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Polarized neutron reflectometry with phase analysis

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Abstract

A novel technique, polarized neutron reflectometry with phase analysis (PNRPA), is suggested, in which not only the moduli of reflection matrix elements but also up to three phase differences are measured. It is realized in the scheme with two flippers and an analyzer, by reflection of neutrons with the spin, in succession, parallel and antiparallel to two inclined axes fixed to the sample. More detailed information about magnetic layered structures can be thus obtained. An adequate mathematical formalism is given. © 1999 Elsevier Science B.V. All rights reserved.

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1. Introduction

Both the magnitude and direction of magnetization can generally vary in thin films. One of the well-known methods that can be used to study such structures is the magneto-optic Kerr effect (e.g. Ref. [1,2]). Electron microscopy is irreplaceable in the study of details of the magnetic structure on the surface, but cannot be used to study its depth dependence. This information for atomically thin layers can be obtained from low-energy polarized electron reflection [3].

The use of neutrons opens new, unrivalled possibilities. The sensitivity of specular neutron reflection both to magnitude and direction of magnetic fields has been used in the study of magnetic multilayers (see reviews [4,5]). If a magnetic structure to be studied is far from the surface of the material, neutrons may happen to be the only tool permitting to get an insight into its details (an excellent example is Bloch's wall investigations [6]).

In fact, polarized neutron reflectometry (PNR) [7] became one of the basic methods of investigation of magnetically complicated thin-film structures. This technique according to the scheme "polarizer-flipper-sample-flipper-analyzer" [8,9] (1D polarization analysis scheme) is reduced to measurement of the 4 moduli

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of the neutron reflection matrix elements. Neutrons are initially polarized either "up" (+) or "down" (−) the guide field. If $P_0 = f_1 = f_2 = 1$ (P_0 is the incident beam polarization, f_1 and f_2 are the efficiencies of the flippers) and $R_a^+ = 1$, $R_a^- = 0$ (the spin-up and spin-down reflectivities of the analyzer, respectively), the NSF and SF reflectivities (for different states of flippers 1 and 2) are

$$R(\text{off, off}) = |r_{++}|^2 \equiv R_{++}, \qquad R(\text{off, on}) = (k_z^-/k_z^+)\cdot|r_{+-}|^2 \equiv R_{+-},$$
$$R(\text{on, off}) = (k_z^+/k_z^-)\cdot|r_{-+}|^2 \equiv R_{-+}, \qquad R(\text{on, on}) = |r_{--}|^2 \equiv R_{--}, \tag{1}$$

where $k_z^\pm$ are two eigenvalues of the normal-to-the-surface component of the wave vector operator of the incident neutron (here and further the z-axis is assumed to be along the surface normal).

It is also worth noting that the four reflectivities can be measured with one flipper (before the sample), if measurements with the analyzer removed (R_+ and R_-) and introduced (R_{++} and R_{-+}) are carried out for two states of the flipper ('off'; and 'on'), since

$$R_+ = R_{++} + R_{+-} \quad \text{and} \quad R_- = R_{--} + R_{-+}. \tag{2}$$

A novel technique, polarized neutron reflectometry with phase analysis (PNRPA), in which not only the moduli (non-spin-flip and spin-flip reflectivities) of reflection matrix elements but also up to three phase differences are measured, is suggested in the present paper.

2. Full neutron reflectometry

Generally, the spin of the incident neutron is inclined to the guide field. If $|\psi_r(z)\rangle$ and $|\psi_i(z)\rangle$ are the spinors of the reflected and incident neutron waves, accordingly, and r is a representative matrix of the reflection operator, then, by definition (the subscript shows that the representation with a quantization axis Z is used; in the presence of a guide field $\boldsymbol{H}$, the Z-axis is normally assumed to be along $\boldsymbol{H}$)

$$|\psi_r(z_0)\rangle_Z = r|\psi_i(z_0)\rangle_Z = \begin{pmatrix} r_{++} & r_{-+} \\ r_{+-} & r_{--} \end{pmatrix} \begin{pmatrix} \cos\left(\frac{\xi}{2}\right) \\ \sin\left(\frac{\xi}{2}\right)\exp(i\delta(x,y,z_0)) \end{pmatrix}$$
$$= \begin{pmatrix} r_{++}\cos\left(\frac{\xi}{2}\right) + r_{-+}\sin\left(\frac{\xi}{2}\right)\exp(i\delta(x,y,z_0)) \\ r_{+-}\cos\left(\frac{\xi}{2}\right) + r_{--}\sin\left(\frac{\xi}{2}\right)\exp(i\delta(x,y,z_0)) \end{pmatrix}, \tag{3}$$

where the angles ξ and δ (Fig. 1) are determined by the spin state of the incident neutron at $z = z_0$. Due to precession in the guide field, the relative phase shift of the opposite spin components δ may be a function of the surface coordinates, x and y. The beam intensities are found by averaging over the illuminated sample surface [10,11]. Each reflection event probability is determined by interaction with a coherent illumination region, and the resultant reflectivity is found by averaging probabilities of reflection at different parts of the sample.

The moduli of the reflection matrix elements $|r_{++}|$, $|r_{+-}$, $|r_{-+}|$, $|r_{--}|$ can be measured as described, e.g. in Refs. [8,9]. To get more information about the magnetic structure, the absolute phases of the reflection matrix elements φ_{++}, φ_{+-}, φ_{-+}, φ_{--} should be additionally measured. These phases can be found only in experiments in which interference of the reflected and incident beams is directly measured, e.g. by placing a mirror into one of the arms of an interferometer. An explicit meaning to the phases of the reflection matrix

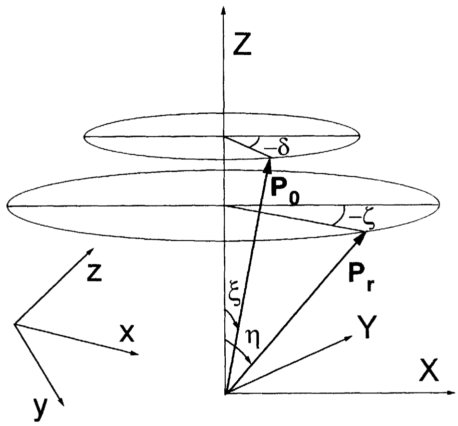


Fig. 1. Geometrical representation of the spin states of the incident and reflected neutrons in terms of polarization vectors, respectively, $\boldsymbol{P}_0$ (ξ and δ are its polar and axial angles) and $\boldsymbol{P}_{\rm r}$ (the corresponding angles are η and ζ) for an arbitrary quantization (Z) axis. The (X, Y, Z) reference frame is generally independent of the system of coordinates (x, y, z) related to the sample. Due to precession in the guide field, the phase difference of the opposite spin components δ (and, consequently, η and ζ) is, generally, a function of the surface coordinates (x, y). The orientation of the polarization vector $\boldsymbol{P}_{\rm r}$ at the sample surface is defined by interference of each pair (NSF and SF) of beams reflected in the same spin state and superposition of the two resultant coherent beams of neutrons in opposite spin states.

elements can be attributed only in special cases (see Section 5). They can be found from theory by calculations on the basis of a model and are results of interference and reflections at the interfaces of layers where the opposite spin eigenstates acquire different phases (inside layers and at interfaces), coherently combine and contribute to each resultant phase shift.

