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THE TIME-OF-FLIGHT FOUR-BEAM NEUTRON REFLECTOMETER REFLEX AT THE HIGH FLUX PULSED REACTOR IBR-2 AND SOME POSSIBLE APPLICATIONS

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1.INTRODUCTION

In the last ten years neutron reflectometry has become widely acknowledged as the effective tool for the investigation of solid and liquid surfaces, hidden boundaries, thin mono- and multilayer films. Invaluable for reflectometry are the polarized neutrons, that allow one to investigate the microscopical magnetic properties of the near-surface layers of bulk samples and thin films of magnetic materials and superconductors. Numerous new results were obtained on the reflectometers of CEN-Saclay [1], Argonne National Laboratory [2], Rutherford Appleton Laboratory [3], KFA-Juelich [4], Los Alamos National Laboratory [5] and Frank Laboratory of Neutron Physics, JINR, Dubna [6]. However, the number of the now existing reflectometers is obviously insufficient to satisfy the growing demand for them from both physicists and chemists.

This paper is dedicated to the new reflectometer REFLEX being built at the high flux pulsed reactor IBR-2. In designing the REFLEX we based on the experience of the world leading laboratories in the field and the five-year experience gained by the FLNP neutron polarization team in the operation of the polarized neutron spectrometer SPN-1 at the IBR-2.

Sections 2 and 3 outline the general principles lying in the basis of the design, give a schematical description of the instrument and brief on the details of the experimental procedure. The high efficiency of the REFLEX is ensured by the double splitting of the neutron beam, that allows one to actually have two double beam reflectometers REFLEX-1 and REFLEX-2 on one beam, the latter being the polarized neutron reflectometer.

The FLNP research programme gives the main priority to the reflectometry with polarized neutrons, because, as is known, it provides one with the information on magnetic surfaces inaccessible with the other methods. At the same time, the theoretical foundation of polarization reflectometry is only in the stage of development. This concerns both the possibilities of the method and the experimental data treatment. So, we think it necessery to consider here these problems in view of their importance for adequate exploitation of the advantages of our instrument.

Section 4 gives the theoretical foundation of the measuring procedure of the local magnetization of the films with inhomogeneous magnetic structure along the normal to their surface. The main inhomogeneous in depth state may arise in films due to light element admixtures in the near-surface layer as well as result from the difference in the symmetry of the surface and depth ions. It will be shown that the polarization reflectometry helps to detail the inhomogeneous magnetic structure of these systems. The task is actual both from the viewpoint of the understanding of the nature of the surface magnetizm in films and their applications, since no reliable information exists as yet of the complex magnetic depth structure of films.

The formalism developed for the description of the reflection process of polarized neutrons from ferromagnets is usually transferred to the study of the penetration depth of an external stationary magnetic field in superconductors. However, here it appears necessary to account for the surface structure of a film.

Section 5 presents the analysis of the influence of the film surface roughness on the determination of the magnetic field penetration depth in a superconductor.

2.PRINCIPAL FEATURES OF THE REFLEX REFLECTOMETER

The REFLEX reflectometer having been designed with account for experience acquired by the neutron laboratories over the world [1 — 6] has some original features making it different from the like instruments.

2.1 The splitted incident beam

It is known that a pulsed neutron source provides for a marked increase in luminosity of a reflectometer. The fact is that the reflection coefficient R depends on the normal to reflecting surface component k_z of the incident neutron wave vector related to the neutron wavelength λ and the reflection angle Θ as :

$$k_z = 2\pi \times \frac{\sin(\Theta)}{\lambda}.$$

At a stationary neutron source the dependence $R(k_z)$ is measured by varying the angle Θ (Θ-scanning) at fixed λ. In that a monochromator is used causing loss of about 99% of the neutron flux.

With a pulsed neutron source, the time-of-flight technique and the de-Broile relationship

$$\lambda = \frac{h}{mv} = \frac{ht}{mL}$$

(h - the Plank's constant), in fact, one can perform λ - scanning without any loss of neutrons by measuring the time of flight, t, and the flight path, L, of the neutron with mass m. At that the possibility remains for varying the angle Θ, without sample position being changed, by splitting the falling beam into two narrow collimated beams.

This idea of double-beam irradiation of a sample was exploited in the design of the SPEAR reflectometer (LANL,LANSCE) [5]. However, it was not realized due to some peculiarities in the neutron moderator construction. The matter is that difference in incident angles must be not too large. Only then the reflectometer's luminosity will increase in result of simultaneous incidence of two beams on a sample. In the reflectometer REFLEX $\Delta\Theta = \Theta_2 - \Theta_1 = 3 \times 10^{-3} rad$, which fact enables measurement of the reflection coefficient spectrum with about equal statistics in spectra reflected at two angles, Θ_1 and Θ_2 as is shown in Fig.1. To illustrate the advantage of using two beams simultaneously falling on a sample Fig.1 shows the ratio of intensities of their reflected spectra calculated for a sample having a $1,000\mathring{A}$ thick multilayer $Nb\ (50\mathring{A})/Ti(50\mathring{A})$ structure on a silicon backing. The reflection coefficient from this structure can be measured in a wide interval of scattering vectors with substantial gain in time and requested statistical accuracy of an equally precise measurement.

