объединенный
институт
ядерных
исследований
дубна

E13-93-67

Yu.V.Nikitenko

POSSIBILITIES OF CREATING WIDE-SPECTRUM NEUTRON POLARIZER FOR PULSED NEUTRON SOURCES

Submitted to «Nuclear Instruments and Methods»

1993

1. Introduction

Polarizers based on the reflection of neutrons from a magnetized mirror (a mirror polarizer) are now integral parts of most neutron laboratories in the World, in which studies with polarized thermal and slow neutrons are performed. Especially widespread are curved Soller polarizers [1]. However, the band of wavelengths corresponding to the effective operation of such polarizers in the case of pulsed neutron sources is insufficient. So the creation of a wide-spectrum neutron polarizer is a very important task. Actually, additional possibilities of fulfilling this task exist precisely in the case of a pulsed neutron source. This is due to neutrons of differing wavelengths being distinguishable from each other by their times of flight from the source to the polarizer. As a result it becomes possible to exert time-dependent influence on neutrons of differing wavelengths. In ref. [2] this possibility has been realized by variation with time (and, consequently, in proportion to the wavelength) of the inclination angle of the stack of flat mirrors relative to the direction from the polarizer to the user of neutrons. Estimations show that in this way one can extend the band of wavelengths for effective operation of the polarizer and make it several times wider. Owing to the inclination angle being small, however, such a polarizer can be utilized in the easily realized mode of constant uniform motion only with sources exhibiting a low pulse repetition frequence f (f = 1 Hz). On the other hand, in the case of neutron sources with high frequencies the polarizer must undergo acceleration during inoperative time intervals, which gives rise to additional difficulties.

In this work various versions are described of a wide-spectrum mirror neutron polarizer, in which uniform rotation of a set of magnetized mirrors is implemented.

2. Physical prerequisites

In the case of a mirror polarizer there exists for neutrons of a given wavelength incident upon the surface of the magnetized mirror a range of grazing angles, $[\theta_{min}, \theta_{max}]$, for which the polarization exceeds a certain fixed value P_{min}. Thus, for example, the $\theta_{max}/\theta_{min}$ ratio is of the order of two for $P_{min} = 0.92$, in the case of the supermirror described in ref. [3].

The process of neutron reflection from a medium is usually decribed with the aid of an interaction potential U [4], which is, generally, a complex quantity. The difference between the potentials for the two spin states (we shall denote them by "+" and "-", respectively) of a neutron in a magnetic field results from the presence of a magnetic interaction potential U_m between the neutron and the magnetic field:

$$U_{\pm} = U_n \pm U_m , \qquad (1)$$

where U_n is the neutron-nucleus interaction potential.

In the case of a mirror polarizer, representing a multilayer structure, the interaction potential depends on the coordinate in the direction normal to the surface of the mirror. Here, the reflection coefficient $R_{\pm}$ is determined by the dependence of $U_{\pm}$ and by the kinetic energy related to the neutron motion normal to the surface of the mirror. Hence, the boundary angles θ_{min} and θ_{max} may be represented in the form:

$$\theta_{min} = \theta_{min1} \cdot \lambda , \qquad \theta_{max} = \theta_{max1} \cdot \lambda , \qquad (2)$$

where θ_{min1} and θ_{max1} are functions of P_{min} and of the interaction potentials U_+ and U_-.

Now, let us fix the direction towards the user by the grazing angle θ_u. Obviously, the polarizer will be effective, i.e. will provide for the neutron beam exhibiting a polarization $P > P_{min}$ within the given range of wavelengths, if the following condition is satisfied:

$$\theta_{min} + \delta\theta < \theta_{u} < \theta_{max} - \delta\theta \ , \qquad (3)$$

where $\delta\theta$ is the deviation of the grazing angle due to various reasons.

In the case of a pulsed source condition (3) must hold for the time interval during which the neutrons within the range of wavelengths between λ_{min} and λ_{max} pass through the polarizer.

Condition (3) can be satisfied in two cases. The first is realized if the following holds:

$$\theta_{u} \pm \delta\theta = \alpha t \ , \qquad (4)$$

where $\theta_{min}/t < \alpha < \theta_{max}/t$, $t = mL_{1}(\lambda-\lambda_{min})/h$ is the time the neutron of wavelength λ arrives at the polarizer, at a distance L_{1} from the source, m is the neutron mass, h is Planck's constant.