As shown in Section 4, in reflectometry only measurements of three relative phases are possible, i.e. the differences between the phases of reflection matrix elements, e.g.

$$\Delta_{+} \equiv \varphi_{-+} - \varphi_{++}, \qquad \Delta_{-} \equiv \varphi_{--} - \varphi_{+-}, \qquad \Delta_{\rm NSF} \equiv \varphi_{--} - \varphi_{++}. \tag{4}$$

They depend on the magnetic structure of layered materials and may provide an additional information about it. The respective technique may be called as polarized neutron reflectometry with phase analysis (PNRPA).

Calculations for a magnetically non-collinear structure shown in Fig. 2 have been made to illustrate the approach. The results are represented in Fig. 3(a)–(c). In Fig. 3(d) and (e) are given the calculations for the case when the magnetization vectors in the layers are parallel. Some comments on the results of calculations will be given later. Here we only mention that the abrupt changes (jumps) of a phase are in the vicinity of values of k_z at which the modulus of the respective reflection element vanishes. A more detailed calculation shows that for the most part the jumps are of finite width in k_z.

Generally, the 2×2 neutron reflection matrix is fully determined by 8 quantities, 4 moduli and 4 phases. Since only relative phases can be measured in reflectometry, the number of quantities to be found is 7. Define “full neutron reflectometry” as the measurement of any set of reflectivities that allow determining the reflection matrix within a phase (see also Section 4). Thus, full neutron reflectometry should include, at least, 7 measurements of intensities (reflectivities). Such a minimum set of reflectivities is defined in the present paper. The analysis given below shows that the moduli and up to three-phase differences can be measured, provided that reflections of neutrons with the spin, in succession, parallel and antiparallel to two inclined axes fixed to the sample are accomplished in the scheme with two flippers and an analyzer. The measured reflectivities can be used directly to fit the model parameters. However, it might be useful for analysis to work with the moduli and relative phases of the reflection matrix elements. When the magnetic induction vectors

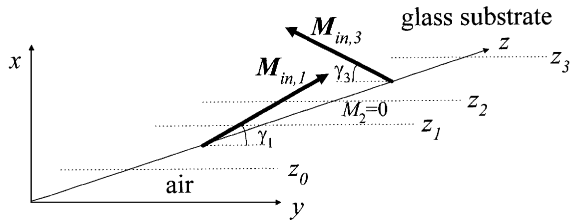


Fig. 2. A structure model (three layers on a glass substrate). The z-axis is normal to the sample surface. Parameters of the model (i stands "for the ith layer"): $d_1 = z_1 - z_0 = 50$ nm, $d_2 = z_2 - z_1 = 4$ nm, $d_3 = d_1$ (d_i is the thickness), $V_1 = V_3 = 100$ neV, $V_2 = 80$ neV (V_i is the nuclear potential), $M_{1,\text{in}} = M_{3,\text{in}} = 10$ kG, $M_2 = 0$ (M_i and $M_{i,\text{in}}$ are the total and in-plane magnetization, respectively), $\gamma_1 = \gamma_3 = \pi/6$, ($\gamma_i$ is the angle between $\boldsymbol{M}_{i,\text{in}}$ and the (y, z)-plane).

inside and outside the structure lie in one plane, both the moduli and phases of the non-diagonal matrix elements in representation with the quantization axis in the same plane are degenerate. It means that full neutron reflectometry in the case of 'in-plane' fields is reduced to the measurement of 5 reflectivities. Or even to the measurement of 3 reflectivities, when the fields in the layered structure are collinear (the reflection matrix can be then diagonalized). It is not unlikely, though, that different reflectivities may be sensitive to different parameters of the layered structure, and it will be wise to measure all reflectivities available in the schemes under consideration.

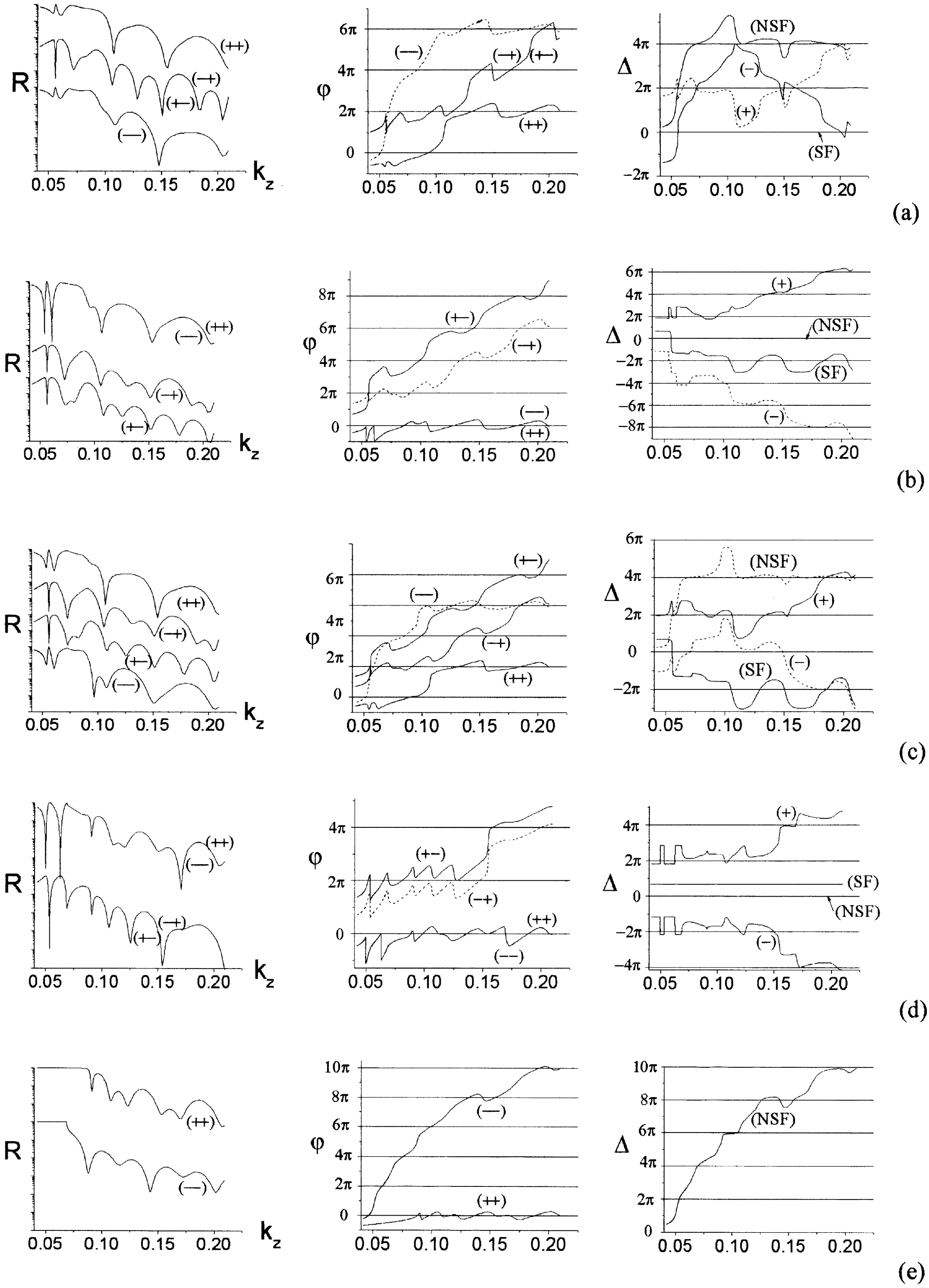
External magnetic fields are usually weak enough, so that refraction under spin-flip reflection of neutrons [10,12,13] can be neglected, and the beams reflected in different spin states merge. One may assume in the weak guide field approximation that the wave vectors for the neutron states with the spin "up" $(+)$ and "down" $(-)$ the field are equal, $\boldsymbol{k}^+ = \boldsymbol{k}^-$. All further analysis is carried out on these assumptions.

