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LAYERED STRUCTURES AS ELEMENTS OF THE NEUTRON SPIN-ECHO REFLECTOMETER

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Introduction

The spin-echo spectrometer making use of neutron spin precession in the magnetic field (NSE) was suggested by Mezei to measure energy transfer to(from) the neutron [1]. The basis for this method is the measurement of the change in the phase shift between the waves of two spin states of the neutron in the magnetic field, $\delta\Delta\varphi$, that arises due to change in the neutron energy at scattering. In the NSE spectrometer the phase shift depends on the product of the magnetic field strength H by the size of the magnetic field region L where spin precession occurs (further referred to as a phase shifting region of the spin-echo spectrometer). In [2] there is proposed a resonance spin-echo spectrometer (NRSE) in which the wave vector difference of two spin states arises in the inside region of the resonance coil where a permanent and an oscillating magnetic field act together. The wave vector shift induces the phase shift in the region between the resonance coils (the phase shifting region). The magnetic field in the phase shifting region of the NRSE spectrometer can be small, which is an advantage of such spectrometer [2]. Pynn [3] related $\Delta\varphi$ to the scattering angle and showed that the spin-echo technique can be used to measure elastic neutron scattering. Rekveldt [4,5] extended the use of phase precession to measurements of the scattering angle at diffraction, small angle scattering, and in reflectometric experiments.

In a reflectometric experiment the angular divergence of the beam is a few milliradian or fractions of a milliradian. That is why layered magnetic structures can be used as elements of the spin-echo reflectometer. In [6], a three-layer structure whose margin layers are one-dimensional lattics of sublayers and whose middle layer is homogeneous and provides the phase shift of the neutron wave is suggested. This paper discusses some new applications of layered structures as different components of the spin-echo spectrometer.

Physical substantiation and realization

The elements of the spin-echo spectrometer that change the neutron beam polarization in some or other way are a polarizer, $\pi/2$ and π rotators of polarization (PR), wave phase shifter (WPS), and a polarization analyzer [1]. The element responsible for the sensitivity of the spectrometer is the WPS. Let us begin with the investigation of a three-layer WPS whose layers are all homogeneous unlike in [6].

a) WPS –1。

Let the spin state (1,1) with the wave vectors κ_x^+ and κ_x^- directed along the axis X be prepared from a polarized neutron beam with the wave vector κ_0 along the axis X using a $\pi/2$ rotator of polarization of any type. Since we investigate the meV neutron energy region, we neglect the change in the kinetic energy caused by the rotation of polatization as soon as it is not more than a few tenths of μeV and assume that $\kappa_x^+ \approx \kappa_x^- = \kappa_0$. Let us investigate the propagation of a neutron in one separate layer of a magnetically noncollinear layered structure in the direction of the axis Z perpendicular to the interface and forming an angle of $\pi/2-\theta$ with the axis X (θ is the glancing angle). For the wave vectors of the plus and minus states in the direction of the Z axis we have $k^{\pm}_z = \alpha\,(E_z - (U_n \pm U_m))^{1/2}$, where U_n and $U_m = \mu B$ are the optical potentials of nuclear and magnetic interaction, respectively, μ is the magnetic moment of the neutron, B is the magnetic induction in the layer, E_z is the part of the kinetic energy of the neutron related to its travelling along the Z axis, $\alpha = (h/\pi)(m/2)^{1/2}$, h is the Planck constant, m is the neutron mass. The phase shift between two spin states at different travelling distances l_z^+ and l_z^- along the Z axis is

$$\Delta\varphi = \varphi^+ - \varphi^- = \kappa^+_z\, l_z^+ - \kappa^-_z\, l_z^- \qquad (1)$$

It is just the structure proposed in [6] where the condition of inequality between l_z^+ and l_z^- is realized. Namely, $l_z^+ \approx 0$ and l_z^-, $\approx 2l_2$, where l_2 is the thickness of the middle layer. Let us study the process of energy transfer in the direction perpendicular to the interface. From Eq. (1) we obtain that the derivative of $\Delta\varphi$ with respect to E_z is

$$\delta(\Delta\varphi)/\delta E_z = \delta\varphi^+/\delta E_z - \delta\varphi^-/\delta E_z =$$

$$l_z^+ [\delta k_z^+ /\delta E_z] - l_z^- [\delta k_z^- /\delta E_z] = (l_z^+ /k^+_z - l_z^- / k^-_z) \times \alpha^2/2 \qquad (2)$$

From Eq. (2) it is seen that since k^+_z and k^+_z decrease with decreasing E_z, the $\delta\Delta\varphi/\delta E_z$ increases. Decreasing E_z we come to the region of total reflection ($E_z \approx U\pm\mu B$) where one does not need layer-lattice any more and can simply use homogeneous layers.