2.2 The Korneev Spin-Flipper

The REFLEX reflectometer has the horizontal geometry arrangement. This fact allows us, as at ANL [2], to have two independent reflectometers on one neutron beam. One of them will operate in the unpolarized neutron mode (REFLEX-1), the second - in the polarized neutron mode (REFLEX-2). The latter uses an original spin-flipper schematically shown in Fig.2.

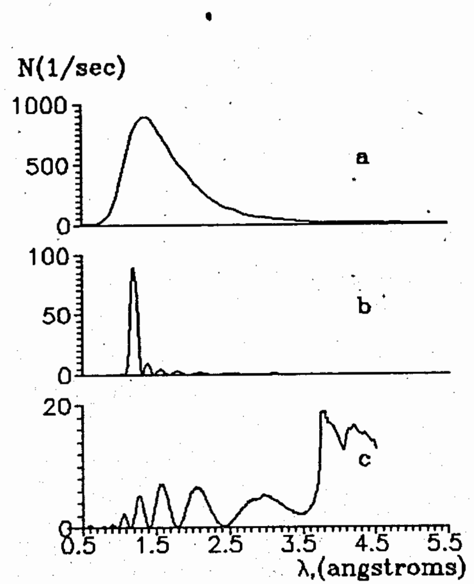

Fig.1. Spectra of intensity obtained for the multilayer structure Nb/Ti on a silicon backing by convolution of the incident spectrum with the reflection coefficient calculated in a wide range of the neutron scattering vector: incident beam (a); beam reflected at $\Theta_1 = 6 \times 10^{-3} rad$ (b) and at $\Theta_2 = 3 \times 10^{-3} rad$ (c).

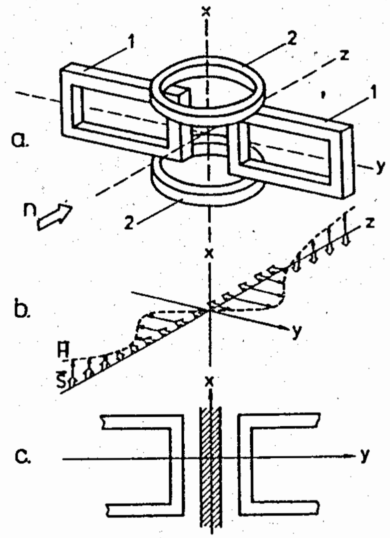

Fig.2. (a) Spin-flipper with a prolonged working area, 1- direct current rectangular coils, 2- compensating coils. The arrow shows the direction of the neutron beam. (b) The behaviour of the vector $\vec{S}$ of neutron spin and H of the magnetic field with the spin-flipper "on". (c) Dashed region is the working area prolonged in the x direction.

Differently from the other spin-flippers, e.g. the Drabkin spin-flipper, the Korneev spin-flipper exploits the total cross section of the neutron beam to bring an increase in luminosity by several times.

2.3 The magnetic system for the sample

The polarization reflectometer has a special electromagnet with a solinoid (Fig.3), which can be rotated about the neutron beam axis to create an arbitrary orientation field of up to 2 kOe on the sample. This opens the new experimental possibilities detalized in Section 4.

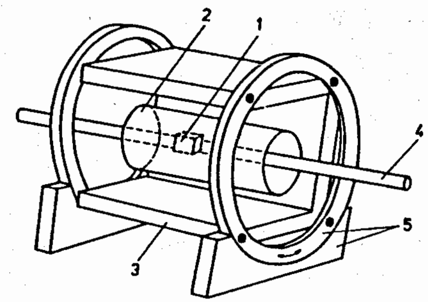

Fig.3. Magnetic system for the reflectometer. 1 - a sample, 2 - a solinoid, 3 - a turnable magnet, 4 - a sample support, 5 - a rotating table. The system enables one to have on the sample the incident neutron polarization vector of any direction or to decrease the magnetic potential $U_M \sim M_p$ by a magnetization of the film in a direction not coincident with the film plane.

3. INSTRUMENT DETAILS

As it has been said above the horizontal arrangement of REFLEX allows positioning of two reflectometers on one neutron beam. The REFLEX-1 and REFLEX-2 reflectometers are schematically shown in Fig.4. In a ring corridor separating the neutron moderator of the reactor from the beam exit window in the biological shielding of the reactor a vertically rotating, 200 mm diameter cylindrical chopper is installed. The chopper's rotation is synchronized with the reactor operation so that totally suppress the background of sattelite peaks and delayed neutrons. The chopper cuts the neutron spectrum from the large wavelength end at $\lambda = 10\mathring{A}$ (at the rotation rate of $150 rev/min$).