To outline the approach, the case of completely polarized neutrons specularly reflected from a homogeneous mirror will be considered. It is necessary that the spins of all incident neutrons be identically oriented at the moment of reflection (at the sample surface). Consequently, the angles ξ and δ do not depend on the surface coordinates, x and y. Besides, the flippers and the analyzer are assumed to be perfect ($f_1 = f_2 = 1$, $R_a^+ = 1$, $R_a^- = 0$), in order to avoid cumbersome corrections irrelevant for our consideration.

Technically, reflection of neutrons with the spin, in succession, parallel and antiparallel to two axes inclined to each other may be realized by (1) changing the beam polarization, as it is practiced in 3D polarization analysis technique, when the field in the sample region is zero, (2) rotating a mirror "neutron 2D polarizer" (described below) about its surface normal, the surfaces of the polarizer and the sample being parallel, (3) rotating the sample about its surface normal, and (4) rotating the magnetic system about the sample. Rotations of the sample and the magnetic system are permissible only if they do not lead to changes in the magnetic state of the sample.

Methodically, full neutron reflectometry consists of two stages. On the first stage are measured the moduli of the reflection matrix elements. The analyzer axis (and, by definition, the quantization axis) is directed along the guide field and is, thus, collinear to spins of the incident neutrons. Fix the orientation of the quantization

Fig. 3. Reflectivities $R_{++}, R_{+-}, R_{-+}, R_{--}$ (left), the phases $\varphi_{++}, \varphi_{+-}, \varphi_{-+}, \varphi_{--}$ of the reflection matrix elements (center) and the phase differences $\Delta_+ \equiv \varphi_{-+} - \varphi_{++}$, $\Delta_- \equiv \varphi_{--} - \varphi_{+-}$, $\Delta_{\text{NSF}} \equiv \varphi_{--} - \varphi_{++}$, $\Delta_{\text{SF}} \equiv \varphi_{-+} - \varphi_{+-}$ (right) are given as a function of the wave vector component normal to the sample surface, k_z. Since all reflectivities approach unity at small k_z, one can easily guess their absolute magnitudes (the curves are shifted to each other by an integer number of orders). Calculations (a, b, c) are for the structure model shown in Fig. 2. Calculations (d, e) are for the same structure, but when the magnetization in the third layer is parallel to that in the first layer. The quantization axis is always along the applied field which is either along the x-axis (a, e) or along the z-axis (b, c, d) (the coordinate system is defined in Fig. 2). The magnitude of the applied field $\boldsymbol{H}$ is assumed to be vanishing except for the case (c) when it is 0.2 T. The magnetic induction vector in the i-th layer is $\boldsymbol{B}_i = \boldsymbol{M}_{i,\text{in}} + \boldsymbol{H}$ ($i = 1, 2, 3$).


R
k_z
0.05 0.10 0.15 0.20
(++)
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0
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Δ
−2π
−4π
−6π
−8π
(NSF)
(SF)
(+)
(−)
(a)
(b)
(c)
(d)
(e)

axis near the sample (taking into account the possible gradual change of the guide field direction in the magnetic region between the sample and the analyzer) and designate it as Z_1. When the sample is rotated or other experimental conditions are changed, the axis Z_1 introduced in this manner preserves the mutual orientation of the incident neutron spins and the sample surface during measurement of the first set of reflectivities.

On the second stage of full neutron reflectometry are determined the differences of reflection matrix element phases. For this aim the methods (1)–(4) provide that the spins of the incidents neutrons at the sample surface are inclined to Z_1. Yet, there is an important difference between methods (1) and (2), on the one hand, and (3) and (4), on the other hand. In methods (1) and (2) the analyzer axis does not change its orientation with respect to the sample (scheme with one analyzing axis). In methods (3) and (4) the spins of the incidents neutrons at the sample surface are supposed to be collinear to the guide field. Therefore, the analyzer axis changes its orientation with respect to the sample surface (scheme with two analyzing axes). Designate the corresponding quantization axis as Z_2. It is to be noted that the change of the orientation of the quantization axis in method (4) by no means signifies that the analyzer itself is rotated, for it can be provided by a gradual change of the magnetic field direction in the region between the sample and the analyzer.

The scheme with one analyzing axis suggests the use of one representation for the neutron spinors and the reflection operator. Therefore, it is simpler for analysis and will be considered first.

3. Scheme with one analyzing axis

Rewrite Eq. (3) as (z_0 denotes that the quantity is calculated at the sample surface)

$$\psi_r(z_0)\rangle_{Z_1} = \exp(\mathrm{i}\varphi_{++})\begin{pmatrix} |r_{++}|\cos\left(\dfrac{\xi}{2}\right) + |r_{-+}|\sin\left(\dfrac{\xi}{2}\right)\exp(\mathrm{i}(\delta + \Delta_+)) \\ \left[r_{+-}|\cos\left(\dfrac{\xi}{2}\right)\exp(-\mathrm{i}\Delta_-) + |r_{--}|\sin\left(\dfrac{\xi}{2}\right)\exp(\mathrm{i}\delta)\right]\exp(\mathrm{i}\Delta_{\mathrm{NSF}}) \end{pmatrix}$$

$$= \exp(\mathrm{i}\varphi_{++})\begin{pmatrix} r_+(z_0) \\ r_-(z_0)\exp(\mathrm{i}\Delta_{\mathrm{NSF}}) \end{pmatrix} = \exp(\mathrm{i}\varphi_{++})\begin{pmatrix} \sqrt{R^+(\xi,\delta)}\exp(\mathrm{i}\gamma_+(\xi,\delta)) \\ \sqrt{R^-(\xi,\delta)}\exp(\mathrm{i}\gamma_-(\xi,\delta) + \mathrm{i}\Delta_{\mathrm{NSF}}) \end{pmatrix}$$

$$= \exp[\mathrm{i}\varphi_{++} + \mathrm{i}\gamma_+(\xi,\delta)]\sqrt{R^+(\xi,\delta) + R^-(\xi,\delta)}\begin{pmatrix} \cos\left(\dfrac{\eta(\xi,\delta)}{2}\right) \\ \sin\left(\dfrac{\eta(\xi,\delta)}{2}\right)\exp(\mathrm{i}\zeta(\xi,\delta)) \end{pmatrix}, \tag{5}$$

$$R^{\Delta +} \equiv |r_+(z_0)|^2, \qquad R^- \equiv |r_-(z_0)|^2, \qquad \gamma_+ \equiv \arctan\frac{\mathrm{Im}[r_+(z_0)]}{\mathrm{Re}[r_+(z_0)]}, \qquad \gamma_- \equiv \arctan\frac{\mathrm{Im}[r_-(z_0)]}{\mathrm{Re}[r_-(z_0)]},$$

$$\eta \equiv 2\arctan\frac{|r_+(z_0)|}{|r_-(z_0)|}, \qquad \zeta \equiv \gamma_- - \gamma_+ + \Delta_{\mathrm{NSF}}.$$

Here the angles η and ζ (see Fig. 1) define the orientation of the reflected neutron spin at the sample surface and play the same role as the angles ξ and δ for the incident neutron. Therefore, the change of the polarization vector under reflection from a layered magnetic structure can be represented by two consecutive rotations, one in the plane $(Z, \boldsymbol{P}_0)$ by an angle $\eta - \xi$ and the other about the Z-axis (here: about the guide field) by an angle $\zeta - \delta$ (Fig. 1). Note that the phase factor $\exp[i\varphi_{++} + i\gamma_+(\xi, \delta)]$ is independent of the surface coordinates (it is technically provided that the spins of all incident neutrons are identically oriented at z_0) and is insignificant in further considerations.

