Polarization of a neutron beam on reflection from a magnetized mirror

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Attention is directed to the optimal conditions for obtaining a high polarization of a neutron beam on reflection from a ferromagnetic mirror. A polarizing mirror is described, prepared by thermal vacuum sputtering of alloys of TiGd and FeCo of optimal composition and thickness on a polished glass backing. The polarizing ability of a two-layer mirror obtained in this manner is close to 100% at the maximum of the reflection spectrum.

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One of the well-known and widely used methods of obtaining polarized beams of thermal neutrons is reflection of neutrons from magnetized ferromagnetic mirrors[1-5]. Mirror polarizers give a greater beam intensity compared with crystal polarizers, primarily because of the broad spectrum of the reflected beam and the large reflection coefficient $R \approx 1$.

The theory of specular reflection of neutrons is investigated in many papers[2-4] and in many experiments mirrors are used made of cobalt[2], iron[1] and Permendur[5]. As a rule these are mirrors made of ferromagnetic plates[5] or electrodeposited layers[2] with subsequent polishing of the surface. Due to imperfect polishing of a metallic surface the reflected beam is considerably broadened with respect to the incident one. If in the experiment one uses only a single reflection, for example, only from the polarizing mirror, and only the intensity integrated over the angle is of importance then such mirrors can be utilized successfully[2]. For small-angle scattering with angular resolution measured in minutes, and in cases when an analyzing mirror is utilized as well as a polarizer, a broadening of the beam on reflection is unacceptable. This is particularly important in a neutron guide with multiple reflection from mirror walls. The imperfect surface in this case greatly reduces the intensity of the transmitted neutrons, since the glancing angle θ on increasing after reflection can exceed the critical angle θ_c for the reflecting walls.

A polished glass surface is ideal in this sense[1] since it practically does not broaden the beam on reflection. A defect of the glass backing is the fact that when thin polarizing layers (less than a micron in thickness) are deposited on the glass the possibility is not excluded of reflection of neutrons from the glass and this makes the polarization deteriorate. Thicker layers in this case lose their point since they do not preserve the quality of the polished glass surface. It is also essential to realize that thin ferromagnetic layers are easily magnetized to saturation. This is important in order to obtain a high degree of polarization on reflection, since on reflection the neutron wave penetrates to a certain depth into the reflecting layer and depolarization is possible by the magnetic inhomogeneities associated with the incomplete magnetic saturation of the ferromagnetic.

With reference to the polarizing layer itself, it is ordinarily[2] considered to be sufficient that the magnetic scattering amplitude a_m should be not less than

Amplitude characteristics and absorption cross sections δ_a for materials used in the experiment.

Material* (metals)	a_n	a_m	a_n+a_m	a_n-a_m	σ_a, b
	10^{-12} cm				
Co	0.250	0.470	0.720	−0.220	1.4 (λ=1.08 Å)
Fe	0.950	0.600	1.550	0.350	21 (λ=1.08 Å)
^{54}Fe	0.420	0.600	1.020	−0.180	
50Fe 50Co	0.600	0.624	1.224	−0.024	
Ti	−0.330				3.5 (λ=1.08 Å)
Mn	−0.360				7.6 (λ=1.08 Å)
V	−0.050				2.8 (λ=2.8 Å)
Gd	1.500				49 000
Cd	0.380				2650

*For alloys both here and in the text concentrations are given in percentages by weight.

the amplitude of coherent nuclear scattering a_n. In such a situation the total amplitude

$$a_\pm = a_n \pm a_m, \tag{1}$$

where the plus and minus signs refer to the positive and negative spin states of the neutron, can also assume finite negative values, for example in the case of cobalt (cf., table).