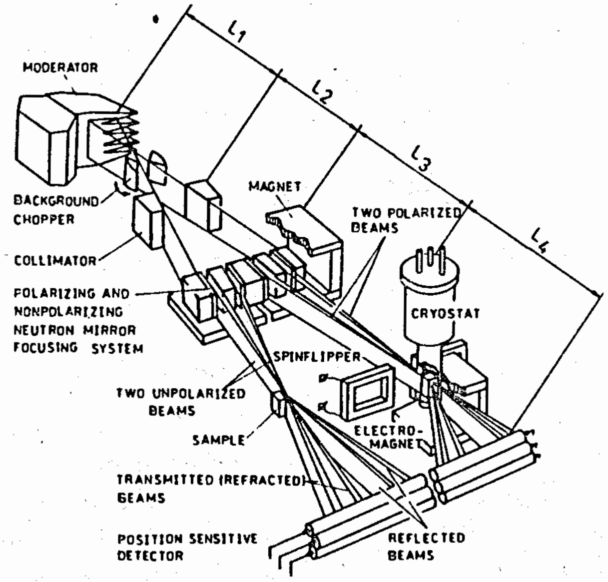

Fig.4. General view of the neutron reflectometer REFLEX
$L_1 = 5\ m,\ L_2 = 25\ m,\ L_3 = 10\ m,\ L_4 = 3 \div 10\ m.$

The beam is split in a system of collimators. The first collimator placed at a distance of $5m$ from the moderator has a slit $6mm$ wide by $200mm$ high. It secures the beam divergence of $1.6 \times 10^{-4} rad$ on the sample. Its slit widths can be varied.

The second - at $20m$ from the moderator divides the neutron beam into two independent ones. The angle of divergence between them is $10^{-2} rad$. At a distance of $30m$ from the reactor a special focusing system is installed on each beam . The system consists of two slits with build-in mirrors $1.6m$ long by $80mm$ high each. In REFLEX-1 the two unpolarized neutron beams are formed with the help of Ni mirrors. In REFLEX-2 the two beams of polarized neutrons are formed by mirror polarizers made of $FeCo$ alloy with a $TiGd$ sublayer on a glass plate. The mirror polarizers are placed in a $400Oe$ field of a permanent magnet. There are permanent magnets to provide for the polarized neutron spin transfer from the polarizer to the sample. The mirrors

cut the small wavelength end of the neutron spectrum at $\lambda = 0.5\mathring{A}$.

The focusing system splits the beam into two and focuses them on a sample. By rotating the sample the incidence angle of one of the beams can be made Θ_1 and of the second - $\Theta_2 = \Theta_1 + \Delta$ at a fixed convergence on sample angle of $\Delta = 3 \times 10^{-3} rad$. The focusing system excludes direct viewing of the reactor core by the detectors and thus helps further reduction of the fast neutron background. Four compact shutters are installed at the entrance to the focusing system to allow independent shuttering of the neutron beams. The opening part of the neutron guide, all collimators and focusing systems for both reflectometers are enclosed in a $800mm$ diameter vacuum tube $42m$ long. The amount of material and air along the neutron path is minimized to avoid losses due to parasitic scattering. The reflectometers are equipped with laser-based optical systems for sample adjustment.

Both reflectometers have moveable mounting tables for sample displacement across the beam and automatic rotation around the vertical axis by the angle $\pm 2 \times 10^{-2} rad$ with a step $10^{-5} rad$. In front and behind the samples there are additionally installed the cadmium collimators with automatically controlled positions and widths of the slits.

REFLEX-2 has also the Korneev spin-flipper [7] in front of the sample at $0.6m$ from it (Fig.2), the special electromagnet (Fig.3) and the helium cryostat for the measurements in the temperature range from 1.8 to $300K$ at the temperature stability level not worse than $0.1K$.

The direct and reflected beams in each reflectometer are registered separately by one-dimensional, position-sensitive He^3 detectors having the resolution $1.8mm$ and the neutron registration efficiency 80%. The reflection coefficients are determined by measuring the intensity of each of the two reflected and incident beams in both reflectometers in a like manner. Besides, it is planned to have an ensemble of eight single detectors that can be moved along the beam at a distance from $3m$ to $10m$ behind the sample. Displacement across the beam of every detector inside the ensemble is accomplished with a step of $0.02mm$ by an auto-system. The detecting systems of both reflectometers are enclosed in one vacuum tube having the diameter of $800mm$.

In the case of single detectors all beams are registered separately by each detector, when necessary. The optimum of transmitted direct intensity is selected with the help of a narrow diaphragm in front of the sample. The reflection angle, Θ, is found from the difference Δx of coordinates of the reflected and direct beam :

$$2\Theta = \frac{x_r - x_d}{L_4} = \frac{\Delta x}{L_4},$$

where L_4 is the changeable sample to detector distance (see Fig.5).