It follows from Eq. (5) that the angle between the quantization axis Z and $\boldsymbol{P}_r$ is

$$\eta = 2\arctan\sqrt{R^-(\xi,\delta)/R^+(\xi,\delta)}. \tag{6}$$

The quantities

$$\begin{aligned} R^+(\xi,\delta) = |r_+(z_0)|^2 &= \left| |r_{++}\cos\left(\frac{\xi}{2}\right) + |r_{-+}|\sin\left(\frac{\xi}{2}\right)\exp(i(\delta + \Delta_+))\right|^2 \\ &= R_{++}\cos^2\left(\frac{\xi}{2}\right) + R_{-+}\sin^2\left(\frac{\xi}{2}\right) + \sqrt{R_{++}R_{-+}}\sin(\xi)\cos(\delta + \Delta_+), \\ R^-(\xi,\delta) = |r_-(z_0)|^2 &= \left| |r_{+-}|\cos\left(\frac{\xi}{2}\right)\exp(-i\Delta_-) + |r_{--}|\sin\left(\frac{\xi}{2}\right)\exp(i\delta)\right|^2 \\ &= R_{+-}\cos^2\left(\frac{\xi}{2}\right) + R_{--}\sin^2\left(\frac{\xi}{2}\right) + \sqrt{R_{+-}R_{--}}\sin(\xi)\cos(\delta + \Delta_-) \end{aligned} \tag{7}$$

are the reflectivities measured with the analyzer, when the flipper after the sample is switched, respectively, off and on. So, Δ_+ and Δ_- can be experimentally found, provided that the incident beam polarization (ξ and δ) is known and $R_{++}, R_{+-}, R_{-+}, R_{--}$ are previously measured.

Generally, only two-phase differences can be determined by preparing incident beam polarization arbitrarily and switching the two flippers on and off. Particularly, for three mutually perpendicular directions of $\boldsymbol{P}_0$ (along X, Y and Z at the moment of reflection) the reflectivities are

$$\begin{aligned} &R^{\pm}_{+X} = \tfrac{1}{2}(R_{\pm\pm} + R_{\mp\pm}) \pm \sqrt{R_{\pm\pm}R_{\mp\pm}}\cos\Delta_\pm = R^{(\pm)}_{-X}, \\ &R^{(\pm)}_{+Y} = \tfrac{1}{2}(R_{\pm\pm} + R_{\mp\pm}) \pm \sqrt{R_{\pm\pm}R_{\mp\pm}}\sin\Delta_\pm = R^{(\pm)}_{-Y}, \\ &R^{(+)}_{+Z} = R_{++}, \qquad R^{(+)}_{-Z} = R_{-+}, \qquad R^{(-)}_{+Z} = R_{+-}, \qquad R^{(-)}_{-Z} = R_{--}, \end{aligned} \tag{8}$$

where the upper and lower symbols in superscripts and subscripts correspond to the states of flipper 2, $(+)$ = 'off' and $(-)$ = 'on', respectively.

Thus, the phase differences Δ_+ and Δ_- are obtained with relative ease. However, Eqs. (7) or (8) are satisfied for two (within 2π) values of Δ_+ and Δ_-. Besides, Δ_+ and Δ_- may exceed 2π, which by no means can be observed directly. Yet, measuring Δ_+ and Δ_- 'continuously' from low-momentum transfers for which they do not exceed π, one can resolve the ambiguities at larger momentum transfers.

When all magnetic induction vectors throughout the layered structure and the external field (the quantization axis) lie in one plane, the direct calculations by numerical methods [14] show that

$$(a)\ k_z^-|r_{+-}| = k_z^+|r_{-+}|, \qquad (b)\ \varphi_{+-} = \varphi_{-+}. \tag{9}$$

(Not to go into numerous details, we do not discuss here the origin of these equalities.) It may be concluded that measurement of 5 reflectivities is then sufficient for full neutron reflectometry.

Equality (9a) means that $R_{+-} = R_{-+}$ (e.g. see calculations in Ref. [5] for different magnetically non-collinear layered structures; see also Fig. 3(a). Measurements of both R_{+-} and R_{-+} are easily made, once the experimental scheme with two flippers is implemented, and the equality $R_{+-} = R_{-+}$ is used in PNR to check or define the measurement conditions. Particularly, the efficiency of the analyzer may be found, provided that the efficiencies of the flippers are known.

Equality (9b) is also important for us. It means that

$$\Delta_{NSF} = \varphi_{--} - \varphi_{++} = \Delta_+ + \Delta_- + \varphi_{-+} - \varphi_{+-} = \Delta_+ + \Delta_-, \tag{10}$$

and one may do without measuring Δ_{NSF} directly.

Another useful configuration for investigating magnetic-layered structures is to arrange the external field so that it is out of plane with the sample surface. Calculations in Fig. 3(b) are for the structure model shown in Fig. 2. Here (a) $|r_{--}| = |r_{++}|$ and (b) $\varphi_{--} = \varphi_{++}$. In calculations represented in Fig. 3(a) and (b) the external field magnitudes are supposed to be vanishing, and the only difference between the two sets of calculations is the choice of the quantization axis, respectively, parallel and perpendicular to the sample surface. One can see that the number of model-dependent quantities is the same.

The external field component normal to the surface penetrates through the layers. When this field component is sufficiently strong, there may appear a magnetization component perpendicular to the sample surface. Though the neutron reflectivity is sensitive to the perpendicular magnetic induction component (see also discussion in Ref. [15]), it is not sensitive to the perpendicular magnetization component, fully compensated by demagnetizing fields. This insensitivity is normally used to point out the restrictions of PNR. However, knowing the saturation magnetization M_s and measuring the in-plane magnetization M_{in}, one may determine its perpendicular component $M_\perp = (M_s^2 - M_{in}^2)^{1/2}$ (for the model of homogeneous layers).

When the external field is inclined to the sample surface, magnetic induction vectors inside and outside layers are no longer in one plane, and there is no universal relation between any pair of reflectivities or phases (e.g. see Fig. 3(c)). Therefore, measurement of the third-phase difference Δ_{NSF} may provide additional information about the structure. In order to measure Δ_{NSF}, the angle ζ should be found (see Eq. (5)) and, hence, the exact orientation of the polarization vector $\boldsymbol{P}_r$ of the reflected neutrons at the sample surface (at the moment of reflection) should be determined. So far, such a problem was not posed before the experimenter. The knowledge of the spin orientation at the moment of scattering is not necessary for measurement of the NSF and SF scattering cross sections. Normally, measurement of the spin orientation at the moment of scattering makes no sense, because not only scattering events are randomly distributed in a comparatively large region in the sample, but also the spins are often orientated differently after scattering events. One of the consequences is that usually the SF scattering leads to reduction in the length of the polarization vector (depolarization) rather than to a change in its orientation. Particularly, in 3D polarization analysis [16,17] the task is to measure the shortening of the polarization vector for differing initial orientations.

