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A FAN ANALYZER OF NEUTRON BEAM POLARIZATION ON THE SPECTROMETER REMUR AT THE PULSED REACTOR IBR-2

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Веерный анализатор поляризации нейтронного пучка
на спектрометре РЕМУР реактора ИБР-2

В Лаборатории нейтронной физики им. И. М. Франка (ОИЯИ, Дубна) создан и введен в эксплуатацию новый спектрометр поляризованных нейтронов РЕМУР. Он предназначен как для проведения исследований многослойных структур и поверхностей путем регистрации отражения поляризованных нейтронов, так и для исследования неоднородного состояния твердого тела путем регистрации малоуглового рассеяния поляризованных нейтронов. Спектрометр работает в интервале длин волн нейтронов $1{,}5 \div 10$ Å и оснащен линейным позиционно-чувствительным детектором и сфокусированным суперзеркальным анализатором поляризации (веерный анализатор поляризации) с телесным углом регистрации поляризованных нейтронов $2{,}2 \cdot 10^{-4}$ рад. В данной работе описаны принцип работы и конструкция веерного анализатора поляризации нейтронов, а также приведены результаты его испытаний на поляризованном пучке нейтронов.

Работа выполнена в Лаборатории нейтронной физики им. И. М. Франка ОИЯИ.

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A Fan Analyzer of Neutron Beam Polarization on
the Spectrometer REMUR at the Pulsed Reactor IBR-2

The new spectrometer of polarized neutrons REMUR has been created and put in operation at the Frank Laboratory of Neutron Physics (JINR, Dubna). The spectrometer is dedicated to investigations of multilayer structures and surfaces by registering the reflection of polarized neutrons and of the inhomogeneous state of solid matter by measuring the small-angle scattering of polarized neutrons. The spectrometer's working range of neutron wavelengths is $1.5 \div 10$ Å. The spectrometer is equipped with a linear position-sensitive detector and a focused supermirror polarization analyzer (the fan-like polarization analyzer) with a solid angle of polarized neutron detection of $2.2 \cdot 10^{-4}$ rad. This paper describes the design and the principle of operation of the fan analyzer of neutron polarization together with the results of the fan tests on a polarized neutron beam.

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

Preprint of the Joint Institute for Nuclear Research. Dubna, 2004

INTRODUCTION

Neutron reflectometry as a method for the investigation of surfaces by specular neutron reflection came into existence in the 1980s [1]. Its specific feature is the use of a well-collimated neutron beam. For example, for 1.8 Å thermal neutrons the angular divergence of the beam is usually $0.1 \div 0.3$ mrad. It means that for the glancing angle of the order of $3 \div 10$ mrad the relative deviation is $1 \div 10\%$. This explains why neutron polarizers and neutron polarization analyzers with magnetic mirrors employing specular neutron reflection [2] have come into a wide use in the neutron experiment. The creation of structures with perfect interfaces in recent years has brought forward the necessity of registration of polarized neutron diffuse scattering. In this connection, the development and construction of polarization analyzers with a neutron transmission cross section of some tens or hundreds square centimeters are of great importance.

A conventional analyzer on the basis of a magnetic supermirror [3] is a stake of parallel mirrors whose planes are perpendicular to the interface of the investigated structure. However, the solid angle of neutron beam capture is not matched with the angular divergence of the reflected beam. As a result, the analyzer has a low luminosity (transmission capability).

This paper describes the supermirror polarization analyzer (a fan analyzer) of the REMUR spectrometer [4] that has a high neutron transmission capability due to the fact that its mirrors are focused and oriented to be parallel to the surface of the investigated sample.

For completeness sake, it should be noted that a bent fan analyzer built in a somewhat different geometry is described in [5].

1. A FAN POLARIZATION ANALYZER

Below, the issues of substantiation, calculation and testing of the fan polarization analyzer are discussed.

1.1. Direct and Bent Neutron Guide Channels. The developed neutron beam polarization analyzer is for analysis of the polarization of the diffusely scattered neutrons and is made as a stake of mirrors. A separate element of the mirror stake is a neutron guide made from two mirrors. The neutrons reflected from the mirrors propagate in the space between them. There exist straight and bent neutron guides.