Here it should be noted that the condition $a_- < 0$ is not sufficient for obtaining a high degree of polarization. The condition $a_- < 0$ corresponds to the reflection of a neutron wave from a negative potential "wall." As is well known from quantum mechanics[6] the coefficient of reflection from a potential "wall" is equal to

$$R = |(k_1 - k_2)/(k_1 + k_2)|^2, \tag{2}$$

where $k_1 = \hbar^{-1}\sqrt{2mE}$ (m and E are the mass and the energy of the neutron) is the propagation vector of the wave incident normally on the boundary of the "wall", while $k_2 = \hbar^{-1}\sqrt{2m(E-U)}$ is the propagation vector in the medium with potential energy U. From (2) it can be seen that there will be no reflection only in the case $k_1 = k_2$, i.e. when $U = 0$. For any negative value of U the coefficient of reflection $R \to 1$ as $k_1 \to 0$ since in this case $k_2 \to \hbar^{-1}\sqrt{2m|U|}$. For the case of reflection from a ferromagnetic mirror this means that R_- increases as the normal component $k_1 = K \sin\theta$ of the propagation vector K of neutrons incident at an angle θ to the surface decreases. Since it is practically impossible to prepare a reflecting material with $U_- = 0$ (i.e., $a_n = a_m$), it is not possible in principle to polarize a beam with arbitrarily small values of K and θ. However, by attaining in an experiment the smallest possible value of $|U_-|$, one can appreciably increase the polarizing ability of the mirror in the domain of long wavelengths and small θ.

The investigations carried out by us on the polarization of a neutron beam on reflection from thin ferromagnetic layers of different composition and the use of an absorbing substratum have enabled us to obtain a beam with a high degree of polarization over a wide range of wavelengths. At the same time the reflecting surface retained the quality of the polished glass utilized as the mirror backing.

DESIGN CALCULATIONS FOR A MULTILAYER MIRROR

When a neutron wave passes across a boundary between two media the propagation vector of the neutrons undergoes a change due to the different optical density of these media for neutrons. Figure 1 shows possible variants of such a change. Here K is the propagation vector of the neutrons in medium 1 incident at an angle θ to the separation boundary, while K′ is the propagation vector in medium 2 which makes an angle θ' with the separation boundary. The refraction of the neutron wave at the boundary of the two media is characterized by the index of refraction n_{12}:

$$n_{12}=\frac{n_2}{n_1}=\frac{K'}{K}=\frac{\cos\theta}{\cos\theta'}, \qquad (3)$$

where n_1 and n_2 are the indices of refraction of media 1 and 2 relative to vacuum which are determined by the scattering properties of the media and are a function of the neutron wavelength λ:

$$n_{12}^2=1-\lambda^2(N_2a_2-N_1a_1)/\pi, \qquad (4)$$

where $a_{1(2)}$ is the amplitude for coherent scattering, while $N_{1(2)}$ is the number of nuclei per unit volume of media 1 and 2. In investigating formula (2) in terms of λ and θ we dwell on three basic cases represented in Fig. 1.

In case I when $N_2a_2 - N_1a_1 > 0$ ($n_{12} < 1$) in medium 2 the angle θ' is always less than θ and can vanish for a certain positive value $\theta = \theta_c$. For $\theta \leq \theta_c$ the phenomenon of total specular or "internal" (in analogy with optics) reflection occurs.

For thermal neutrons the critical angle $\theta_c \ll 1$ and is equal to

$$\theta_c\approx\sin\theta_c=(1-n_{12}^2)^{1/2}=\lambda(N_2a_2-N_1a_1)^{1/2}/\sqrt{\pi}. \qquad (5)$$

A quantitative measure of specular reflection is the reflection coefficient $R = I/I_0$ which determines the fraction of reflected neutrons (I) with respect to the incident ones (I_0). For angles $\theta > \theta_c$ reflection diminishes with increasing θ in accordance with the expression[2]

$$R=\left|\frac{(n_{12}^2-1+\theta^2)^{1/2}-\theta}{(n_{12}^2-1+\theta^2)^{1/2}+\theta}\right|^2. \qquad (6)$$

In case III which occurs when $N_2a_2 - N_1a_1 < 0$ ($n_{12} > 1$), there exists no positive critical angle and R will be determined by expression (6) for all $\theta > 0$. Only in case II, when $N_2a_2 - N_1a_1 = 0$ ($n_{12} = 1$) is the coefficient of reflection equal to zero for neutrons of all wavelengths λ and for all glancing angles θ, as follows from (5) and (6). Case II is equivalent to the absence of a boundary between media 1 and 2, i.e., to the equation

$$n_1=n_2. \qquad (7)$$

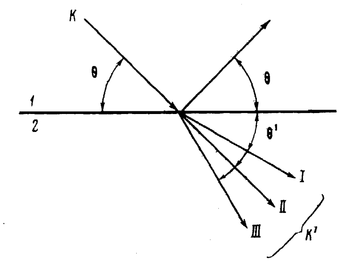

FIG. 1. Refraction of a neutron wave at the boundary between two media.