Let us investigate a WPS that is a three-layer structure with the first magnetic layer, second nonmagnetic layer with a low potential, and the third nonmagnetic layer but with a large potential of interaction. We are mainly interested in the region of E_z variation, that is limited by the energy of the potential interaction of the neutron with a minus spin state in the magnetic layer U_1^- on one side and by the energy of the potential nuclear interaction U_3 in the third layer on the other side ($U_1^- < E_z < U_3$), in which the reflection coefficients R^+ and R^- are close to unity. Figure 1 illustrates the results of the calculation of the dependence $\Delta\varphi_r$ (E_z) for the structure Fe(20nm)/Bi(200nm)/Cu(3000nm)/ Si(substrate). In the discussed case, $\varphi_r^\pm$ is the phase of the reflection amplitude $r^\pm = |r^\pm|\exp(i\varphi_r^\pm)$. It is seen that $\Delta\varphi_r$ is a periodic function. At the same time, the negative derivative sections mainly correspond to changes in the phase φ_r^- while the positive derivative sections mainly correspond to changes in the phase φ_r^+. The positive derivative is larger in absolute value than the negative derivative. This is due to the effect of resonance enhancement of the phase derivative that takes place when the resonance condition holds [7]

$$2\varphi_2 + \Delta\varphi_2 = n\pi, \quad \text{where} \quad n=0,1,.. \tag{3}$$

where $\varphi_2 = k_{2z} \times l_{2z}$, index "2" marks the middle layer , $\Delta\varphi_2=\varphi(\bar{r}_3) + \varphi(\bar{r}_1)$, $\varphi(\bar{r}_3)$, and $\varphi(\bar{r}_1)$ are the phases of the reflection amplitudes of the neutron in the middle layer from the first and the third layers, respectively. From the following it is easy to understand why the resonance enhancement effect of the phase derivative is larger for the plus than the minus spin state. The wave function of the neutron in the second layer is

$$\psi=B/(1-\bar{r}_1\,\bar{r}_3\exp(2i\varphi_2)), \tag{4}$$

where $B = |B|\exp(i\varphi_B)$ is a complex number.

Transforming Eq. (4) we obtain

$$\psi=B\times\exp(i\chi)/[(1-|r_1r_3|)^2+4|r_1r_3|\sin^2((2\varphi_2+\Delta\varphi_2)/2)]^{1/2}, \tag{5}$$

here $\chi=-|r_1r_3|\text{arctag}[\sin(2\varphi_2+\Delta\varphi_2)/(1-|r_1r_3|\cos(2\varphi_2+\Delta\varphi_2)]$

Assuming that $\delta\varphi_B/\delta\varphi_2 << \delta\chi/\delta\varphi_2$ we only investigate the derivative $\delta\chi/\delta\varphi_2$. From Eq. (5) we have

$$\delta\chi/\delta\varphi_2 = 2(\cos(2\varphi_2+\Delta\varphi_2)-|r_1r_3|)/$$
$$[(1-|r_1r_3|\cos(2\varphi_2+\Delta\varphi_2))^2+\sin^2(2\varphi_2+\Delta\varphi_2)] \tag{6}$$

Making use of Eq. (3) and assuming that the total reflection condition $|r_3|=1$ holds we obtain that the maximum value of the derivative $\delta\chi/\delta\varphi_2$ is

$$(\delta\chi/\delta\varphi_2)_{max}=2/(1-|r_1|) \quad (7)$$

Making use of $\delta\varphi_2=\alpha^2 l_2\, \delta E_z/2k_{2z}$ we obtain

$$(\delta\chi/\delta E_z)_{max}=\alpha^2\ l_2/[(1-|r_1|)\times(E_z-\ U_2)^{1/2}] \quad (8)$$

If one introduces the energy of neutron travel along the Z axis in the medium $E_z^{'}= E_z - U_2$, Eq. (8) can be rewritten as follows

$$(\delta\chi/\delta E_z')_{max}=\alpha^2\ l_2\ (E_z^{'})^{-1/2}(1-|r_1|)^{-1} \quad (9)$$

Finally, from Eqs. (8,9) it is seen that if actually $|r_1^+|>|r_1^-|$, then $\delta\chi^+/\delta E_z > \delta\chi^-/\delta E_z$. And it is equivalent to the calculated (Fig. 1.) relationship $\delta\varphi_r^+/\delta E_z > \delta\varphi_r^-/\delta E_z$.