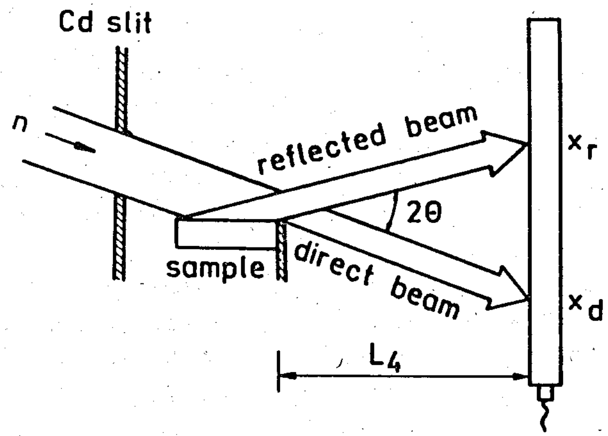

Fig.5. Scheme of the neutron beam division into a direct and reflected beam.

Resolution in k_z depends on geometrical factors mainly and may be expressed in the form:

$$\left(\frac{\Delta k_z}{k_z}\right)^2 = \left(\frac{\Delta\Theta}{\Theta}\right)^2 + \left(\frac{\Delta\lambda}{\lambda}\right)^2$$

At $\lambda = 1\mathring{A}$ the summands in the right hand side of this equation are about equal.

The main parameters of the reflectometers REFLEX-1 and REFLEX-2 are given in Table 1.

Table 1. The REFLEX details

Moderator	water at 320 K
Neutron wavelength range on sample	$0.6 < \lambda < 10\mathring{A}$
Q range	$0.003 < Q < 0.2\mathring{A}^{-1}$
Beams cross section at exit of double mirror reflecting setup	$1.5\ mm\ (W) \times 80\ mm\ (H)$
Beam cross section at sample position (maximum sample acceptance)	$2\ mm\ (W) \times 60\ mm\ (H)$
Fixed angle between two incident beams	$\Delta\phi = 3 \cdot 10^{-3}\ rad$
Grazing angles θ_1, θ_2	$-10^{-2}\ rad < \theta_1 < +10^{-2}\ rad$ $\theta_2 = \theta_1 + \Delta\phi$
Horizontal resolution	$\Delta\theta_\perp\ /\ \theta \leq 3\%$ $(\Delta\theta_\perp = 1.6 \times 10^{-4} rad)$
Vertical divergency	$\Delta\theta_{\|} = 5 \cdot 10^{-3} rad$
Neutron flux on samples	
polarized beams	$1.3 \cdot 10^5 n/cm^2/sec$
unpolarized beams	$2.6 \cdot 10^5 n/cm^2/sec$
Polarizer	double $FeCo/TiGd$ mirror $P = 0.95$(spectrum averaged)
Spin-flipper with a prolonged reverse area	two coplanar rectangular direct current coils (spin reverse probability = 0.99)
Turnable electromagnet	130 mm gap, $H(max) = 2.0$ kOe
Position sensitive detectors (number of detectors 2×1)	1.8 mm resolution linear, position sensitive tubes He^3, 200 mm long
Single counters (number of detectors 2×4)	He^3
Cryostat	$T = 1.8 \div 300\ K$
Minimum reflectivity	$5. \cdot 10^{-6}$
Typical measuring time	30 minutes to 10 hrs
Magnetometer	automatic, Hall

4. REFLECTOMETRY OF MAGNETIC FILMS WITH NONCOLLINEAR MAGNETIC DEPTH STRUCTURES

In a reflectometry experiment with polarized neutrons the polarizability $P_s(k_z)$ of the sample is usually found by measuring the intensity of neutrons reflected from the sample surface with a spin flipper "on", $I_-(k_z)$, and "off", $I_+(k_z)$. Note, that in the general case the polarizability is the vector [8]. So, by introducing the surface polarizability vector $\vec{P}_s(k_z)$ we write the essential equation of polarization reflectometry as:

$$\vec{P}_o(k_z)\vec{P}_s(k_z) = \frac{[I_+(k_z) - I_-(k_z)]}{[I_+(k_z) + I_-(k_z)]}, \qquad (1)$$

where $\vec{P}_o(k_z)$ is the incident beam polarization vector.

For determination of magnetic structure of the sample one needs to perform model calculations of $\vec{P}_s(k_z)$ components and fit them to the experimental data. Below we consider this procedure for concrete magnetic structures of films with inhomogeneous megnetic structure along the normal to the surface.