The use of a homogeneous mirror sample makes the difference. Numerous events of scattering are then distributed on the mirror surface, i.e. spatially correlated in a definite way. If the incident neutrons polarized either "up" or "down" the guide field is reflected from homogeneous layers magnetized non-collinear to the guide field, the spins of the reflected neutrons point in one direction, generally inclined to the guide field (Fig. 4). The orientation of the polarization vector is defined by the fact that each pair (non-spin-flip and spin-flip) of beams reflected in the same spin state interfere ("cross interference" [10]), and the two resultant beams of neutrons in opposite spin states coherently superpose. However, the polarization vector does not retain its direction in the region between the sample and the analyzer, because of its precession in the external field. Since the directions of all spins of the reflected neutrons at the sample surface are the same, the reflected beam is polarized only in the cross section parallel to the sample surface (the precessing component of the polarization vector is reduced or even vanishes, when averaging is made in other beam cross sections). The plane in which the polarization vector is constant in direction is parallel to the mirror surface (Fig. 4), i.e. almost parallel to neutron trajectories (detailed consideration of "non-frontal neutron spin precession" is given in Ref. [18]). In order to restore the polarization vector orientation at the mirror surface, one has to know the neutron paths and magnetic fields in the "sample-analyzer" region.

Owing to "non-frontality" of neutron spin precession, measurement of the angle ζ requires that the surface of the analyzer be parallel to that of the sample. An analyzer made from a polarizing (super)mirror on the basis of magnetically anisotropic films could be used. The possibility to work with such polarizers in weak

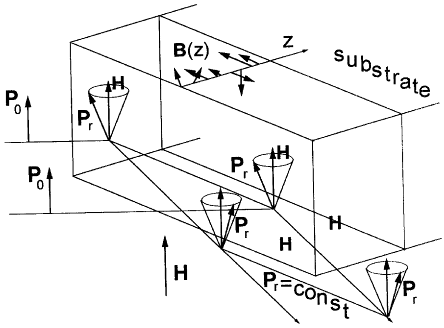

Fig. 4. The incident neutrons polarized 'up' the guide field ($\boldsymbol{P}_0 \| \boldsymbol{H}$) are assumed to be reflected in a state with the spins non-collinear to $\boldsymbol{H}$. Since the spins of the reflected neutrons start precessing at different points of the sample surface, they are oriented identically ($\boldsymbol{P}_r$ = const) only in the beam cross sections parallel to the sample surface.

external fields, owing to remanent magnetization, has been mentioned (e.g. Ref. [19]). Moreover, the remanence property of a FeCo film has been used [20] to make a polarizer that can produce neutrons of opposite spins without using a spin flipper. A "neutron 2D polarizer" rotated about its surface normal was proposed [21] to be used in zero field for preparation and/or analysis of neutron beam polarization. Rotating the spin-selective axis of the "neutron 2D analyzer" in sufficiently weak fields and changing either the distance sample-analyzer or the field magnitude in this region, one can restore the polarization vector orientation at the sample surface for a given neutron wavelength. It is to be noted, however, that the glancing angles are very small and the paths from the sample to the analyzer may essentially differ in length for different neutrons. The precessing component of the measured polarization vector is then reduced or even vanishes, for neutron spins accumulate different precession angles before the analyzer. It requires a precise alignment of the sample and analyzer surfaces and restricts vertical and horizontal divergences of the incident beam, as well as the magnitude and variations of the field in the region between the sample and the analyzer.

To summarize, the relative phase shifts reveal themselves due to cross interference (Δ_+ and Δ_-) and superposition of the opposite spin states of the reflected neutron (Δ_{NSF}).

4. Scheme with two analyzing axes

The neutron spin state is a superposition of the states with the spin "up" and "down" an arbitrary quantization axis. Transition from one quantization axis (Z_1) to another (Z_2) is made by a standard unitary transformation

$$U = \begin{pmatrix} \cos(\chi/2)\exp(-\delta/2) & -\sin(\chi/2)\exp(-\delta/2) \\ \sin(\chi/2)\exp(\delta/2) & \cos(\chi/2)\exp(\delta/2) \end{pmatrix}, \tag{11}$$

where χ and δ are the angles, respectively, between Z_1 and Z_2, and between the planes (Z_1, X_1) and (Z_2, X_2). Sometimes, a neutron state in a given region is more conveniently described when the quantization axis is parallel to a mean magnetic field in this region. Depending on the choice of the quantization axis, the following notations were used earlier [18]:

- (↑) and (↓) for the neutron states with the spin, respectively, parallel and antiparallel to an arbitrary quantization axis;

- (+) and (−) for the neutron states with the spin, respectively, parallel and antiparallel to the mean magnetic induction in a given region.

Up to now the notations (+) and (−) used in this paper comply with this convention.

Consider the full neutron reflectometry scheme with two analyzing axes. Mention that at the first stage are measured the moduli of the reflection matrix elements. The axis Z_1 gives the mutual orientation of the incident neutron spins and the sample surface during this measurement. On the second stage are determined the differences of reflection matrix element phases. In methods (3) and (4) the analyzer axis changes its orientation with respect to the sample surface. The corresponding quantization axis is Z_2. Neutron spins on the second stage are either parallel (a) or antiparallel (b) to Z_2. Reflection processes can be described as follows:

$$|\psi_r(z_0)\rangle_{Z_2} = \rho|\psi_i(z_0)\rangle_{Z_2} = \begin{pmatrix}\rho_{++} & \rho_{-+}\\ \rho_{+-} & \rho_{--}\end{pmatrix}|\psi_i(z_0)\rangle_{Z_2},$$

$$(a)\ |\psi_i(z_0)\rangle_{Z_2} = \begin{pmatrix}1\\0\end{pmatrix}, \qquad (b)\ |\psi_i(z_0)\rangle_{Z_2} = \begin{pmatrix}0\\1\end{pmatrix}, \tag{12}$$

where ρ is the reflection matrix in the representation with the quantization axis Z_2.

The same reflection processes can be described in the representation with the quantization axis Z_1:

$$|\psi_r(z_0)\rangle_{Z_1} = r|\psi_i(z_0)\rangle_{Z_1} = \begin{pmatrix}r_{\uparrow\uparrow} & r_{\downarrow\uparrow}\\ r_{\uparrow\downarrow} & r_{\downarrow\downarrow}\end{pmatrix}|\psi_i(z_0)\rangle_{Z_1},$$

$$(a)\ \psi_i(z_0)\rangle_{Z_1} = U\begin{pmatrix}1\\0\end{pmatrix} = \begin{pmatrix}\cos\left(\frac{\xi}{2}\right)\exp(-\mathrm{i}\delta/2)\\ \sin\left(\frac{\xi}{2}\right)\exp(\mathrm{i}\delta/2)\end{pmatrix}, \qquad (b)\ |\psi_i(z_0)\rangle_{Z_1} = U\begin{pmatrix}0\\1\end{pmatrix} = \begin{pmatrix}\sin\left(\frac{\xi}{2}\right)\exp(-\mathrm{i}\delta/2)\\ \cos\left(\frac{\xi}{2}\right)\exp(\mathrm{i}\delta/2)\end{pmatrix}. \tag{13}$$

Here the subscripts (↑) and (↓) are used, because Z_1 is inclined to the guide field direction.