For the investigated structure the negative derivative of the reflection amplitude $\delta\varphi^-/\delta E_z$ over the interval E=127÷158 neV is equal in absolute value to $\delta\varphi_r^-/\delta E_z$ =0.17 rad/neV while the positive derivative over the interval 159÷161 neV equals $\delta\varphi_r^+/\delta E_z$ =1.5 rad/neV, i.e. is 9 times larger. The growth of $\delta\varphi_r/\delta E_z$ with increasing l_{1z} can be envisioned as the growth of the average number N of neutron transmissions through layer 2. In place of Eq. (2) the new realationship can be then written

$$\delta\Delta\varphi/\delta E_z = l_{2z}\ [N^+\delta k_z^+/\delta E_z - N^-\delta k_z^-/\delta E_z], \quad (10)$$

where $N^{\pm}=(1-|r_1^{\pm}|)^{-1}$. However, it is realized over a narrow interval of E_z variation numerically equal to 4 neV in this case. For the mean square deviation ΔE_z we obtain

$$\Delta E_z = G_E = [(E_z - U - \mu B)/(\alpha\, r_1)]^{1/2} (N l_{2z})^{-1}, \qquad (11)$$

In Eq. (11) it is seen that G_E is inversely proportional to both N and l_{2z}. This means that it is possible to work in different sections of the $\delta(\Delta\varphi_r)/\delta E_z$ dependence where the derivative is realized or in other words, in sections with different sensitivity to the energy variation δE_z.

b) WPH-2.

WPS-1 works in the reflection mode. Next, let us investigate a WPS operating in the transmission mode. It also has three layers the first and the third of which have a finite thickness d and are magnetic. For the plus spin state neutrons the optical potential is the sum of the nuclear U_n and the magnetic U_m potentials, for the minus spin state neutrons it is the difference of U_n and U_m. The optical potential of the middle layer U_2 is taken to be smaller than the minus spin state potential of the magnetic layers: $U_2 < U_n - U_m$. Let us investigate neutrons with the energy E_z satisfying the condition $U_n - U_m < E_z < U_n + U_m$.

Figure 2 depicts the results of the calculation of the structure Fe(20nm)/Bi(200nm)/Fe(20nm)/Si in the magnetic field 100 Oe. It is seen that the transmission coefficient of the plus spin state T^+ has a resonance behavior reaching unity at E_z equal to 100, 130, and 165 neV. The transmission coefficient of the minus spin state T^- is somewhat smaller than the transmission coefficient of the plus spin state due to reflection. Nevertheless, changing the parameters of the structure it is easy to realize the necessary condition $T^+ = T^-$. For example, the phase shift derivative at E_z = 100 neV equals 6.5 rad/neV, which is close to the value of the phase shift derivative in WPS-1 by the order of magnitude. .

Let us discuss the issue of realization in practice of such WPS for the minimum allowed wavelength width $G_{\lambda,min}$. For the L-length structure we have $L/l_2=4\pi N^2(l_2G_\lambda/\lambda^2)$. Taking N=100, l_{2z}=1000Å and $G_{\lambda,min}$ =0.001Å we obtain L≈3 mm. In this case, we have the maximum mean square deviation of the thickness of the second layer $\Delta l_{2z}=\lambda/(N\sin(\theta))=4\pi l_{2z}G/\lambda$ =6Å at θ≈3mrad, which is feasible today.

c) Polarization rotators.