A straight neutron guide with parallel mirror walls is characterized by the length L, the distance between the mirrors d and the density of the neutron scattering amplitude on the mirror wall material $\sigma = Nb/2\pi$, where N is the density of atoms in a unit volume, b is the neutron scattering amplitude on the nucleus. The most important characteristic of the polarization analyzer is a minimum neutron wavelength at which it operates effectively. In analyzer with mirror neutron guides it is the critical wavelength corresponding to the neutron reflection boundary from the mirror. For the mean glancing angle of a single neutron reflection in the neutron guide $\theta = d/L$, the critical neutron wavelength $\lambda_{\rm cd} = \theta/\sigma^{1/2} = d/(L\sigma^{1/2}) \propto 1/S$, where S is the total area of the mirror surface.

A bent neutron guide is, in addition, characterized by the radius of curvature $\rho = L_{\rm d}^2/8d$, where $L_{\rm d} \approx L$ is the direct vision length. The critical wavelength of the bent neutron guide $\lambda_{\rm cc} = 4d/(L_{\rm d}\sigma^{1/2})$ [6]. It is seen that for $\lambda_{\rm cd}$ equal to $\lambda_{\rm cc}$, the length of the bent neutron guide is four times larger than that of the straight one. As a result, the area of the mirror surface in the bent neutron guide is four times larger than that in the straight one. To effectively increase σ and, as a result, decrease the critical wavelength, a real mirror is a compound multilayer structure (called a supermirror [7, 8, 9]). The laboriousness of supermirror coating production, which is proportional to the surface area of the mirror, determines the cost of the polarization analyzer. This was a decisive argument for the construction of the analyzer as a system of straight neutron guides (in the form of a straight stake of mirrors).

1.2. The Orientation of Neutron Guide Channels. There are two orientation geometries of mirrors in the polarization analyzer. In the perpendicular geometry the mirrors are perpendicular (the geometry is further referred to as ANG) and in the parallel geometry, they are parallel (the geometry is further referred to as APG) to the plane of the investigated structure. Let us show the principle difference between them. Let the angular divergence of the neutron beam be defined through mean square deviations of the angle determining the neutron propagation direction in the vertical plane as $\delta\theta_{\rm v}$ and in the horizontal plane as $\delta\theta_{\rm g}$. On the sample, $\delta\theta_{\rm gs} \approx 0.1 \div 0.3$ mrad and $\delta\theta_{\rm vs} \approx 1 \div 10$ mrad. The analyzer in the ANG geometry transmits the neutron beam with a divergence in the horizontal plane of the order of 100 mrad and a divergence in the vertical plane of the order of 1 mrad. As a result, the analyzer decreases the divergence of the beam in the vertical plane by an order of magnitude (the exact value depends on the geometric parameters) and consequently, decreases the luminosity of the measurement. The analyzer in the APG geometry does not practically change the divergence of the beam transmitted though it and reflected on the sample.

Let us obtain a more correct estimate of the luminosity gain in APG compared to ANG. For ANG, the product of the analyzer transmission cross section area S_a by the solid angle of the sample $\Omega_{\rm s}$ is $T_{\rm ANG} = S_{\rm a}\ \Omega_{\rm s} = S_{\rm s}\delta\theta_{\rm a}(Y_{\rm a}/L_{\rm sa})$, where $S_{\rm s} = Y_{\rm s}Z_{\rm s}$ is the cross section area of the sample, $S_{\rm a} = Y_a Z_{\rm a}$ is the cross section area of the analyzer, Y_s and $Y_{\rm a}$ are the dimensions of the sample and analyzer in the direction of the y-axis, respectively, $Z_{\rm s} = L_{\rm s} \sin(\theta)$ and $Z_{\rm a}$ are the effective dimensions of the sample and of the entrance window of the analyzer in the direction perpendicular to the plane of the sample (z-axis), $L_{\rm s}$ is the length of the sample, $L_{\rm sa}$ is the sample to analyzer distance, $\delta\theta_{\rm a}$ is the mean square deviation of the glancing angle for which the mirror in the analyzer works effectively. For the APG geometry, $T_{\rm APG} = S_{\rm a} S_{\rm s}/L_{\rm sa}^2$.