One can find also the following relations between the matrix elements in the two representations:

$$\rho = UrU^{-1},$$

$$\rho_{++} = r_{\uparrow\uparrow}\cos^2(\chi/2) + r_{\downarrow\downarrow}\sin^2(\chi/2) + \tfrac{1}{2}\sin\chi[r_{\downarrow\uparrow}\exp(\mathrm{i}\delta) + r_{\uparrow\downarrow}\exp(-\mathrm{i}\delta)],$$

$$\rho_{-+} = \tfrac{1}{2}\sin\chi(r_{\downarrow\downarrow} - r_{\uparrow\uparrow}) + r_{\downarrow\uparrow}\cos^2(\chi/2)\exp(\mathrm{i}\delta) - r_{\uparrow\downarrow}\sin^2(\chi/2)\exp(-\mathrm{i}\delta),$$

$$\rho_{+-} = \tfrac{1}{2}\sin\chi(r_{\downarrow\downarrow} - r_{\uparrow\uparrow}) - r_{\downarrow\uparrow}\cos^2(\chi/2)\exp(\mathrm{i}\delta) + r_{\uparrow\downarrow}\sin^2(\chi/2)\exp(-\mathrm{i}\delta),$$

$$\rho_{++} = r_{\uparrow\uparrow}\sin^2(\chi/2) + r_{\downarrow\downarrow}\cos^2(\chi/2) - \tfrac{1}{2}\sin\chi[r_{\downarrow\uparrow}\exp(\mathrm{i}\delta) + r_{\uparrow\downarrow}\exp(-\mathrm{i}\delta)]. \tag{14}$$

Each element of ρ is a linear combination of the four elements of r. Two important consequences for neutron reflectometry are: (1) only the phase differences (up to 3), not the absolute phases of the reflection matrix elements, can be found from measurements of the moduli of ρ; (2) the phase differences found for one representation define the differences between the phases of the reflection matrix elements in any other representation.

Provided that the induction vectors in the layered structure on the first and second experimental stages are essentially the same, one may suppose that $r_{\uparrow\uparrow} = r_{++}, r_{\uparrow\downarrow} = r_{+-}, r_{\downarrow\uparrow} = r_{-+}, r_{\downarrow\downarrow} = r_{--}$.

The result of the two stages of full neutron reflectometry is the measurement of the moduli of the elements of the matrices r and ρ. The respective differences between the phases of the elements of r (and ρ) can be numerically found from Eq. (14).

Mention that in methods (1) and (2) the axis Z_2 can be also inclined to Z_1 by rotation of the "neutron 2D analyzer" about its surface normal. Obviously, the surface of the analyzer should be parallel to that of the sample. Besides, since the analyzer axis is then inclined to the guide field, the orientation of the respective quantization axis at the sample surface will depend on neutron wavelength, sample-analyzer distance and guide field magnitude.

5. Magnetically collinear layered structures

When all magnetic fields inside a layered structure are collinear, only spin-up and spin-down reflectivities are usually measured. The use of PNRPA may yield additional information on the magnetic state of thin layers.

Indeed, assume that all magnetic fields (***B***) inside a layered structure are collinear (Fig. 5). Introduce a unit vector ***b*** specifying one of the two possible (opposite) directions of ***B***. In general, ***b*** is not collinear with the guide field ***H***. It has been shown [10] that the reflection matrix in the weak guide field approximation ($k^+_{1z} \cong k^-_{1z}$) is diagonal in a representation with the quantization axis collinear to ***b***, the diagonal elements being common Fresnel coefficients calculated on assumption that ***H*** is collinear with ***b***. Therefore, the reflection matrix elements in the representation with the quantization axis parallel to ***H*** can be expressed in terms of the Fresnel coefficients as follows [10]:

$$r_{++}(\chi) = r_{++}(0)\cos^2\left(\frac{\chi}{2}\right) + r_{--}(0)\sin^2\left(\frac{\chi}{2}\right),$$

$$r_{-+}(\chi) = r_{+-}(\chi) = \tfrac{1}{2}[r_{--}(0) - r_{++}(0)]\sin\chi,$$

$$r_{--}(\chi) = r_{++}(0)\sin^2\left(\frac{\chi}{2}\right) + r_{--}(0)\cos^2\left(\frac{\chi}{2}\right), \tag{15}$$

where χ is the angle between ***H*** and ***b***. Of course, this expression can be obtained by substitution of $r_{\uparrow\downarrow} = r_{\downarrow\uparrow} = 0$ into Eq. (14).

The Fresnel coefficients ($\chi = 0$) can be written as

$$r_{++}(0) \equiv r_+(0) \equiv |r_+(0)|\exp(i\varphi_+),$$

$$r_{--}(0) \equiv r_-(0) \equiv |r_-(0)|\exp(i\varphi_-), \tag{16}$$

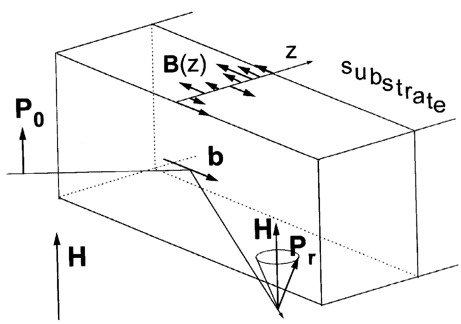

Fig. 5. All magnetic fields (***B***) inside a stratified structure are assumed to be collinear. The unit vector ***b*** specifies one of the two opposite directions of ***B***.

where $\varphi_\pm$ are the phase shifts of the opposite (along $\pm\boldsymbol{b}$) spin components with respect to the phases of the corresponding incident neutron spin components, and Eq. (15) can be written as

$$r_{++}(\chi) = |r_+(0)|\cos^2\left(\frac{\chi}{2}\right)\exp(i\varphi_+) + |r_-(0)|\sin^2\left(\frac{\chi}{2}\right)\exp(i\varphi_-),$$

$$r_{-+}(\chi) = r_{+-}(\chi) = \tfrac{1}{2}[|r_-(0)|\exp(i\varphi_-) - |r_+(0)|\exp(i\varphi_+)]\sin\chi,$$

$$r_{--}(\chi) = |r_+(0)\sin^2\left(\frac{\chi}{2}\right)\exp(i\varphi_+) + |r_-(0)|\cos^2\left(\frac{\chi}{2}\right)\exp(i\varphi_-). \tag{17}$$

Consequently, the reflectivities are

$$R_{++}(\chi) = |r_{++}(\chi)|^2 = R_+(0)\cos^4\left(\frac{\chi}{2}\right) + R_-(0)\sin^4\left(\frac{\chi}{2}\right) + \tfrac{1}{2}\sqrt{R_+(0)R_-(0)}\sin^2(\chi)\cos(\Delta\varphi),$$

$$R_{-+}(\chi) = |r_{-+}(\chi)|^2 = R_{+-}(\chi) = |r_{+-}(\chi)|^2 = [R_+(0) + R_-(0) - 2\sqrt{R_+(0)R_-(0)}\cos(\Delta\varphi)]\sin^2(\chi)/4,$$

$$R_{--}(\chi) = |r_{--}(\chi)|^2 = R_+(0)\sin^4\left(\frac{\chi}{2}\right) + R_-(0)\cos^4\left(\frac{\chi}{2}\right) + \tfrac{1}{2}\sqrt{R_+(0)R_-(0)}\sin^2(\chi)\cos(\Delta\varphi), \tag{18}$$

where $\Delta\varphi = \varphi_- - \varphi_+$ is the phase difference of the Fresnel coefficients. It follows that

$$\cos\chi = \frac{R_{++}(\chi) - R_{--}(\chi)}{R_+(0) - R_-(0)}, \qquad \cos(\Delta\varphi) = \frac{R_+(0) + R_-(0) - 4R_{-+}(\chi)/\sin^2(\chi)}{2\sqrt{R_+(0)R_-(0)}}. \tag{19}$$

To summarize, PNRPA for collinear layered structures comes to the following. First, two reflectivities, $R_\pm(0)$, are measured with a guide field $\boldsymbol{H}$ made collinear to the magnetic fields inside the layered structure. Then, an angle between the spins of the incident neutrons and $\boldsymbol{b}$ is introduced by one of the methods mentioned in Section 2, and four reflectivities (two NSF and two SF reflections) are measured in the scheme with two flippers and an analyzer. (If the method consists in rotation of either the sample or the external magnetic field, precautions should be made to minimize any possible changes in the magnetic structure. Particularly, the external field can be changed so that the magnitude and direction of its in-plane component remains constant.) As a result, one finds not only the angle between $\boldsymbol{H}$ and $\boldsymbol{b}$, but also the relative phase shift of the Fresnel coefficients. Mention that only 3 reflectivities are required to define the neutron reflection matrix for a given model of the structure. It follows from the fact that the reflection matrix is diagonal when $\boldsymbol{H}$ is collinear to $\boldsymbol{b}$. The reflectivities $R_+(0)$ and $R_-(0)$ define the moduli of its diagonal elements, and the respective phase difference $\Delta\varphi$ can be found from each of the four reflectivities (18).