The problem of neutron reflectometry in the mentioned above case is reduced to the solution of a one-dimensional quantum-mechanical problem of reflection from a potential

$$U(z) = U_N + U_M(z), U_M(z) = -\mu\vec{\sigma}(\vec{B}(z) - \vec{H}_o), \qquad (2)$$

where $U = 2\pi\frac{\hbar^2}{m} \cdot N \cdot b$ is the effective potential enegry of the neutron-nucleus interaction related to the mean coherent neutron scattering length b and number N of nuclei in a unit volume. $U_M(z)$ is the operator of the magnetic potential related to the operator of neutron magnetic moment $\mu\vec{\sigma}$, the magnetic induction vector in medium $\vec{B}(z)$ and the external magnetic field vector $\vec{H}_o$. The $U_M(z)$ is, as a rule, of the same order of magnitude as the U_N which is of the order of about 10^{-7} eV. Composition inhomogenieties arising in films (e.g. due to surface penetrating admixtures) as well as a surface roughness can bring also the dependence of U_N on the coordinate along the normal to the film surface (z).

The neutron wave function with account of spin $\Psi(z) = \begin{pmatrix} \Psi_+(z) \\ \Psi_-(z) \end{pmatrix}$ obeys the one-dimentional Pauli equation

$$\frac{\hbar^2}{2m}\frac{d^2}{dz^2}\Psi(z) + \left[E - U_N + \mu\vec{\sigma}(\vec{B}(z) - \vec{H}_o)\right]\Psi(z) = 0, \qquad (3)$$

where $E = \frac{\hbar^2 k_z^2}{2m}$, k_z is the z-component of the wave vector of the incident neutron, $\vec{\sigma}$ is the vector with the components σ_x, σ_y, σ_z as the Pauli matrices. The wave functions of the incident $\Psi_i(z)$ and reflected $\Psi_f(z)$ ($z < 0$) neutrons look as follows:

$$\Psi_i(z) = e^{ik_z z}\begin{pmatrix} \Psi_+^{(i)} \\ \Psi_-^{(i)} \end{pmatrix}; \quad \Psi_f(z) = e^{-ik_z z}\begin{pmatrix} \Psi_+^{(f)} \\ \Psi_-^{(f)} \end{pmatrix}$$

The spinors $\begin{pmatrix} \Psi_+^{(i)} \\ \Psi_-^{(i)} \end{pmatrix}$ and $\begin{pmatrix} \Psi_+^{(f)} \\ \Psi_-^{(f)} \end{pmatrix}$ are related as:

$$\begin{pmatrix} \Psi_+^{(f)} \\ \Psi_-^{(f)} \end{pmatrix} = R \cdot \begin{pmatrix} \Psi_+^{(i)} \\ \Psi_-^{(i)} \end{pmatrix}, \qquad (4)$$

where R is the 2×2 reflection matrix, that depends on k_z. The matrix elements R_{nm} are the reflection probability amplitudes with $(n \neq m)$ and without $(n = m)$ spin-flip. The matrix R is to be found from eq.(3) with account for the standard boundary conditions and the concrete form of the potential $U(z)$.

To establish the relation of the R matrix with the values being measured in experiments on polarized neutron reflection we construct the film polarizability vector as

$$\vec{P}_s = \frac{tr(RR^+\vec{\sigma})}{tr(RR^+)}, \qquad (5)$$

where R^+ is the hermitian conjugated matrix. The eq.(5) follows from the general spin-density matrix theory [8]. The eqs (1),(5) give the solution of the problem on determination of magnetic depth structures of surfaces after eq.(3) has been solved with some model potential $U_M(z)$ in (2), or magnetic induction $\vec{B}(z)$.

Hereafter we consider films which are plain and infinite in x and y coordinates, e.g. thin films. Let denote the continual vector of local magnetization as $\vec{M}$ and assume it dependent on the z coordinate only:

$$\vec{M}(z) = M_x(z)\vec{n}_x + M_y(z)\vec{n}_y + M_z(z)\vec{n}_z. \tag{6}$$

In this case the magnetic induction vector $\vec{B}(z)$ lies in the plane of the film and equals

$$\vec{B}(z) = 4\pi\vec{M}_p(z) + \vec{H}_o, \tag{7}$$

where $\vec{M}_p(z)$ is the component of $\vec{M}(z)$ along the film plane, i.e. $\vec{M}_p(z) = M_x\vec{n}_x + M_y\vec{n}_y$. This relation is the simple generalization of the corresponding one obtained in [9] for infinite plates with $M_z(z) = const$.

Here we note

$$U_M(z) = 4\pi\mu(\vec{\sigma}\vec{M}_p).$$

The latter relation is easy to get considering the well known coherent neutron magnetic scattering length

$$b_m = F(q)\frac{2m}{\hbar^2}\vec{\mu}\left(\frac{\vec{q}(\vec{\mu}_a\vec{q})}{q^2} - \vec{\mu}_a\right)$$

dependent on an atomic magnetic moment $\vec{\mu}_a$, where $F(q)$ is a magnetic formfactor. Taking into account the orientation of a scattering vector $\vec{q}$ in a reflected and a refracted beam, which is perpendicular to the surface, and using the condition $F(q \to 0) = 1$ we can write

$$b_m = \frac{2m}{\hbar^2}\vec{\mu}\vec{\mu}_{ap}.$$

Then from the relation $U_M = 2\pi\frac{\hbar^2}{2m}Nb_m$ we obtain $U_M = 4\pi(\vec{\mu}N\vec{\mu}_{ap}) = 4\pi(\vec{\mu}\cdot\vec{M}_p)$, where $\vec{M}_p = N\vec{\mu}_{ap}$ and N is an atomic density.