Let us first study the possibility of realization of the π/2 PR. It is clear that in the neutron transmission geometry a magnetic layer with magnetization lying in its plane and directed perpendicular to the external magnetic layer strength can be used as a π/2 or π PR. Of interest is the fact that in the reflection geometry, a magnetic layer can be a π/2 and even π PR. Figure 3 illustrates the wavelength dependence of R^{++} and R^{+-} for a 150 nm iron layer on a silicon substrate at a neutron beam glancing angle of 3 mrad. To realize a π/2 PR in the reflection geometry, the condition $R^{++} = R^{+-}$ must be met. It is seen that this condition is satisfied for a set of wavelengths and at λ=3.17Å the corresponding reflection coefficients are maximum and are equal to 0.5. In the case of cobalt that has a smaller nuclear potential than iron it is possible to realize a π PR. Figure 4 presents the wavelength dependence of R^{+-} and of the reflected beam polarization $P=(R^{++}/R^{+-}-1)/(R^{++}/R^{+-}-1)$ for a 150 nm cobalt layer on a silicon substrate and a glancing angle of 1 mrad. It is seen that the curves both have an oscillating behavior and the polarization may become negative reaching, for example, a minimum of –0.998 at λ=3.79 Å.

d) Layered structure as a PR and a WPS together.

Actually, a layered structure itself can be a spin-echo spectrometer (if not to mention the polarizer and the polarization analyzer that are always necessary). Let us investigate the structure Fe(100nm)/Bi(X)/ Fe(200nm)/Bi(20000nm)/Fe(100nm)/Si comprising three magnetic Fe layers and two nonmagnetic Bi layers. Let the magnetization of the iron layers equal to the saturation magnetization 21.6κOe lie in the plane and be directed perpendicular to an external magnetic field equal to say 1κ Oe. Figure 5 shows the dependence of the transmission T^{++} on the thickness X of the bismuth layer for the neutrons with the wavelength 1.53Å and the glancing angle 10 mrad. It is seen that the dependence is periodic and its period is ΔX=8500 nm. Change in the thickness X is equivalent to change in the precession phase $\Delta\varphi_p=\gamma H\Delta X/(v\sin(\theta))$ in the layer. It is easy to calculate that as it must be expected, $\Delta\varphi_p=2\pi$. An important feature of the spin-echo spectrometer is that the requirements for the neutron beam monochromatization and collimation are not strict because of the compensation of the phase shifts developed in the spectrometer shoulders before and after the sample. Figure 6 illustrates the wavelength dependence of T^{++} for the structure Fe(100nm)/Bi(20000nm)/Fe(200nm)/ Bi(20000nm)/Fe(100nm)/Si. It is seen than the dependence on the wavelength is periodic. This makes it possible to use neutrons of different wavelengths as for example, in time of flight experiments with a neutron beam of white spectrum. On the other hand, the wavelength interval of constant transmission, the working interval, is considerable and it is 0.4Å in the vicinity of the mean wavelength 1.6Å, which is 25%. The practical realization of such spin-echo spectrometer with the investigated sample poses the problem of determination of the parameters of the structure without the sample. It can be solved in two ways. The first is to prepare the structure Fe(X)/Bi(Y)/Fe(Z)/ Bi(Y)/Fe(X)/substrate and the structure with a sample Fe(X)/Bi(Y)/Fe(Z)/sample/ Bi(Y) /Fe(X)/substrate. The structures must be identical. The second is to prepare two Fe(Z/2)/Bi(Y)/Fe(X)/Substrate structures to be the two shoulders of the spin-echo spectrometer. They combine into the structure Substrate/Fe(X)/Bi(Y)/Fe(Z/2)/ Fe(Z/2)/Bi(Y)/Fe(X)/substrate playing the role of the spin-echo spectrometer. After the characteristics of this structure are measured a sample is applied on one of the structures Fe(Z/2)/Bi(Y)/Fe(X)/substrate and as a result, the structure sample/Fe(Z/2)/Bi(Y)/Fe(X)/substrate is formed. Then the structures Fe(Z/2)/ Bi(Y)/Fe(X)/substrate and sample/Fe(Z/2)/Bi(Y)/Fe(X)/substrate are combined into