The second case occurs when a constant angle θ_{u} is realized. To this end the following must be satisfied:

$$\theta_{min1} \propto t^{-1} \quad \text{and} \quad \theta_{max1} \propto t^{-1} \qquad (5)$$

Now, consider the possibility of conditions (4) and (5) being satisfied by the polarizer being set into motion. In this connection we shall first consider the features peculiar to the passage of a neutron through the elements of a moving mirror polarizer.

In Fig. 1a the scheme is shown of a neutron of velocity V_{n} undergoing reflection from a mirror travelling in a direction normal to its surface with a velocity $V_{m\perp}$. When the velocity $V_{m\perp}$ is relatively small, the mirror interacts with the neutron as a whole [4]. In this case the reflection takes place so that in the reference system of the moving mirror the component of the neutron velocity normal to the surface, $V'_{n\perp}$, remains unaltered. At the same time, it undergoes a change by ± $2V_{m\perp}$ in the laboratory system (the sign "+" is valid when the mirror travels towards the incident neutron, and the sign "-" corresponds to the neutron catching up with the mirror). The resulting change in the grazing angle amounts to $\delta\theta/\theta = \pm 2V_{m\perp}/V_{n\perp}$. Evidently, the mirror does not affect the reflection process in this way, if no movement normal to its plane occurs. A particular case of such situation is the case when the mirror moves in its own plane. Consider the concrete case of a plane mirror rotating about the O-axis (Fig. 1b). The mirror's plane is tilted at an angle ψ to the radius-vector R of point A. The velocity component of the mirror, $V_{m\perp}$, at a point situated at a distance x from A is determined as follows:

$$V_{m\perp} = W\cdot(x + R\cdot\cos(\psi)) \;, \tag{6}$$

where W is the angular velocity of the mirror. Obviously, $V_{m\perp}=0$ in the case of a mirror having the shape of an arc of a circle.

It must be noted that, instead of one, two mirrors forming a separate neutron guide (Fig. 1c) serve as the elementary part of a Soller polarizer. In such a neutron guide the neutrons undergo multiple reflection from both mirrors, depending on the grazing angle. Here, in the case of an even number of reflections compensation occurs of the variations of differing signs in the grazing angle.

In Fig. 1d the transmission of a straight motionless neutron guide is presented as a function of the grazing angle θ_{out} of a neutron leaving the neutron guide (the transmission indicatrix is T). The grazing angle θ_{in} of the incoming neutrons is taken to be within the interval $[0, \pi/2]$. The transmission indicatrix is seen to be determined by the characteristic angle $\theta_{ch} = d/L$, where d is the distance bewteen the planes, L is the length of the neutron guide. Here, neutrons with reflection multiplicities differing in parity occur in output angular intervals differing in sign. One can also see that, as the grazing angle increases, the requirements of the admissible divergence, limited by the passage of the neutron when $\theta < \theta_{ch}$, are reduced. In the case of a neutron guide moving with a velocity $V_{m\perp}$, the indicatrix is shifted along the abscissa axis by an angle of $\delta\theta_{mov}=\mathrm{arctg}(V_{m\perp}/V_n)$.

On the basis of the above one can write down the condition for the polarizing moving neutron guide to be effective:

$$\theta_{ch} < \theta_{min} < \theta_u \pm (\delta\,\theta + \delta\theta_{mov}) < \theta_{max}\,. \qquad (7)$$