The luminosity gain is a factor of $\beta = T_{\rm APG}/T_{\rm ANG} = Z_{\rm a}/(\delta\theta_{\rm a} L_{\rm sa})$. Let us define $\delta\theta_{\rm a}$ as $d/4L$, then $\beta = 4Z_{\rm a}L/(dL_{\rm sa})$. For the REMUR analyzer $Z_{\rm a} = 120$ mm, $L = 260$ mm, $d = 0.95$ mm, $L_{\rm sa} = 4400$ mm and $\beta = 29$. It is seen that the gain grows with increasing $Z_{\rm a}$ and decreasing $L_{\rm sa}$. The parameter L/d is fixed and is proportional to the critical neutron wavelength for a given mirror. It is obvious that for a smaller critical neutron wavelength, i.e., for a better «quality» supermirror, the luminosity gain is smaller.

1.3. The Calculation of the Parameters. Figure 1 shows the arrangement geometry of one neutron guide channel of the analyzer with respect to the sample of the length $L_{\rm s}$ from point B to point P with the center in point O. Let us introduce the radius-vector R directed from point O ($BO = OP$) to point $M(MD = CM)$ so that $OM\perp$ ($CD \equiv h_{\rm ai}$ is the dimension of the neutron guide channel at the entrance). In the calculation of the analyzer the determining condition is that neutrons leaving the sample are reflected from the neutron guide side EC. Let us determine the angles α between the lengths PDE and EC and $\alpha + \Delta\alpha$ between BC and CG (or CF and EC). Let us write a system of interconnected relationships determining the characteristic dimensions of the analyzer.

$$MN = R - L_{\rm s}\cos(\theta_{\rm f})/2, \quad AC = [MN^2 + (h_{\rm ai} - L_{\rm s}\sin(\theta_{\rm f})/2)^2]^{1/2},$$

$$BC = [(MN)^2 + (h_{\rm ai} - L_{\rm s}\sin(\theta_{\rm f})/2)^2]^{1/2},$$

$$PD = [(MN + L_{\rm s}\cos(\theta_{\rm f}))^2 + (h_{\rm ai} + L_{\rm s}\sin(\theta_{\rm f})/2)^2]^{1/2},$$

$$PC^2 = l_{\rm a}^2 + PE^2 = 2l_{\rm a}\cdot PE\cdot\cos(\alpha), \quad ED = PE - PD,$$

$$h_{\rm ai}^2 = l_{\rm a}^2 + ED^2 - 2l_{\rm a}\cdot ED\cdot\cos(\alpha),$$

$$\Delta\alpha \approx (h_{\rm ai}/R)\cdot[1 + L_{\rm s}\sin(\theta_{\rm f})/h_{\rm ai}]\cdot[1 + L_{\rm s}\cos(\theta_{\rm f})/2R].$$

It is seen that $\Delta\alpha$, which determines the divergence of the incident neutron beam, increases with increasing Z-dimension of the neutron beam on the sample $Z_{\rm s} = L_{\rm s}\sin(\theta_{\rm f})$. Note that the analyzer can «operate» in the mode of single or multiple neutron reflection from the walls of the channel. The modes differ by beam divergence at the entrance of the analyzer. The divergence is smaller in single reflection. In fact, in the case of single reflection the angular range of changes in the direction of the neutron beam coming out of the analyzer is $\Delta\beta = \Delta\alpha$ while in multiple reflection, it can reach $\Delta\beta = 2\Delta\alpha$. Meanwhile, $\Delta\beta$