In turn for the films with $\vec{M}$ perpendicular to the surface it follows $U_M = 0$.

When $\frac{M_x(z)}{M_y(z)} \neq const$, eq.(7) describes a spiral-like structure with a nonconserved direction of $\vec{M}_p(z)$ in space. The structures of this type may emerge in uni-axis anisotropic magnetic films having different values of the surface and interior anisotropy constants due to the action of an external magnetic field not coinciding in direction with the easy axis, or in films with the depth rotating anisotropy axis.

With the $\vec{M}_p(z)$ given by (7) being introduced into eq. (3), the latter is reduced to a system of two dependent equations with respect to $\Psi_+(k_z)$ and $\Psi_-(k_z)$. From this it follows that the matrix $R_{n,m}$ is a non-diagonal one in this case, i.e. all elements of the $R_{n,m}$ may differ from zero. There follow the expressions for the components of the polarizability vector, $\vec{P}_s$, in this type of structures:

$$\begin{aligned} P_s^x(k_z) &= \frac{(|R_{11}(k_z)|^2 + |R_{12}(k_z)|^2) - (|R_{22}(k_z)|^2 + |R_{21}(k_z)|^2)}{\sum_{n,m}|R_{nm}|^2} \\ P_s^y(k_z) &= \frac{2Im\,(R_{11}(k_z)\cdot R_{21}^*(k_z) + R_{12}(k_z)\cdot R_{22}^*(k_z))}{\sum_{n,m}|R_{nm}|^2} \\ P_s^z(k_z) &= \frac{2Re\,(R_{11}(k_z)\cdot R_{21}^*(k_z) + R_{12}(k_z)\cdot R_{22}^*(k_z))}{\sum_{n,m}|R_{nm}|^2}, \end{aligned} \tag{8}$$

where R_{nm}^* are the complex-like conjugated values. From the non-diagonality condition: $R_{12},\ R_{21} \neq 0$, it follows, that the component $P_s^z(k_z)$, being perpendicular to the film surface, is, in the general case, different from zero. This peculiarity in the $\vec{P}_s$ vector behaviour results in difference from zero of the film polarizability along the normal to its suface. Then a complete experiment is reduced to independent measurements of the combination $\frac{I_+(k_z)-I_-(k_z)}{I_+(k_z)+I_-(k_z)}$ for three orthogonal directions of the $\vec{P}_o(k_z)$ vector. It is clear that the dependence of the components $P_s^{x,y,z}$ on the k_z component of the wave vector is defined by the magnetic structure parameters.

When $\frac{M_x(z)}{M_y(z)} = const$, eq.(7) describes the collinear structures $\vec{M}(z)$ in which the $\vec{M}_p(z)$ component conserves its direction in space. Then, with properly choosed coordinate axes, it can be written as

$$\vec{M}_p(z) = M_x(z)\cdot\vec{n}_x, \frac{M_x(z)}{M_y(z)} = const. \tag{9}$$

According to theory [10, 11] the corresponding $\vec{M}(z)$ dependence takes place in films with the volume anisotropy of the easy plane or easy axis type and with the surface anisotropy of the easy axis or easy plane type, respectively. Besides, the condition (8) holds for the films with the easy axis anisotropy of both the volume and surface, when only the module of $\vec{M}$ depends on z.

By introducing $\vec{M}_p(z)$ (8) into (3) we reduce it to the system of two independent equations with respect to $\Psi^{\pm}(z)$. In this case the reflection matrix becomes diagonal in the coordinate system with the x axis directed along $\vec{M}_p$, i.e.

$$R = \begin{pmatrix} R_{11} & 0 \\ 0 & R_{22} \end{pmatrix},$$

and from (8) we get only one component of $\vec{P}_s^x(k_z)$:

$$P_s^x(k_z) = \frac{|R_{11}(k_z)|^2 - |R_{22}(k_z)|^2}{|R_{11}(k_z)|^2 + |R_{22}(k_z)|^2}.$$

In the other words, for the structure under consideration the polarizability $\vec{P}_s(z)$ lies in the film plane and coincides in direction with the magnetic induction vector $\vec{B}$. This is true for any neutron wave vector k_z.

From what has been said above it follows that there is a possibility to determine the complicate $\vec{M}_p(z)$-structure of magnetic films with the help of the specular reflection of polarized thermal neutrons. To do that one has to measure the spectra of the three components of the film polarizability vector $\vec{P}_s(k_z)$ according to (1) by performing independent measurements of reflected neutrons at three mutually orthogonal directions of the incident neutron beam polarization $\vec{P}_o(k_z)$.