When neutrons are scattered by a magnetized ferromagnetic due to interference between nuclear and magnetic scattering which are characterized by the amplitudes a_n and a_m the effects of the interaction between the neutrons and the medium are characterized by the total amplitude $a_\pm$ (formula (1)). The expression for the magnetic amplitude has the form[2]

$$a_m=2\pi m\mu(B-H)/h^2N, \qquad (8)$$

where m and μ are the mass and the magnetic moment of a neutron, B is the magnetic induction in the ferromagnetic, H is the magnitude of the magnetizing field, h is the Planck constant. From expression (1) it follows that neutrons with parallel and antiparallel spin orientation will have different values of the refraction coefficients $n_{12+} \neq n_{12-}$ and different critical angles $\theta_{c+} > \theta_{c-}$, and this enables one to obtain a polarized beam on reflection from a magnetized ferromagnetic. Indeed, if $\theta_{c-} < \theta < \theta_{c+}$, then $R_+ > R_-$ and the polarizing ability of the mirror can be written in the form[2-4]

$$P=(R_+-R_-)/(R_++R_-). \qquad (9)$$

In order that the mirror be a good polarizer for a broad spectrum of neutrons over a wide range of glancing angles it is necessary to exclude completely the reflection from the ferromagnet of the antiparallel component of the neutron beam, and for mirrors with a thin ferromagnetic layer one should also exclude reflection from the backing, i.e., it is necessary to require R = 0. This can be accomplished only if condition (7) is satisfied for the antiparallel component of the beam:

$$n_{f-}=n_{\rm back}=n_{\rm Nac}=1, \qquad (10)$$

where n_f and $n_{\rm back}$ are the indices of refraction respectively at the vacuum-ferromagnet boundary and the ferromagnet-backing boundary.

When using a glass backing in order for condition (10) to be satisfied a special composition of the glass if required which would guarantee the vanishing of the average amplitude of coherent nuclear scattering a_n for the glass;

$$a_n=\sum_i a_{ni}C_i,$$

where a_{ni} and C_i are the coherent amplitude and the density of atoms of type i in the glass. Preparation of such a glass is possible in principle, but appears to be quite difficult. And glass produced industrially has a positive amplitude for coherent scattering $a_n \approx 0.3 \times 10^{-12}$ cm.

However, this problem can be solved by introducing an absorbing substratum situated between the glass backing and the ferromagnetic layer and having an index of refraction $n_{\rm subst} \approx 1$ with an accuracy up to the imaginary part Im n associated with a large absorption cross section. The imaginary part Im n gives rise to

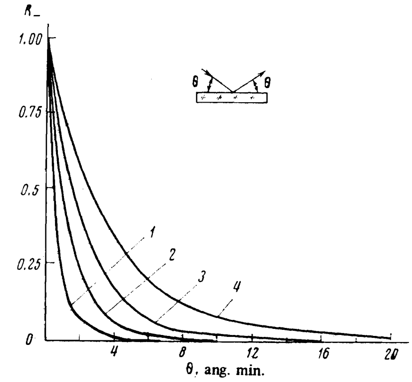

FIG. 2. Calculated dependence of the reflection coefficient R on the glancing angle θ for a 50Fe50Co alloy: curve 1—λ=3 Å, 2—λ=6 Å, 3—λ=10 Å and for Ti: curve 4—λ=6 Å.

a "metallic" reflection of neutrons and in the general case is an essential disadvantage of absorbing materials since it does not permit condition (10) to be completely satisfied.

It is possible to satisfy Eq. (10) for a polarizing layer, for example, by a FeCo alloy (with an appropriate concentration of Co) or by iron appropriately enriched in the isotope ^{54}Fe. Materials suitable for the substratum (on neglecting Im n) are alloys of highly absorbing substances such as gadolinium or cadmium with titanium, manganese or vanadium which have negative scattering amplitudes needed to cancel the positive amplitudes of gadolinium or cadmium (cf., table).