determines the spatial resolution of the neutron detector with an analyzer in front of it. Let us determine the limit of $\Delta\beta$ that depends on the allowed decrease of spatial resolution. If the neutron flux at the entrance of the analyzer is isotropic, the spatial resolution of the detector with an analyzer $\Delta z = [\Delta z_{\rm det}^2 + h_{\rm ao}^2 + (\Delta\beta L_{\rm an,det})^2/3]^{1/2}$, where $\Delta z_{\rm det}$ is the own spatial resolution of the detector, $L_{\rm an,det}$ is the analyzer to detector distance, $h_{\rm ao}$ is the exit dimension of the analyzer channel. Let the decrease in the resolution of the detector with an analyzer be not higher than 30%, i.e., there fulfils the condition $(\Delta z/\Delta z_{\rm det})^2 = \{1 + [h_{\rm ao}^2 + (\Delta\beta L_{\rm an,det})^2/3]/\Delta z_{\rm det}^2\} = 1.69$. For the known resolution of the detector $\Delta z_{\rm det} = 1.5$ mm [10], the technically executable minimum $L_{\rm an,det} = 7$ cm and the chosen $h_{\rm ao} = 1$ mm, we obtain $1 + (\Delta\beta L_{\rm an,det})^2/3 = 1.55$, that gives $\Delta\beta \approx 18$ mrad. In connection with the above said it is clear that the single reflection mode allows, in principle, having a better resolution. Due to design constraints, however, the single reflection mode can be only realized at small $\Delta\alpha \ll 18$ mrad. The design constraints are due to that $(h_{\rm ai} + h_{\rm w})/(h_{\rm ao} + h_{\rm w}) = R/(R + L)$ and $h_{\rm ai}/h_{\rm ao} = \alpha/(\alpha + \Delta\alpha)$, where $h_{\rm w}$ is the guide channel wall thickness. If it is chosen that $R = 4400$ mm, $L = 250$ mm, $h_{\rm w} = 0.3$ mm and $h_{\rm ao} = 1$ mm, $h_{\rm ai} = 0.93$ and $\alpha/(\alpha + \Delta\alpha) = 0.93$. At the same time, $\alpha + \Delta\alpha$ must not be larger than the critical glancing angle of the supermirror used equal to 3.3 mrad for the neutron wavelength $\lambda = 1$ Å. In the REMUR spectrometer, where the minimum neutron wavelength is chosen equal to 1.35 Å, we have $\alpha + \Delta\alpha \approx 4.5$ mrad and $\Delta\alpha = 0.31$ mrad. The value of $\Delta\alpha = 0.31$ mrad corresponds to $z_{\rm s} = L_{\rm s}\sin(\theta_{\rm f}) = 0.48 h_{\rm ai} \approx 0.45$ mm, that results in the maximum outgoing glancing angle on the sample $\theta_{\rm f,max} \approx 22.5$ mrad for a 20 mm length sample (characteristic dimension of a high-quality sample). The small value of $\theta_{\rm f,max}$, that corresponds to single neutron reflection in the analyzer, makes it unsuitable for the registration of the diffusely scattered neutrons. Thus,

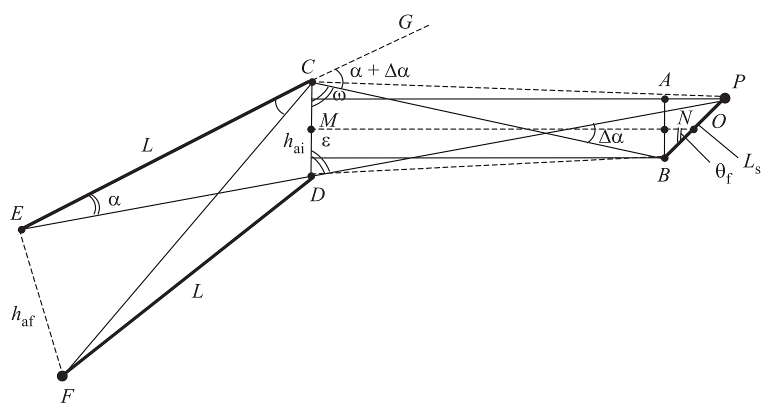

Fig. 1. The sample to analyzer inter-positioning layout

the conclusion follows that the analyzer should work in the multiple neutron reflection mode.

So, from the above said it follows that in the multiple reflection mode $\Delta\alpha$ reaches a value of 9 mrad, but $\Delta\alpha$ is limited by a value of 4.5 mrad due to that the minimum wavelength is 1.35 Å. For $\Delta\alpha = 4.5$ mrad we have $z_{\rm s} \approx 3.24$ mm, which results in $\theta_{\rm f,max} \approx 0.2$ rad for a sample 20 mm long. Thus, if the minimum wavelength is 1.35 Å, the analyzer can be used effectively to detect diffuse scattering in the multiple reflection mode with the resolution of the detector reduced by not more than 30%. It is obvious that if the wavelength is larger than 1.35 Å, the exit glancing angle of the reflected neutrons can be even larger.

