such as the Institut Laue Langevin in France the ISIS Laboratory in the UK or the PSI Laboratory in Switzerland and who may be uncertain as to which instrument to use

Neutron Scattering In Condensed Matter Physics Albert Furrer,Joel F Mesot,Thierry Straessle,2009-05-22 Neutron scattering has become a key technique for investigating the properties of materials on an atomic scale The uniqueness of this method is based on the fact that the wavelength and energy of thermal neutrons ideally match interatomic distances and excitation energies in condensed matter and thus neutron scattering is able to directly examine the static and dynamic properties of the material In addition neutrons carry a magnetic moment which makes them a unique probe for detecting magnetic phenomena In this important book an introduction to the basic principles and instrumental aspects of neutron scattering is provided and the most important phenomena and materials properties in condensed matter physics are described and exemplified by typical neutron scattering experiments with emphasis on explaining how the relevant information can be extracted from the measurements

□□□□□□□□□□(21□□□□□□□□□□□□□□□2□) Sellmyer,2005 *Handbook of Magnetism and Advanced Magnetic Materials, 5 Volume Set* Helmut Kronmüller,Stuart Parkin,2007-09-11 From the first application of the oxide magnetite as a compass in China in ancient times and from the early middle ages in Europe magnetic materials have become an indispensable part of our daily life Magnetic materials are used ubiquitously in the modern world in fields as diverse as for example electrical energy transport high power electro motors and generators telecommunication systems navigation equipment aviation and space operations micromechanical automation medicine magnetocaloric refrigeration computer science high density recording non destructive testing of materials and in many household applications Research in many of these areas continues apace The progress made in recent years in computational sciences and advanced material preparation techniques has dramatically improved our knowledge of fundamental properties and increased our ability to produce materials with highly tailored magnetic properties even down to the nanoscale dimension Containing approximately 120 chapters written and edited by acknowledged world leaders in the field The Handbook of Magnetism and Advanced Magnetic Materials provides a state of the art comprehensive overview of our current understanding of the fundamental properties of magnetically ordered materials and their use in a wide range of sophisticated applications The Handbook is published in five themed volumes as follows Volume 1 Fundamentals and Theory Volume 2 Micromagnetism Volume 3 Novel Techniques for Characterizing and Preparing Samples Volume 4 Novel Materials Volume 5 Spintronics and Magnetoelectronics

Handbook of Neutron Optics Masahiko Utsuro,Vladimir K. Ignatovich,2010-01-12 Written by authors with an

international reputation acknowledged expertise and teaching experience this is the most up to date resource on the field The text is clearly structured throughout so as to be readily accessible and begins by looking at scattering of a scalar particle by one dimensional systems The second section deals with the scattering of neutrons with spin in one dimensional potentials while the third treats dynamical diffraction in three dimensional periodic media The final two sections conclude with incoherent and small angle scattering and some problems of quantum mechanics With its treatment of the theories experiments and applications involved in neutron optics this relevant reading for nuclear physicists and materials scientists alike

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