In order to estimate quantitatively how accurately must condition (10) be satisfied the coefficients R_- were calculated for $a_- = -0.024 \times 10^{-12}$ cm (this is the value of a_- for the incompletely compensated alloy 50Fe50Co) and for $a_- = -0.33 \times 10^{-12}$ cm (the amplitude for titanium) as a function of the glancing angle θ and for different λ. The results are shown in Fig. 2. From the diagram it can be seen that even for such small values as $a_- = -0.024 \times 10^{-12}$ cm considerable specular reflection of neutrons occurs at small angles. We note that for pure cobalt the value of a_- is bigger by a factor 10 ($a_- = -0.22 \times 10^{-12}$ cm) and $R_-^{Co}(\theta)$ will lie closer to curve 4. From Fig. 2 it can also be seen that in the case of incomplete cancellation of nuclear and magnetic amplitudes ($a_n < a_m$) reflection increases with increasing wavelength (curves 1—3), i.e., in this case for a fixed angle θ the long wavelength part of the spectrum will be polarized worse, and maximum polarization will be observed for neutrons reflected at large angles, i.e., near the critical angle θ_{c+}.

As materials for experimental mirrors we have chosen for the polarizing layer the alloy FeCo as a cheaper one compared to the isotopic mixture Fe^{54}Fe, and for the substratum we have chosen the TiGd alloy as having a high absorption cross section and good corrosion resistance.

At a value of B − H = 23500 G condition (10) is satisfied at a concentration of cobalt C(Co) = 46% by weight in the FeCo alloy and at a gadolinium concentration C(Gd) = 42% by weight in the TiGd alloy. Since the depth of penetration of neutrons into the reflecting medium in the case of total reflection is insignificant (of the order of 400 Å), the thickness of the ferromagnetic layer was assumed to be equal to δ = 1500 Å. The effective thickness of the substratum 60Ti40Gd which reduces the intensity of the incident beam by a factor of 200 is equal to δ = 2200 Å. These calculated values of the parameters of the layers were the starting points for the experimental optimization of the composition and the thickness of the layers in order to obtain maximum polarizing ability of the mirror. The layers were deposited sequentially by thermal vacuum sputtering of the FeCo and TiGd alloys on a glass backing[1]. At first the TiGd layer was optimized for minimum reflection, and then a layer of FeCo was deposited on the TiGd.

THE TECHNOLOGY OF MIRROR PREPARATION

A typical glass backing had the dimensions 210 × 50 × 5 mm. The high-quality glass surface was quite satisfactory for neutron mirrors since according to the data from our measurements a beam of angular width of approximately 30″ was practically not broadened on reflection. The curvature of the substratum did not exceed 25 Newton fringes per 100 mm.

The titanium-gadolinium substratum and the ferromagnetic layer were deposited by thermal vacuum sputtering. A diagram of the sputtering equipment is shown in Fig. 3. The backing 3 was placed in the heater 1 which was placed in the magnetic field of the permanent magnet 2. The value of the field was H = 250 Oe. The temperature of the backing at the beginning of the sputtering is 300°C. The sputtering of the TiGd-substratum and of the ferromagnetic layer was carried out from the tungsten spirals 5. The spirals for obtaining the FeCo layer were prepared by the method of electrolytic deposition of twenty alternating layers of iron and cobalt with a subsequent baking of the layers in hydrogen at a temperature of 700°C for two hours. In order to obtain the substratum a shaving of the TiGd alloy of the desired composition was placed into a clean tungsten spiral previously heated in hydrogen.

The volume underneath the bell jar was evacuated through the exhaust pipe 6 by means of a diffusion pump with a nitrogen trap with the bell jar heated to 60°C. Then the bell jar was cooled to a temperature of approximately 15°C. Sputtering began when a vacuum of 3 × 10^{-5} Torr had been obtained. With the shutter 4 closed the spiral was heated for degassing. Then the shutter was opened and the spiral was heated to the temperature of melting of the material being sputtered. After sputtering the mirror cooled in vacuo.