3. Polarizers and estimation of their parameters

To start with, let us consider three types of polarizers based on utilization of plane mirrors used earlier. The first two realize condition (4). A polarizer of the first type is depicted in Fig. 2a. The polarizer is a cylindrical drum rotating with the same frequency as the pulse repetition frequency of the neutron source. The mirrors are situated in a sector of polar angle F of a circular section of the drum. This angle depends on the ratio of the time interval, during which the neutrons pass through the polarizer, to the period of the source. A separate mirror is oriented so that its edge is directed along the radius of the entrance section, while the plane of the mirror is inclined at an angle $\theta_m = \theta_{uz} = \gamma\cdot\phi$ where $\gamma = (\theta_{min1} + \theta_{max1})/\phi_{min}$, $\phi_{min} = W \cdot t_{min}$, $t_{min} = t \cdot \lambda_{min}/\lambda$, to the Y_eZ_e-plane of the local reference system (the local system is related to current polar angle ϕ, while the Z_e-axis is directed along the Z-axis of the polarizer, the Y_e-axis along the radius of the section, and the X_e-axis along the tangent of the circular section). To achieve a certain number of collisions with the mirrors, independently of the wavelength, the ratio d/L is proportional to the current angle ϕ. The optimum is to have, on the average, two collisions; we then obtain for the j-th neutron guide $(d/L)_j = \theta_{m,j}/2$. The deviation $\delta\theta$ of the grazing angle in the polarizer is due to the deviation $\delta\theta_\lambda$, caused by the finite width of the pulse of the source leading to uncertainty in the wavelength; to the deviation $\delta\theta_n$ related to the dependence $\theta_m(\phi)$ in the section of the neutron beam, and also to the "useful" deviation $\delta\theta_{us}$ resulting from the divergence of the neutron beam utilized by the user. Let us estimate the parameters of such a polarizer for the IBR-2 reactor exhibiting a pulse repetition frequency of 5 Hz. We choose the working range of wavelengths from 2 to 22 A. We set L_1= 4m, then $\delta\lambda/\lambda$=0.08. As the material for the mirror we take the supermirror CoTi+TiGd [3], for which $\theta_{max} = 3.5 \times 10^{-3}$ λ(A). Then we obtain the admissible value of $\delta\theta+\delta\theta_{mov} = 0.9 \cdot 10^{-3}\lambda$ and $\theta_{us}= 2.6 \times 10^{-3}\lambda$. Assuming that each of the three components of deviation of the grazing angle (with the exception of the small $\delta\theta_\lambda/\theta_{us}$=0.08) must not exceed half of the total admissible deviation we obtain: the radius of the polarizer - 6 cm, the angle F = 2π/10, the cross section of the beam - 1.6 mm (X-axis) · 2 cm (Y-axis), the admissible size of a sample placed at a distance of 10 m from the polarizer not larger than 2 cm (X-axis). Note that in this polarizer the largest restriction on the size of the beam along the X-axis is due to the influence of the motion of the polarizer, since the angle ψ=0. As a result, this not only determines $\delta\theta_{mov}$, but $\delta\theta_n$, also. A positive feature of such a polarizer is the small total area of the mirror.

Now consider the second type of polarizer (Fig. 2b). The polarizer consists of a set of N stacks of flat mirrors placed around the circle in a sector of angle F. This polarizer differs from the others in that the angle $\psi=\pi/2$. Its second special feature consists in the angle between the plane of the mirror and the Z-axis being $\theta_m=\gamma\cdot\phi + \Delta y_s/L_2$, where L_2 is the distance between the polarizer and the sample. While the first term in this expression is, like in the case of the first type of polarizer, related to the grazing angle increasing with time, the second term is new. It is connected with the drop in influence of the user's beam's divergence on the efficiency of polarization. Consequently, equation (7) turns out to be applicable not to the entire stack of mirrors, but only to pairs of adjacent mirrors (see insertion to Fig. 2b). For economy of the total area of the mirror and to provide for the same number of collisions the angular width of the stack and the parameter d/L_1 respectively, must both be taken to be proportional to the angle ϕ. For the same concrete example, that was used in estimating the parameters of a polarizer of the first type, we obtain: the number of stacks N=16, the width of the stacks is between 0.5 cm and 5.5 cm, the parameter d/L varies within the limits from 0.0026 to 0.0286 as ϕ increases, the section of the beam is 1 cm x 10 cm, the radius of the polarizer is 50 cm. It must be noted that in the case of this type of polarizer the requirements of the width of the stack, arising from the influence of the motion, are not severe. For this reason the radius of the polarizer may be chosen to be large, so the size of the beam along the X-axis is enhanced.

A feature peculiar to the third type of polarizers (Fig. 2c), as compared with the second, consists in that the motion itself of the mirror is utilized for providing the required value of the neutron velocity normal to the plane of the mirror. Considering the divergence of the neutron beam not to

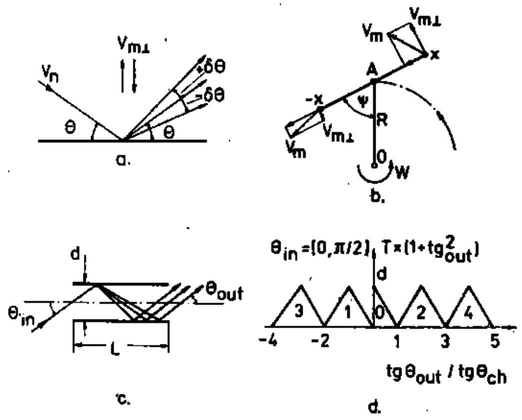

Fig.1: a–reflection of a neutron from a moving flat mirror; b–illustration of the existence of a mirror velocity component, normal to the mirror's surface, when the mirror rotates about the O–axis; c – passage of a neutron through a moving neutron guide; d– indicatrix for a neutron flux passing at a grazing angle within the range between 0 and $\pi/2$ through an idealized motionless neutron guide, reflecting neutrons incident at any grazing angle.