Two sets of calculations (Fig. 3(d) and Fig. 3(e)) made for reflection from a magnetically collinear structure illustrate the situation. Note that the only difference between the models used in calculations represented by Fig. 3(b) and 3(d) is that the direction of the magnetization in the third layer is, respectively, inclined (see Fig. 2) or parallel to that in the first layer. In Fig. 3(d) $\varphi_{-+} - \varphi_{+-}$ is constant and depends only on the choice of the X-axis in the reference frame with the quantization axis Z along the sample surface normal. Since the X-axis coincides then with the x-axis (see Fig. 2), $\varphi_{-+} - \varphi_{+-} = 2(\pi/2 - \gamma) = 2\pi/3$. Usually only reflectivities shown in Fig. 3(e) (i.e. $R_+(0)$ and $R_-(0)$) are measured when the guide field is collinear to the directions of magnetization in the layers. However, only combination of measurements as described above may yield information about the phase difference $\Delta\varphi = \Delta_{\mathrm{NSF}}$.

(Calculations show that a conspicuous difference in the behavior of φ_{++} and φ_{--} seen in Fig. 3(e) persists also with a similar magnetic single layer, when the reflected wave amplitude R in the q-region far from the total reflection plateau may be described with the Fresnel reflection coefficients for the upper (R_1) and lower

(R_2) boundaries: $R = R_1 + R_2 e^{i\beta} = R_1 + R_2 \cos\beta + iR_2 \sin\beta$, where β is the difference between the phases of the waves reflected from the upper and lower boundaries. Beyond the total reflection plateau both R_1 and R_2 are real. For the structure model under consideration R_1 for spin-up neutrons is positive and noticeably larger than $|R_2|$. Consequently, $R_2 \cos\beta$ as a function of k_z do not exceed R_1 and the real part of R is always positive. Oscillations of the phase φ_{++} about zero are due to the fact that $R_2 \sin\beta$ as a function of k_z changes its sign. The situation is different for spin-down neutrons. The sign of both real and imaginary parts of R change, and the phase accumulates when the complex number vector turns on the complex plane.)

The phase information can, in principle, be used to find the potential profile *directly* from neutron measurements (to solve the inverse problem [22]). Particularly, if the potential for one of the spin components is known, i.e. one of the phases is known from a theoretical model based on an additional information, the unknown potential profile for the other spin component can be found *directly* from measurements of the respective reflectivity and $\Delta\varphi$. Mention also that the nuclear part of the potential can be known from complimentary methods, such as X-ray reflectometry. It is not unlikely that the *direct* information about the magnetic part of the potential profile can be extracted from the relative phase-shift measurements. The possibility of the retrieval of the phase information by the technique described in the present paper has not been so far discussed in literature on different aspects of the inverse scattering problem in neutron reflection [23–26]. It might play an important role in solution of the inverse problem. However, more detailed consideration is still required.

Under total reflection of neutrons $R_+(0) = R_-(0) = 1$, and it follows from Eq. (19) that

$$R_{++}(\chi) + R_{+-}(\chi) = R_{--}(\chi) + R_{-+}(\chi) = 1,$$
$$R_{-+}(\chi) = R_{+-}(\chi) = \sin^2\left(\frac{\Delta\varphi}{2}\right)\sin^2(\chi). \tag{20}$$

Thus, knowing χ, the relative phase shift under total reflection $\Delta\varphi$ can be obtained directly from the moduli of the reflection matrix elements:

$$\sin\left(\frac{\Delta\varphi}{2}\right) = \pm |r_{-+}(\chi)|/\sin\chi, \ \ldots, \tag{21}$$

where the sign can be often deduced from physical considerations (e.g. see below).

If neutrons are totally reflected from a boundary between vacuum and a medium with a potential $V > 0$, the phase shift is [27]

$$\varphi = -2\arccos\sqrt{E_\perp/V} = -2\arccos(\lambda_c/\lambda_\perp), \tag{22}$$

where the energy $E_\perp < V$ and the wavelength $\lambda_\perp$ correspond to the component of the particle momentum perpendicular to the boundary of partition of the two media, and λ_c is the so called characteristic wavelength of the medium.

For neutrons totally reflected at the boundary of partition with a magnetic medium (**B** is its magnetic field), the relative phase shift $\Delta\varphi$ can be found (in the approximation of weak external field) from

$$\cos(\varphi_\pm/2) = \sqrt{E_\perp/(V \pm |\mu_n|B)} = \lambda_c^\pm/\lambda_\perp \quad (\varphi_\pm < 0). \tag{23}$$

Evidently, since $\Delta\varphi = \varphi_- - \varphi_+ = |\varphi_+| - |\varphi_-|$,

$$\sin(\Delta\varphi/2) = \cos(\varphi_-/2)\sin(\varphi_+/2) - (\cos(\varphi_+/2)\sin(\varphi_-/2)$$
$$= \lambda_c^-/\lambda_\perp\sqrt{1-(\lambda_c^+/\lambda_\perp)^2} - \lambda_c^+/\lambda_\perp\sqrt{1-(\lambda_c^-/\lambda_\perp)^2} \quad (\lambda_\perp \geqslant \lambda_c^- \geqslant \lambda_c^+). \tag{24}$$

Therefore, $\Delta\varphi > 0$, and the sign in Eq. (21) is 'plus'. It is to be noted that the positive phase difference corresponds to an anti-clockwise spin precession, i.e. its sense is the same as in the common Larmor precession of the neutron spin (its magnetic moment is negative). However, the Larmor precession angle is known to be proportional to the neutron wavelength λ, whereas under total reflection it decreases with $\lambda_\perp$. The latter corresponds to the fact that neutron waves with smaller $\lambda_\perp$ penetrate under total reflection deeper into the medium. Of interest is also that, due to a difference in exponential extinction of the opposite (along $\pm \boldsymbol{B}$) spin components tunneling through a homogeneous magnetic medium, the spin precession will be from the direction of the polarization vector of the incident beam at the boundary of partition ($\boldsymbol{P}_0$) to $\boldsymbol{B}$, i.e. about the axis perpendicular to the plane ($\boldsymbol{B}, \boldsymbol{P}_0$), in contrast to common precession about $\boldsymbol{B}$.

Generally, when quantum mechanical effects are dominant, as is the case in reflectometry and for UCN in sufficiently strong fields, the conception of the Larmor precession originating from classical physics should not be uncritically used for the neutron spin precession. When the difference in velocities of neutrons with the spin up and down the field is essential, the neutron motion and the spin motion are no longer related as usually: even if the expected spin orientation is known for a neutron at any given point and instant, the spin evolution in magnetic fields cannot be, without loss in rigor, described by attaching the spin to a neutron moving with a certain velocity. Therefore, the usual description of the neutron motion and the related spin motion, incl. precession, is no longer exact, even if the spin behavior is fully defined. Only when this difference in velocities is negligible, and usually it is, "precession in space" (a change of the spin orientation from point to point) is precession in time for a neutron moving with a certain velocity along a classical trajectory. Mention that in static fields the spin orientation is fixed at any point of the neutron trajectory.