The spirals were weighed before and after sputtering. The length of the spiral was 250 mm with the mirror

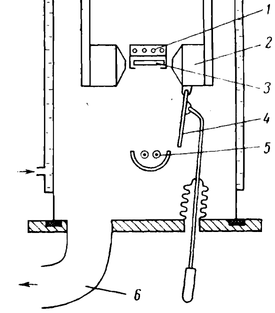

FIG. 3. Apparatus for vacuum sputtering: 1—heater, 2—magnet, 3—backing, 4—shutter, 5—tungsten spiral, 6—exhaust pipe.

being 210 mm in length. The distance from the spiral to the mirror was l = 145 mm. Such a geometry enabled us to obtain a film with uniformity with respect to thickness no worse than 30%. Under these conditions the deviation from the average thickness determined by weight δ_{av} amounted to +10% halfway along the length of the mirror and −20% at the edges of the mirror. The determination of the thickness of the layer at different areas of the backing with subsequent adjustment for the total weight of the sputtered material was carried out by means of weighing foils simulating the whole area of the mirror after sputtering. A check of the thickness of the layers on the mirrors by means of the interference microscope MII-4 showed good agreement with calculation, and this indicates that the density of the film was close to the density of the monolithic material.

TESTING OF MIRRORS

Testing of mirrors was carried out in the beam of the reactor VVR-M using the apparatus described in[1]. Diagramatically the apparatus is shown in Fig. 4. The beam was formed by the steel collimator 1 in the reactor channel producing an angle of divergence of 7′, and by additional cadmium slits 4,6 of variable width from 0.15 to 10 mm. For the polarizer 2 a calibrated mirror of 50Fe50Co was utilized. The mirrors under test were situated in place of the analyzing mirror 5. For a non-adiabatic reversal of the neutron spin with respect to the guiding magnetic field required for the measurement of polarization a spin-flipper was inserted between the polarizer and the analyzer. In order to measure the polarization in various parts of the spectrum a crystal spectrometer based on a GUR-4 goniometer was placed between the analyzer 5 and the detector 7. A lead single crystal 8 with the reflecting plane (111) was used as a monochromator. In order to calibrate the polarizing ability of the polarizing mirror two identical mirrors selected with the aid of a third one were introduced in place of the polarizer and the analyzer with the same glancing angle $\theta_P = \theta_A$. In this case the polarizing ability of the mirror was calculated from the relation

$$P_P = P_A = \sqrt{P_P P_A} = \sqrt{\varepsilon}, \quad \varepsilon = (I_+ - I_-)/(I_+ + I_-),$$

where ϵ is the directly measured polarization determined from the measurement of the intensity at the detector 7 when the flipper is switched on (I_+ when the flipper is switched off I_- when the flipper is switched on). The efficiency of the flipper was assumed to be equal to unity. The accuracy of the measurement of the polarization amounted to fractions of a percent near the maximum of the reflection spectrum. The dependence of the polarizing ability of the mirror undergoing the test on the glancing angle $P(\theta_A)$ was determined using a constant polarizer angle θ_P (with $\theta_A \le \theta_P$). The polarizing ability of the mirror under test was determined from the relation $P_A(\theta_A) = \epsilon(\theta_A)/P_P(\theta_P = \text{const})$ and this enabled us to carry out a relative comparison of mirrors under test without a precise determination of the absolute value of P_A.

For the determination of the reflection coefficient R of the mirror 5 we measured the intensity of the direct beam I_0 without a mirror and then the intensity of the beam I_1 reflected from the mirror 5. The reflection coefficient was calculated from $R = I_1/I_0$.

OPTIMIZATION OF THE TiGd-SUBSTRATUM

Since in the case of thermal sputtering a redistribution of the concentration of Ti and Gd is possible along the depth of the substratum deposited due to the difference in the pressure of their saturated vapors at the same temperature, the required concentration of Gd in Ti and the thickness of the substratum were determined experimentally. Mirrors were prepared from alloys of the following concentrations of Gd by weight in the material being sputtered: 2, 5, 10, 15, 20 and 40% of different thickness.

The mirrors under test were put in place of the analyzing mirror and the intensity of the reflected beam was measured for the same value of the glancing angle θ_A = 21′, and then the individual mirrors were tested for different values of θ_A. The results of these measurements are shown in Fig. 5 in the form of the dependence of the intensity of the reflected beam on the thickness of the TiGd layer for four concentrations by weight of gadolinium in the initial material. In Fig. 6a the dependence of the reflection coefficient on the glancing angle is shown for two mirrors.