1.4. Experimental Characteristics. The fan analyzer of polarization is assembled of 94 supermirrors. The analyzer has a focal length of 4400 mm and an entrance window cross section of 120 (horiz.) $\times$ 40 (vert.) mm^2. The critical neutron wavelength is 1.35 Å. A supermirror is a glass plate measuring $250 \times 60 \times 0.3$ mm^3 onto which neutron absorbing and reflecting layers are ap-

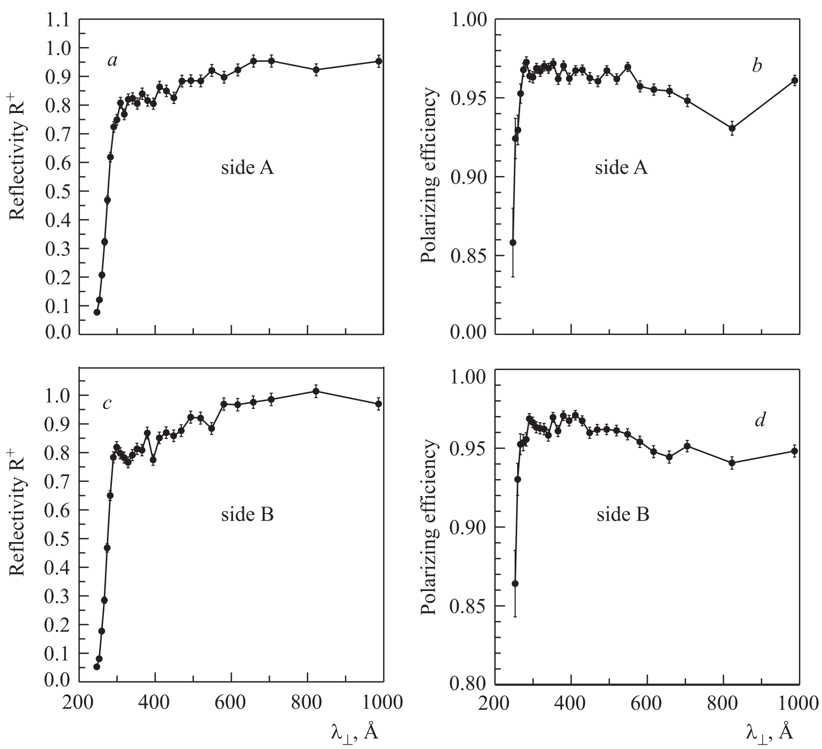

Fig. 2. The reflection coefficient of the «+» neutron spin component (*a, c*) and the polarization efficiency (*b, d*) for two sides of the supermirror in dependence on the perpendicular wavelength $\lambda_\perp$

plied. An absorbing layer is the TiZrGd layer 250 nm thick. A reflecting layer is a multistructure with alternating FeCoV and TiZr layers (55 pairs) whose thickness varies in a certain way.

Figure 2 shows the dependence curves of the reflection coefficient of the «+» neutron spin component (Fig. 2, *a, c*) and of the polarization efficiency (Fig. 2, *b, d*) on the «perpendicular» wavelength $\lambda_\perp = \lambda/\theta$ for the first (Fig. 2, *a, b*) and the second (Fig. 2, *c, d*) sides of the supermirror the analyzer is made from. There were carried out measurements of monochromatic neutrons with the wavelength 1.435 Å. It is seen that the characteristics of the two sides of the mirror are practically coinciding. At the same time, for a critical wavelength at which the neutron reflection coefficient starts decreasing sharp a value of $\lambda_{\perp,\mathrm{c}} = 300$ Å is obtained. As $\lambda_\perp$ further increases and reaches a value of 500 Å the polarization efficiency start to decrease, that reflects an increase in the reflection coefficient of the «−» neutron spin component.

The experimental investigation of the analyzer was conducted on the REMUR spectrometer. The analyzer was placed on a platform with an axis of rotation. On the axis there was a 0.5 mm wide diaphragm for neutron beam focusing. To determine the focal distance and find out whether the characteristics of the analyzer are homogeneous, the integral neutron counts over the wavelength interval $1.4 \div 7$ Å, j_{on} and j_{off} were measured with a spin-flipper on and off, respectively. In Fig. 3 there is presented the polarization ratio of neutron counts $\eta = j_{\mathrm{off}}/j_{\mathrm{on}}$ in dependence on the detector rotation angle γ for the on-the-left, in-the-center and on-the-right situations of the beam on the analyzer and the analyzer-to-neutron focusing diaphragm distances of 4.15, 4.45 and 4.95 m. Note that on the detector