It is to be emphasized that observation of the phase difference may give additional information on the magnetic state of thin layers. For example note that the 'spin-up' and 'spin-down' reflectivities under total reflection of neutrons are equal to 1 and give no information about the sample. On the other hand, measurement of the phase difference in the total reflection region of momentum transfers yields a direct information on the magnetic state of the surface (the signal in the region of large momentum transfers is defined by the whole structure, rather than by its surface only).

When the magnitude of magnetization of a film is small, the spin-down and spin-up reflectivities are indistinguishable, whereas the phase differences of the corresponding amplitudes may be noticeable, if the film is sufficiently thick. Not only low magnetization, but also large thickness can be measured in this way, even when the interference patterns for the spin-down and spin-up reflectivities are completely blurred out by instrumental resolution.

However, PNRPA may be especially useful in the study of complicated, magnetically non-collinear layered structures (e.g. rare-earth superlattices Gd/Y, Dy/Y, Ho/Y or giant magnetoresistance superlattices Co/Cu, Fe/Cr, etc.). Full neutron reflectometry yields additional information related to the features of the magnetic structure and may contribute to the correct choice of the structure model and more precise determination of its parameters.

6. Summary

A novel technique, polarized neutron reflectometry with phase analysis (PNRPA), in which not only the moduli of reflection matrix elements (non-spin-flip and spin-flip reflectivities) but also the phase differences are measured, has been suggested and considered. More detailed information about magnetic layered structures can be thus obtained. Obviously, the phase information for transmission matrix elements can be obtained in the same manner.

The operator formalism developed for reflectometry of spin particles [10,14] has been used to formulate an appropriate mathematical approach for PNRPA.

Generally, the 2×2 neutron reflection matrix is fully determined by 8 quantities, 4 moduli and 4 phases. It has been shown that only relative phases can be measured in reflectometry, so the number of quantities to be found is 7. Thus, 'full neutron reflectometry' should include, at least, 7 measurements of intensities (reflectivities). Such a minimum set of reflectivities has been defined in the present paper. The measured reflectivities can be used either directly to fit the model parameters or first to determine the moduli and relative phases of the reflection matrix elements and then to fit the model parameters. For 'in-plane' fields full neutron reflectometry may be reduced to measurement of 5 reflectivities. Or even to measurement of 3 reflectivities, when the fields in the layered structure are collinear (the reflection matrix can be diagonalized and only one phase difference is model-dependent). Of course, it may be wise to measure all reflectivities available in the scheme under consideration for more precise determination of different parameters of the layered structure or experimental conditions.

Up to three phase differences of reflection matrix elements can be measured, provided that reflections of neutrons with the spin, in succession, parallel and antiparallel to two inclined axes fixed to the sample are accomplished in the scheme with two flippers and an analyzer. Technically, it may be realized by (1) changing the beam polarization, as it is practiced in 3D polarization analysis technique, when the field in the sample region is zero, (2) rotating a mirror "neutron 2D polarizer" about its surface normal, the surfaces of the polarizer and the sample being parallel, (3) rotating the sample about its surface normal, and (4) rotating the magnetic system about the sample. Generally, the possibility of precise alignments and rotations of polarizer, sample, and analyzer about their surface normals is useful for retrieval of more detailed information about magnetic layered structures.

Now it is important to experimentally demonstrate the complimentary nature of the phase information to conventional measurements of cross sections. The differences between the phases of the four (two NSF and two SF) amplitudes of not only specular but also diffuse scattering from layered structures can be measured in addition to measurements of the respective cross sections. As different models of roughness and magnetic domain structure lead to different phase shifts, it could yield additional information about inhomogeneities of magnetic-layered structures. Note that the SF-scattering from inhomogeneities leads to some depolarization (the spins of neutrons scattered in one direction are oriented differently). However, when the dephasing is not complete, the relative phase shifts reveal themselves and complimentary information can be obtained.

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References

[1] G.S. Krinchik, V.E. Zubov, L.V. Nikitin, Poverkhnost' 1 (1982) 22.
[2] G.S. Krinchik, Physics of Magnetic Phenomena, Moscow State University, Moscow, 1985.
[3] S. Alvarado, M. Campanga, H. Hopster, Phys. Rev. Lett. 48 (1982) 51.
[4] G.P. Felcher, Physica B 192 (1993) 137.
[5] H. Zabel, Physica B 198 (1994) 156.
[6] O. Schärpf, H. Strothmann, Phys. Scripta T 24 (1988) 58.
[7] G.P. Felcher, Phys. Rev. B 24 (1981) 1595.
[8] R.M. Moon, T. Riste, W. Koehler, Phys. Rev. 181 (1969) 920.
[9] C.F. Majkrzak, S. Satija, D.A. Neumann, J.F. Ankner, NIST reactor: summary of activities, July 1989–June 1990, in: C. O'Connor (Ed.), NIST Technical Note 1285, Washington, DC, US Government Printing Office, p. 55, 1990.
[10] N.K. Pleshanov, Z. Phys. B 94 (1994) 233.
[11] V.M. Pusenkov, N.K. Pleshanov, V.G. Syromyatnikov, V.A. Ul'yanov, A.F. Schebetov, J. Magn. Magn. Mater. 175 (1997) 237.
[12] V.K. Ignatovich, Physics of Ultracold Neutrons, Nauka, Moscow, 1988.

[13] G.P. Felcher, S. Adenwalla, V.O. De Haan, A.A. Van Well, Nature 377 (1995) 409.
[14] N.K. Pleshanov, Z. Phys. B 100 (1996) 423.
[15] N.K. Pleshanov, Physica B 234–236 (1997) 516.
[16] A.I. Okorokov, V.V. Runov, V.I. Volkov, A.G. Gukasov, Zh. ETP 69 (1975) 590.
[17] M.Th. Rekveldt, J. Van Woesik, J. Meijer, Phys. Rev. 181 (1977) 920.
[18] N.K. Pleshanov, Phys. Lett. A (1998) submitted for publication.
[19] P. Böni, D. Clemens, H.A. Grimmer, H. Van Swyygenhoven, Annual Report 1994, Annex F3A, PSI Condensed Matter Research and Material Sciences.
[20] D.A. Korneev, Neutron optical devices and applications, in: C.F. Majkrzak, J.L. Wood (Eds.), Proceedings of the SPIE, vol. 1738, 1992, p. 477.
[21] N.K. Pleshanov, Preprint PNPI-2131, 1996.
[22] K. Chadan, P.C. Sabatier, Inverse Problems in Quantum Scattering Theory, Springer, New York, 1977.
[23] R. Lipperheide, G. Reiss, H. Leeb, S.A. Sofianos, Physica B 221 (1996) 514.
[24] C.F. Majkrzak, N.F. Berk, Physica B 221 (1996) 520.
[25] V.O. de Haan, A.A. van Well, P.E. Sacks, S. Adenwalla, G.P. Felcher, Physica B 221 (1996) 524.
[26] G. Reiss, Physica B 221 (1996) 533.
[27] N.K. Pleshanov, Physica B 198 (1994) 70.
[28] N.K. Pleshanov, V.M. Pusenkov, Z. Phys. B 100 (1996) 507.