From the analysis of the results obtained one can draw the following conclusions:

1) Qualitatively the angular dependence of the reflection coefficient $R(\theta)$ corresponds to the calculated one shown in Fig. 2.

2) An increase in the concentration of gadolinium in titanium at least up to 15–20% reduces the reflection from the substratum. The substratum with a gadolinium concentration of 40% (the concentration was calculated with the aid of (10)) has a reflection coefficient larger by a factor of 1.5–2 than in the case of a 15% concentration (Fig. 6a).

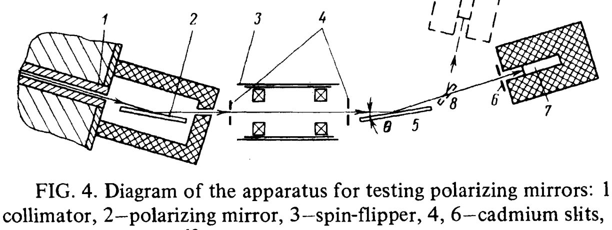

FIG. 4. Diagram of the apparatus for testing polarizing mirrors: 1—collimator, 2—polarizing mirror, 3—spin-flipper, 4, 6—cadmium slits, 5—analyzing mirror, 7—$^{10}BF_3$ detector, 8—crystal-monochromator of the spectrometer.

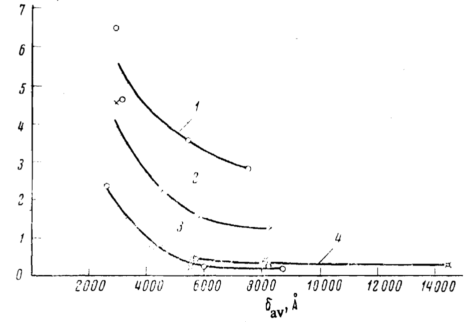

FIG. 5. Dependence of the intensity I of beams reflected at a glancing angle of θ=21′, on the thickness of the film for Ti-Gd mirrors of different compositions: 1—98Ti2Gd, 2—95Ti5Gd, 3—85Ti15Gd, 4—60Ti40Gd.

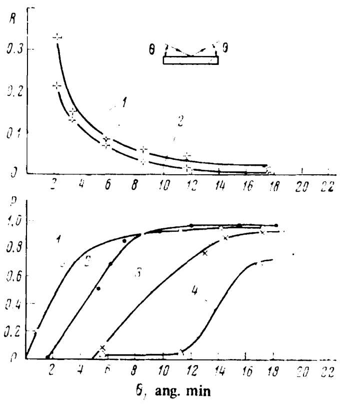

FIG. 6. a) Dependence of the reflection coefficient on the glancing angle: 1—for a 60Ti40Gd mirror, 2—for a 85Ti15Gd mirror. b) Dependence of the polarizing ability on the glancing angle. Composition of the ferromagnetic layer with a 85Ti15Gd substratum: 1—40Fe60Co, 2—50Fe50Co, 3—54Fe46Co and without a substratum: 4—50Fe50Co.

3) As the thickness of the substratum δ is increased the reflection coefficient R ceases to depend on the thickness, and this testifies that the range of δ selected for the test is adequate and that it is possible to choose an optimal thickness (a minimal thickness in the present case) which guarantees a minimum reflection coefficient. A thickness of $\delta \geq 6000$ Å is satisfactory.

We recall that the calculated concentration by weight in accordance with (10) amounted to 42%, while the thickness of the substratum for a 58Ti42Gd mirror was equal to $\delta = 2200$ Å under the condition that the incident beam intensity is reduced by a factor of 200. If an experimental increase in the thickness by a factor of 2.7 compared to the calculated value can be explained by a decrease in the concentration of Gd by a factor of 2.8 (in the optimum case), then a considerable diminution of the concentration itself (C (Gd) = 15% by weight) compared to the calculated value is explained apparently by the fact that condition (10) does not take into account the contribution of the "metallic" reflection due to the large absorption cross section of gadolinium.

In order to carry out further investigations we have assumed that the substratum of TiGd with a concentration of C(Gd) = 15% by weight in the initial alloy has been optimized when the thickness of the substratum is $\delta = 6000$ Å.