The suggested method will be complete after the solution of eq.(3) for the reflectivity matrix $\vec{R}$. It is to note that this task is not simple and it is model-dependent. An attempt was made in [12] to describe a possible approach to the solution of the neutron-optical problem for non-collinearly magnetized films. In detail this problem was solved in [13].

Our model calculations for the films with a spiral-like structure have shown that a rotation of $\vec{M}_p$ by 10^o in the $FeCo$ film of about $1000\AA$ thickness results in $P_s^z \simeq (1 \div 2) \cdot 10^{-2}$ with a specific k_z dependence. The modern pulsed neutron sources provide the measuring accuracy in P of the order of $5 \cdot 10^{-3}$. So it is possible to measure with the help of

polarized neutrons the spiral-like structural deviations from magnetic depth homogeneity on the level of 5^o per $1000\AA$.

For a more detailed study of magnetic structures of use can be the determination of the reflected beam polarization. In general a polarized neutron beam is described by a spin density marix [8]

$$\rho = \sum_n a_n |\Psi_n >< \Psi_n|,$$

where a_n are the mixing coefficients of the pure spin states of the neutron, Ψ_n. The neutron beam polarization vector is expressed through the matrix ρ as:

$$\vec{P} = \frac{tr(\rho\vec{\sigma})}{tr(\rho)}.$$

So, to determine the polarization of the reflected beam it is sufficient to know how the incinent beam matrix, ρ_i, is transformed into reflected beam matrix, ρ_f, in result of neutron reflection. It can be shown that the polarized beam spin density matrix ρ is transformed as:

$$\rho_f = R\rho_i R^+.$$

Thus, the described procedures allows complete investigation of non-collinear magnetic structures in thin films.

5. ON THE PROBLEM OF CORRECT DETERMINATION OF A MAGNETIC FIELD PENETRATION DEPTH

Investigations of the magnetic field penetration depth in classical superconductors by the specular reflection of polarized neutrons were initiated by G.P.Felcher [14] in 1984. The first estimate on the superconducting penetration depth $\Lambda = 225\AA$ in a superconducting high T_c 123 ceramics was also obtained with the help of polarized neutrons [15]. The experiments of the Dubna group on the measurement of the superconducting penetration depth in a single crystal 123 film gave the result $\Lambda = 980\AA$ [16]. This value is in accord with those obtained by the other methods. The possible reason for the difference between the results of works [15, 16] may be different approaches to the accounting of film surface roughness conditions. In this connection we have performed a model analysis of the surface roughness influence on the estimation of the London depth Λ from the neutron experiment data.

To be more concrete we have performed this analysis for the 123 ceramics. In [16, 17] when considering the problem of specular neutron reflection we kept to the following model of a rough boundary: the optical neutron-nucleus potential is graded with a gradient obeying the Gauss law with a dispersion σ^2. The σ is the roughness parameter. The calculated curves in the frame of this model (Fig.6) show strong correlation of Λ and σ values. So curves 1 and 2 practically coincide in

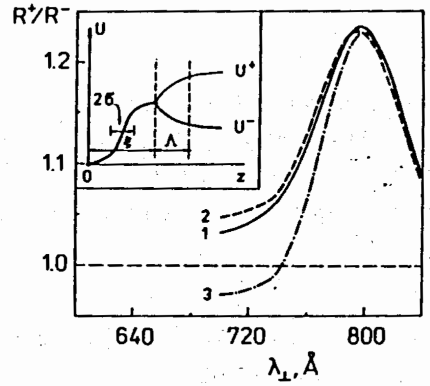

Fig.6. The flipping ratio as the function of a normal to film surface component of the neutron wavelength calculated for the high T_c superconductor $YBa_2Cu_3O_7$. The insert shows schematically the neutron optical potential U for two neutron beam polarizations, U^+ and U^-. σ, ξ, Λ are the parameters that characterize the depth-profile of the neutron-nucleus and magnetic interaction potentials in the case of a superconductor in a Meissner phase: σ is the surface roughness parameter, ξ the thickness of the "dead", nonsuperconducting layer, Λ the London penetration depth. Curves 1,2,3 represent the $\frac{R_+}{R_-}$ values calculated for: (1) $\Lambda = 225\mathring{A}$, $\sigma = 0\mathring{A}$, $\xi = 0\mathring{A}$; (2) $\Lambda = 800\mathring{A}$, $\sigma = 90\mathring{A}$, $\xi = 0\mathring{A}$; (3) $\Lambda = 400\mathring{A}$, $\sigma = 90\mathring{A}$, $\xi = 300\mathring{A}$. The calculation was performed for the external magnetic field of 420 Oe at the resolution $\frac{\Delta\lambda}{\lambda}$ about equal to 0.06 and the correction for polarization about 0.8.

the considered k_z interval at $\Lambda = 225\mathring{A}$, $\sigma = 0\mathring{A}$ and $\Lambda = 800\mathring{A}$ $\sigma = 90\mathring{A}$, respectively, i.e. when the Λ-values differ by more than a factor of 3.5. Curve 3 was obtained with account for the "dead" layer on the surface thickness $\xi = 300\mathring{A}$. Thus it is clear that the accuracy of the Λ estimate is connected with the accuracy of σ determination. As a rule, the parameter σ is extracted from the experimental curve for the reflection coefficient at $T > T_c$ with the help of a formula:

$$R_{D.-V.}(k_z) = R_F \cdot exp(-4k_z k_z' \sigma_D^2), \tag{10}$$

where $R_F(k_z)$ is the Fresnel reflection coefficient from a sharp boundary, $exp(-4k_z k_z' \sigma_D^2)$ is the Debye-Waller factor, k_z' the wave vector in a medium.

