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Exact determination of phase information in spin-polarized neutron specular reflectometry

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Abstract. A method is proposed to determine the complex reflection coefficient of any real scattering length density (i.e., in the case where there is no effective absorption, which is a good approximation for neutrons) in neutron specular reflectometry. The method makes use of a magnetic reference layer mediated between the substrate and an unknown sample and measurements of the polarization direction of the reflected beam or a suitable choice of polarization and reflectivity analysis of the reflected beam. It corresponds to the concept proposed recently, but has been derived in the formalism of the transfer matrix. The method is based upon relations between the polarization of the incident and reflected beams, and the transfer matrix elements of the unknown and known layers. Thus, in this manner, only by final polarization orientation measurement can we find the reflection coefficient of any unknown sample which is surrounded on both sides by a uniform medium. Apart from the final polarization orientation measurement of the reflected beam, which is hampered by complications in selecting the physical solution, we show that the reflection coefficient can be determined by more flexible ways using a suitable choice of possible measurements of reflectivity and polarization of the reflected beam. A schematic example is presented to illustrate the method.

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1 Introduction

Cold and ultracold neutron specular reflection experiments are potentially powerful tools to probe the physics of many surfaces and interfacial microstructures of condensed matter [1–5]. In these experiments, the reflectivity profile $R(q)$ of a flat film sample, where $q = 2\pi \sin\theta/\lambda$, in terms of the neutron wavelength λ and the reflection angle θ, is measured to obtain information about the atomic or magnetic density profile of the sample along its depth.

However, the reconstruction of the surface profile has been hampered because of the so-called phase problem which has a long history in others fields such as optics and crystallography [6,7]. This problem refers to the fact that in reflection experiments only the square of the complex reflection coefficient, $R(q) = |r(q)|^2$, is measured and as any other scattering technique the phase of reflection is lost [8]. In the absence of the phase, generally least-squares methods are used to extract the scattering length density (SLD) depth profile [9,10] but in general more than one SLD may be found to correspond to the same reflectivity [11,12]. By using the phase and the reflectivity data, it is possible to solve the one-dimensional inverse scattering problem directly to obtain a unique SLD depth profile [13–15]. However, if the SLD profile is nowhere negative (i.e. supported potentials without bound states), Kramers-Kronig relations between the real and the imaginary parts of the reflection coefficient ensure that the inversion is unique and either the real or the imaginary part of $r(q)$ provides sufficient data [16].

Several methods for measuring the phase have been explored in neutron reflectometry [17–25]. Among these methods, however, the reference layer method first proposed in references [17,18] seems the most attractive because of its experimental application which was first achieved with good success by Majkrzak et al. [25], who also proposed and tested experimentally the related surrounding method [27,28].

The reference layer method based on using a magnetic reference layer for a polarized incident neutron beam and explicit polarization measurements instead of reflectivity, has been proposed by Leeb et al. and discussed in several works [29–31]. This method is of particular interest because it also works in the total reflection regime, and allows unique reconstruction of surface profiles of magnetic or absorptive nonmagnetic media. In this method, by using a magnetic reference layer mounted on top of the unknown layer, the polarization measurements rather than the reflectivity of the reflected beam are used to determine the phase of the reflection coefficient when the incident beam polarization is non-collinear to the magnetization

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