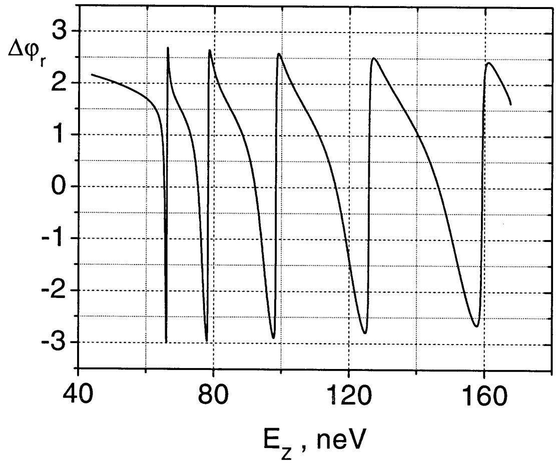

Fig. 1. The dependence of the phase shift $\Delta\varphi_r$ (E_z) for the structure Fe(20nm)/Bi(200nm)/Cu(3000nm) /Si(substrate).

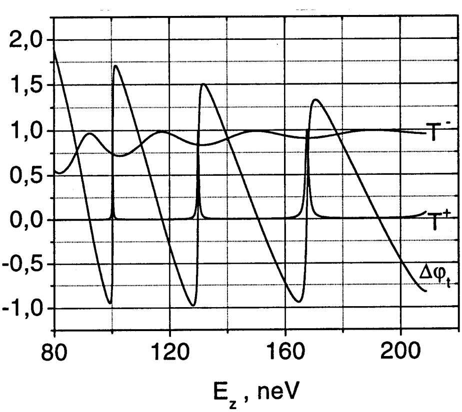

Fig. 2. The dependence curves of T^{+}(E_z), T^{-}(E_z), and $\Delta\varphi_t(E_z)$. for the structure Fe(20nm)/Bi(200nm)/ Fe(20nm)/Si.

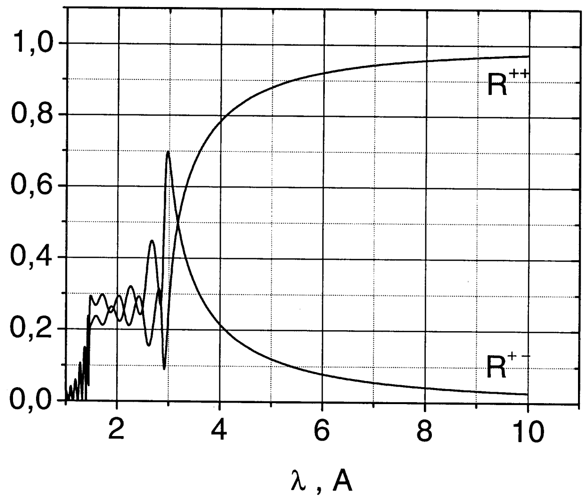

Fig. 3. The wavelength dependence curves of R^{++} and R^{+-} for a 150 nm iron layer on a silicon substrate and the neutron glancing angle 3 mrad.

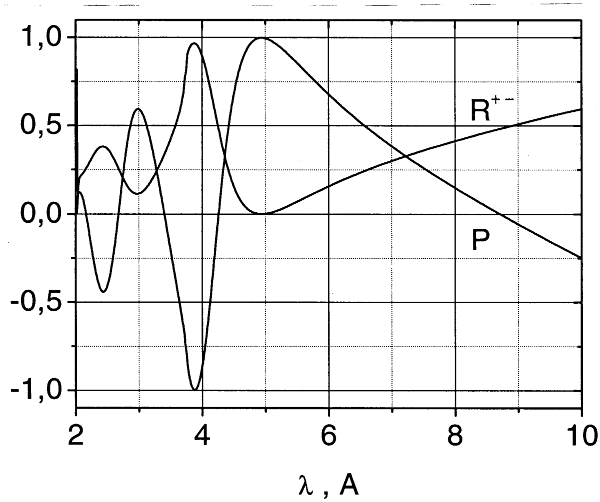

Fig. 4. The wavelength dependence curves of the reflection coefficient R^{+-} and the reflected beam polarization $P=(R^{++}/R^{+-}-1)/(R^{++}/R^{+-}-1)$ for a 150 nm cobalt layer on a silicon substrate and the glancing angle 1 mrad.