Taking as the basis the reflection coefficients, $R_G(k_z)$, calculated in the frame of the Schrodinger problem of reflection from a graded potential with a Gaussian-like gradient with different σ_G, we have determined the parameters σ_D and σ_G that provide for the equality of the coefficients $R_{D.-V.}(k_z)$ and $R_G(k_z)$ over a wide k_z range. The calculations have shown, that the dependence of the ratio of these parameters, $\frac{\sigma_G}{\sigma_D}$, can be presented by a universal curve that depends on the ratio $\frac{\sigma_D}{\lambda_c}$ (see Fig.7),

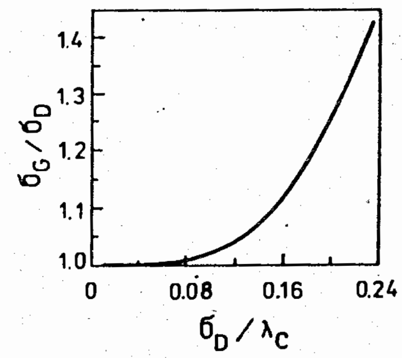

Fig.7. The universal dependence of $\frac{\sigma_G}{\sigma_D}$ on $\frac{\sigma_D}{\lambda_c}$, that allows determination of the surface roughness parameter, σ_G, for the model potential with a Gaussian-like gradient in σ_D, obtained from the data by the formula (10) using the Debye-Waller factor $(exp(-4k_z k_z' \sigma_D^2))$. λ_c is the critical neutron wavelength in a medium.

where λ_c is the critical wavelength of the neutron, which is the characteristic of the reflecting medium ($\lambda_c = (\frac{\pi}{\rho b})^{\frac{1}{2}}$, ρ the number of nuclei in a unit volume, b the neutron-nucleus scattering length). As is seen from Fig.7 noteable distortions in the σ_G value take place at $\frac{\sigma_D}{\lambda_c}$ larger than

0.08. Further calculations have demonstrated that the systematic error in the estimate of the London depth of the magnetic field penetration is linearly related to the error $\delta\sigma$ in σ determination. In a particular case of $YBaCuO$ in a magnetic field of 420 Oe, $\delta\Lambda = 6.4 \cdot \delta\sigma$.

6. CONCLUSIONS

In conclusion let us emphasize again the fact that the REFLEX design bases on all known to the authors achievements in neutron reflectometry, including the time-of-flight method, the possibility of simultaneous positioning of two reflectometers on divided neutron beams, which, in turn, are split into two, the changeable direction of the field on the sample, the high efficient spin-flipper with a prolonged reverse area. These will give the advantage of the highest possible with modern neutron sources intensity on the sample and the resolving power of the instrument.

With the REFLEX built the users will be able to carry out a wide range of investigations in the physics and chemistry of surfaces.

The first priority in the research program being developed for the REFLEX is given to the investigation of the microscopical magnetic properties of superconductors (the magnetic field penetration depth, the magnetic field distribution in the interior of a sample), of inhomogeneous magnetic structures (ferromagnetic and antiferromagnetic spirals, soliton structures, etc.), of multilayer metallic structures and superlattices.

The REFLEX project continues in a natural way the investigations started on the polarized neutron spectrometer SPN at the pulsed reactor IBR-2. The SPN was built in 1985 to investigate the process of neutron depolarization on transmission through inhomogeneously magnetized materials, e.g. ferromagnetic and superconducting materials. After the 1987 year reconstruction it appeared possible to operate the SPN in the reflectometry mode. The IBR-2 happens to generate sufficiently high intensity on the sample of a narrow collimated beam of neutrons ($\Delta\theta = 1.5 \cdot 10^{-4}$ rad) to carry out reflectometry experiments. The result was that the typical measuring time of two reflection coefficients of oppositely polarized neutron beams amounted to $6 - 12$ hours at the sample area of $2 - 3\ cm^2$, the minimum value obtained for the reflection coefficient being 10^{-5}. Some of the neutron reflectometry experiments on the SPN are described in [6].

It is hoped that the REFLEX instrument specially designed for the neutron reflectometry measurements and which test operation on the IBR-2 without polarizing neutron mirrors is to take place in the summer of 1993 will satisfy the requirements of the neutron reflectometrists.

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