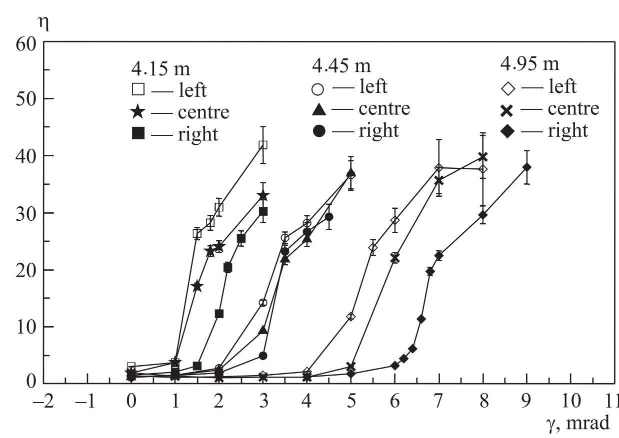

Fig. 3. The polarization ratio of the neutron counts in dependence on the analyzer rotation angle for the on-the-left, in-the-center and on-the-right situations of the neutron beam on the analyzer and the analyzer-to-neutron beam focusing diaphragm distances of 4.15, 4.45 and 4.95 m

the beam has a width of 14 mm. It is seen that the curves corresponding to the distance of 4.45 m are practically coinciding. This confirms that the focal distance of the analyzer is really close to 4.4 m.

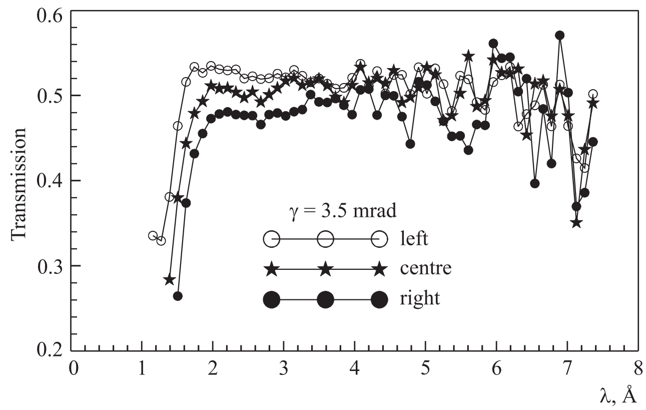

Fig. 4. The transmission of the sections of the analyzer on the left side from the center, in the center and on the right side from the center as a function of the neutron wavelength

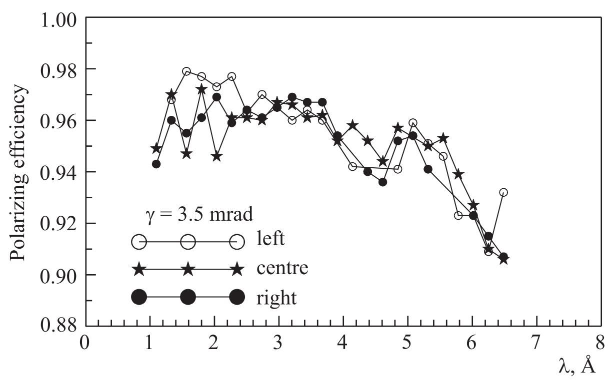

Fig. 5. The polarization efficiency of the sections on the left side from the center, in the center and on the right side from the center of the analyzer for the diaphragm-to-analyzer distance equal to the focal distance as a function of the neutron wavelength

Figure 4 depicts the curves of the transmission dependence on the wavelength for the sections of the analyzer to the left of the center, in the center and to the right of the center. It is seen that on-the-left transmission is larger than on-the-right one by about 10%. This, as is established, is explained by that that the channels are more densely packed on the right because the assembling of the detector begins from the first channel.

In Fig. 5 there are presented the curves of the wavelength dependence of the polarization efficiency of the analyzer $P\ (\lambda) = (\eta - 1)/(\eta + 1)$ for the section to the left of the center, in the center and to the right of the center of the analyzer for the diaphragm-to-analyzer distance equal to the focal distance of the diaphragm. Quite good coincidence of the curves is observed, which evidences of the expected homogeneity of the polarization efficiency of the analyzer channels.

In conclusion, it should be noted that to conduct precise polarization analysis (with an accuracy better than 1%) or absolute measurements of the reflection coefficients (with an accuracy better than 5%) of the diffusely scattered neutrons, it is necessary to perform per-channel measurements of the transmission and the polarization efficiency of the analyzer. The characteristics of the analyzer must be measured anew with a sample whose dimensions are considerably changed.

The analyzer was tested on the new polarized neutron spectrometer REMUR in the course of measurements to investigate the effect of superconductivity on the magnetic profile in a Fe/V ferromagnetic layered structure [12] and it demonstrated a high registration efficiency of the diffuse scattering of polarized neutrons on the structure interfaces.

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