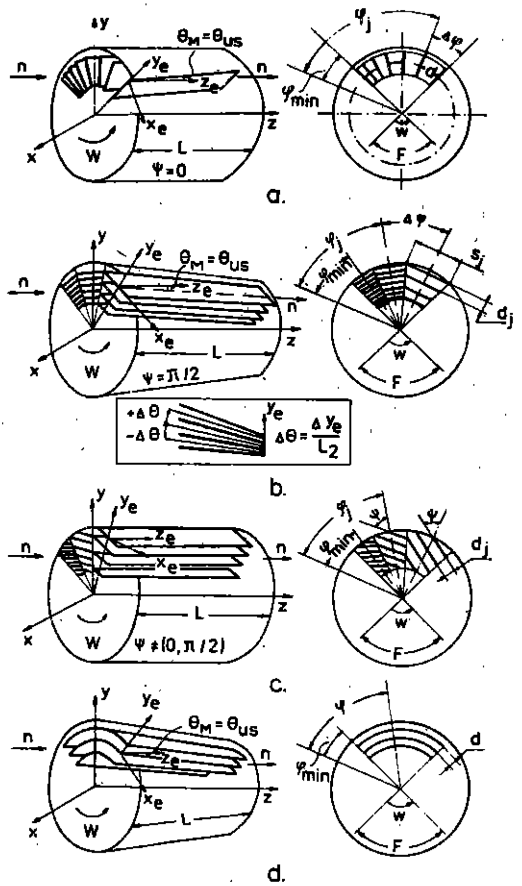

Fig.2 . General outlook and section, normal to the rotation axis, of a wide-spectrum mirror neutron polarizer; a, b, c, d - four versions of the polarizer; the solid lines indicate the mirrors.

be large, and consequently the normal component of the neutron velocity in the laboratory system to be small, also, we obtain from $\theta_{us} = 2.6\cdot10^{-3}\lambda$ that $V_{n\perp} = \theta_{us}\cdot V_{n} = 10.4$ m/s. As a result, we have $\cos(\psi)=0.66$ for the inclination angle of the mirror in the stack in the case of a polarizer with a radius of 50 cm. This polarizer provides for the same parameters of the neutron beam as the polarizer of the second type.

Finally, we note the possibility of realizing a polarizer satisfying condition (5). Such a polarizer (Fig. 2d) is a set of coaxial truncated cones with generatrices inclined at an angle to the axis, which equals the user angle θ_{us}. The surface layer of matter reflecting neutrons is such that the condition $\theta_{min1} \infty \phi^{-1}$ and $\theta_{max1} \infty \phi^{-1}$ is satisfied. For additional enhancement of the aperture of the polarized beam along the radius correction may be applied of the properties of the cones for reflection by $\Delta\theta_{min1}$, $\Delta\theta_{max1} \infty \Delta y_e/L_2$. The polarizer is simple in construction, but its realization requires creation of a surface layer, that is not so simple.

Conclusion

The presented investigation shows that a wide-spectrum polarizer for a pulsed neutron source can readily be constructed utilizing plane super-mirrors. Truly, owing to the necessity of excluding the flight of neutrons without collisions with the mirror, severe requirements of the manufacturing precision arise. This can be avoided, if, as the elementary part of the polarizer, instead of a sole flat mirror, two plane mirrors, placed at an angle to each other are used, or a single curved mirror.

Acknowledgements

The author is grateful to E.B.Dokukin, D.A.Korneev and O.Schaerpf for helpful advice and discussions.

References

[1] O. Schaerpf, AIP Conf.Proc., 89 (1982) 182.

[2] Yu.V.Nikitenko, Yu.M.Ostanevich, JINR Commun.,E13-92-316, Dubna,1992; Accepted by NIM.

[3] O.Schaerpf, Physica B, 156 & 157 (1989) 639.

[4] V.K.Ignatovich , The Physics of Ultracold Neutrons. Oxford University Press, NY, 1990

Received by Publishing Department
on March 4, 1993.