OPTIMIZATION OF THE POLARIZING LAYER

Layers of the alloy FeCo of thickness 1500 Å with different concentrations of Co near the calculated one C(Co) = 46% were deposited on the optimized coatings of TiGd. Results for some values of C(Co) are shown in Fig. 6b in the form of the dependence of the polarization of the reflected beam on the glancing angle. In making the measurements a neutron beam with $\lambda \geq 3$ Å has been utilized. From the diagram it can be seen that the optimum concentration of Co in the initial alloy differs from the calculated one. Apparently, this is associated with a redistribution of the concentrations of iron and cobalt in the sputtered layer compared with the original alloy. Even for the concentration C(Co) = 50% $P \to 0$ down to an angle of $\theta = 1.5'$, and this testifies to the existence of a positive critical angle $\theta_{c-} = 1.5'$, i.e., to an incomplete cancellation of a_n and a_m. In this case $a_n > a_m$ while the calculated value of $a_n - a_m = -0.024 \times 10^{-12}$ cm. Of all the coatings investigated that layer appears to be the best which has been sputtered from an alloy with a concentration of C(Co) = 60% by weight.

Figure 6b also shows the effectiveness of the action of the TiGd-substratum. Curve 4 corresponds to the polarization of a beam reflected from a layer of 50Fe50Co of thickness $\delta = 1500$ Å deposited on glass without a TiGd-substratum. It can be seen that $P \to 0$ already for an angle $\theta = 12'$, equal to the critical angle for glass. For mirrors with a TiGd substratum over a wide range of angles θ the polarization of the beam is at a level of 0.95—0.97. This is the average polarization over the spectrum of the neutron beam.

From Figs. 6a and 6b one can see the correlation between the polarization and the magnitude of the reflection of neutrons from the substratum. In the case of such a functional dependence $R_-(\theta)$, as has been noted earlier, the long wavelength part of the spectrum must have a lower degree of polarization. This affects the average polarization of the beam. The spectral distribution of polarization in the range $\lambda = 3.5$—5 Å measured by the crystal spectrometer is shown in Fig. 7 for a 50Fe50Co mirror. From the diagram it can be seen that the intensity of the reverse component of the beam I_- does not stand out above the background. Estimates taking experimental error into account show that polarization of neutrons for $\lambda = 4$ Å amounts to P = 1.00—0.01, while for $\lambda = 5$ Å it is equal to P = 1.00—0.03.

CONCLUSION

The results of the experiments that have been carried out have shown that the use of a thin absorbing substratum and the optimization of the polarizing layer make it possible to produce a high efficiency polarizing mirror with a thin ferromagnetic layer on a glass backing and to obtain highly polarized beams of thermal, cold and ultracold neutrons. In preliminary experiments with ultracold neutrons a polarization P > 70% has been obtained for $\lambda = 700$—800 Å using the mirrors described above. On the basis of experimental mirrors a working model of a polarizing neutron guide has been produced with an efficiency averaged over the spectrum of P = 0.97—98 and with transmission close to unity for $\lambda \geq 2.7$ Å. We are also continuing experiments with the aim of a more complete optimization of the layers and a reduction of "metallic" reflection, which would enable us to increase the polarization of neutrons reflected at small angles. This problem is a pressing one in experiments utilizing polarized cold and ultracold neutrons.

In conclusion we consider it our pleasant duty to

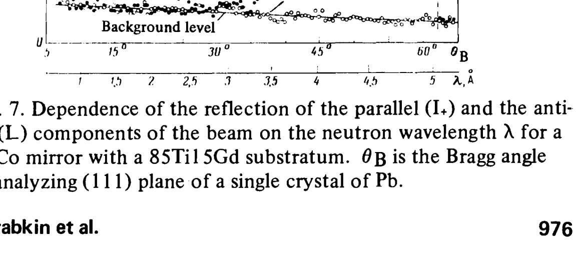

FIG. 7. Dependence of the reflection of the parallel (I_+) and the antiparallel (I_-) components of the beam on the neutron wavelength λ for a 50Fe50Co mirror with a 85Ti15Gd substratum. θ_B is the Bragg angle for the analyzing (111) plane of a single crystal of Pb.

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[1)]During the first stages of this work the experimental samples of the mirrors were prepared for us by the Khar'kov Polytechnical Institute.

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