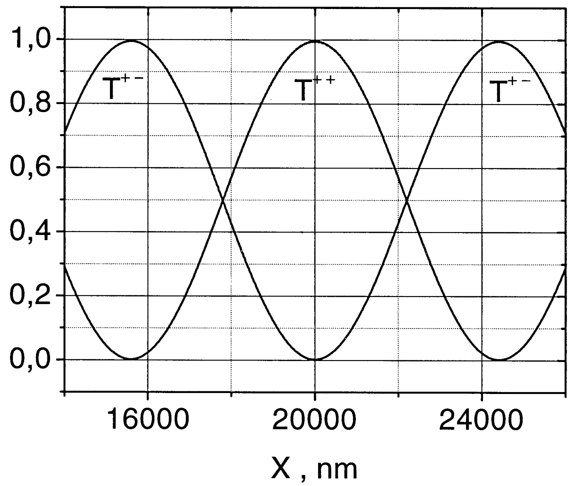

Fig. 5. The dependence of the transmission T^{++} of neutrons with the wavelength 1.53Å and the glancing angle 10 mrad through the structure Fe(100nm)/Bi(X)/Fe(200nm)/ Bi(20000nm)/Fe(100nm)/Si on the thickness of the bismuth layer X.

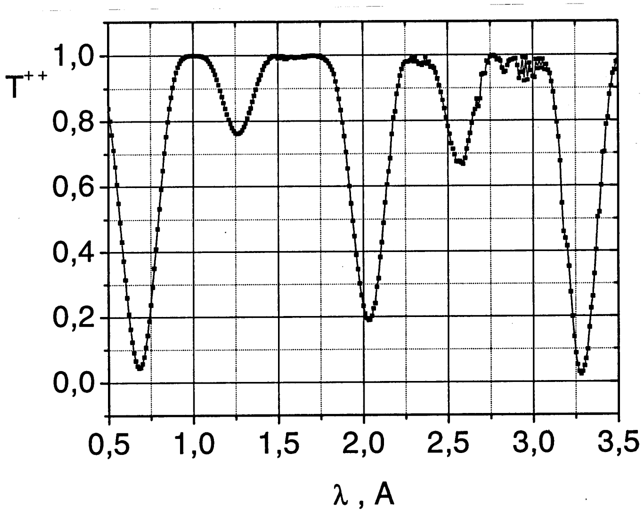

Fig.6. The wavelength dependence $T^{++}(\lambda)$ for the structure Fe(100nm)/ Bi(20000nm)/ Fe(200nm)/ Bi(20000nm)/Fe(100nm)/Si.

one structure, substrate/Fe(X)/Bi(Y)/Fe(Z/2)/sample/Fe(Z/2)/Bi(Y)/Fe(X)/substrate, which in fact is the spectrometer with the investigated sample.

Conclusion

Thus, it is theoretically shown that any element of the spin-echo spectrometer can be realized with the help of different layered structures. In this case, it is easy to vary the parameters of the spectrometer by changing the thickness of individual layers in the structure.

References

[1]. F. Mezei. Z. Phys. 255, 146 (1972).

[2]. R. Gahler and R. Golub. J. Phys. (Paris) 49, 1195 (1988); D. Dubbers et al.: Nucl. Instr. Methods A 275, 294 (1989).

[3]. R. Pynn, Lecture Notes in Physics (Springer, Berlin 1980, ed. by F. Mezei): 128, 170 (1980).

[4]. M. Th. Rekveldt. Nucl. Instr. and Meth. B 114, 366 (1996).

[5]. M. Th. Rekveldt. Physica B 276-278, 55 (2000).

[6]. T. Ebisava et al. J. Neutron Research 4, 157 (1996).

[7]. V.L. Aksenov, Yu.V. Nikitenko. Physica B 297/1-4, 101 (2001).

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Аксенов В.Л., Никитенко Ю.В. E14-2001-82
Слоистые структуры
как элементы спин-эхо-рефлектометра

Обсуждаются особенности отражения и пропускания нейтронов через магнитные слоистые наноструктуры. Показано, что слоистые магнитные наноструктуры могут быть использованы в качестве элементов или комбинаций элементов спин-эхо-рефлектометра.

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Aksenov V.L., Nikitenko Yu.V. E14-2001-82
Layered Structures as Elements
of the Neutron Spin-Echo Reflectometer

The specific features of neutron reflection and transmission through layered magnetic nanostructures are discussed. The possibility of using layered magnetic nanostructures as elements or combinations of the elements of the spin-echo reflectometer is demonstrated.

The investigation has been performed at the Frank Laboratory of Neutron Physics, JINR.

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