Polarization of neutrons that pass through a magnetized doubly bent neutron guide

S. S. Stepanov and F. M. Zelenyuk

Moscow Engineering Physics Institute
(Submitted July 25, 1976)
Zh. Eksp. Teor. Fiz. 72, 1242–1246 (April 1977)

A method is described for obtaining polarized neutrons by passage through a magnetized doubly bent neutron guide made of the ferromagnetic alloy 50^N (50% Fe–50% Ni). Attention is called to the fact that such a neutron guide polarizes the neutrons effectively in a certain wavelength band, even though the magnetic scattering amplitude a_m is several times smaller than the nuclear amplitude a_n. The degree of polarization in this band is equal to 0.85 ± 0.04.

PACS numbers: 07.77.+p

The advantages of using neutron-guide systems in physical experiments have been discussed many times and are incontrovertible. These advantages are the phononless operating conditions, and the gain in the flux to the sample in comparison with the ordinary geometry of the experiment. If the reflecting surface of the neutron guide is a magnetized ferromagnet, then the beam emerging from the neutron guide is polarized. It is known[1] that to obtain high polarization of the neutrons it is necessary that the magnetic amplitude of the scattering be equal to the nuclear amplitude of the coherent scattering: $a_m=a_n$. When a doubly bent polarizing neutron guide is used, however, this condition is not necessary and it is possible to obtain a high degree of polarization in a certain neutron wavelength range even at $a_n>a_m$.

A doubly bent neutron guide is a neutron filter.[2] The limiting wavelength of the spectrum is given by

$$\lambda_0=k\theta^*(\pi/Na_n)^{1/2}. \tag{1}$$

Here N is the nuclear density, θ^* is the characteristic angle of the neutron guide, and the theoretical value of k is 0.707.[2] For a magnetized neutron guide made of a ferromagnet, the end points of the spectra for the positive and negative spin states of the neutron are determined respectively by

$$\lambda_\pm=k\theta^*(\pi/N(a_n\pm a_m))^{1/2}. \tag{2}$$

It is clear therefore that in the case $a_n>a_m$ the polarizing ability at $\lambda_+<\lambda<\lambda_-$ is close to unity.

Experiment can yield directly two values, λ_0 and λ_+, from the neutron spectra at the exit from a non-magnetized and magnetized neutron guide, respectively. The values of λ_- can be calculated from (2) by substituting the already known value of the magnetic scattering amplitude, determined from the formula

$$a_m=\pi(\theta^*)^2k^2/N\lambda_+^2-a_n, \tag{3}$$

obtained from (2), or directly from the induction of the ferromagnetic material

$$a_m=2\pi\mu mB/h^2N, \tag{4}$$

where μ and m are respectively the magnetic moment and the mass of the neutron, and h is Planck's constant.

It is of interest to analyze the angular distribution of the neutron beam emerging from such a neutron guide. For an unmagnetized neutron guide, the half-width α_0 of this distribution is proportional over the extent of the entire spectrum to the critical angle θ_n of the nuclear coherent scattering, defined by the formula

$$\theta_n=\lambda(Na_n/\pi)^{1/2}, \tag{5}$$

where λ is the neutron wavelength. On the other hand, the half-width α of the angular distribution at the exit from a magnetized neutron guide is proportional to the critical scattering angle θ_{n-m} for neutrons with negative spin states at $\lambda<\lambda_-$ and is proportional to θ_n at $\lambda>\lambda_-$,

$$\theta_{n-m}=\lambda\left(\frac{N(a_n-a_m)}{\pi}\right)^{1/2}. \tag{6}$$

Thus, the quantity α has a discontinuity at $\lambda=\lambda_-$ and it is possible to determine directly the position of the hidden cutoff λ_-. At $\lambda>\lambda_-$ we haee $\alpha_0=\alpha$. The polarizing ability at $\lambda>\lambda_-$ can be calculated in the following manner. Let $I_0=I_0^++I_0^-$ be the intensity of the neutrons at the exit from the unmagnetized neutron guide, equal to the sum of the intensities I_0^+ and I_0^- with spins oriented with and against the field, respectively. It is obvious that $I_0^+=I_0^-=I_0/2$. If the neutron guids is magnetized, the intensities of the neutrons with spins parallel and antiparallel to the field are, respectively,

$$I^\pm=I_0^\pm\left(\frac{\theta_{n\pm m}}{\theta_n}\right)^2\frac{R^{n_{n\pm m}}}{R^{n_n}}=\frac{I_0}{2}\frac{a_n\pm a_m}{a_n}R^{n_{n\pm m}-n_n},$$

where R is the reflection coefficients; n_{n+m}, n_{n-m}, and n_n are the average numbers of collisions of the neutrons emitted from the neutron guide in the angle intervals θ_{m+n}, θ_{n-m}, and θ_n, respectively. The polarizing ability is then

$$p=\frac{I^+-I^-}{I^++I^-}=\left[\left(1+\frac{a_m}{a_n}\right)R^{n_{n+m}-n_{n-m}}-\left(1-\frac{a_m}{a_n}\right)\right]$$

$$\times\left[\left(1+\frac{a_m}{a_n}\right)R^{n_{n+m}-n_{n-m}}+\left(1-\frac{a_m}{a_n}\right)\right]^{-1}. \tag{7}$$

At

0038-5646/77/4504-0651$02.40

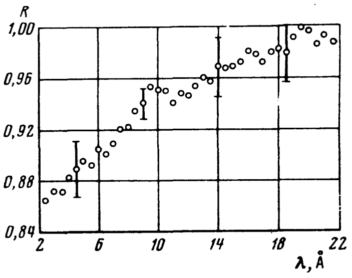

FIG. 1. Reflection coefficient as a function of the wavelength.

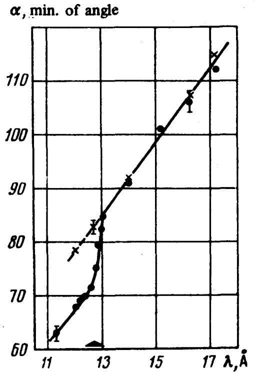

FIG. 3. Half-width of angular distributions at the exit of the unmagnetized (○) and magnetized (●) neutron guide.

$R^n_{n+m}/R^n_{n-m}\sim 1$ we have $p\approx a_m/a_n$. (8)

The experiment was performed with a neutron guide in the form of a cylindrical tube with inside diameter $d=23$ mm, bent twice in the horizontal plane, first in one direction and then in the other, with a curvature radius $\rho=20$ m. Accordingly, the characteristic angle was 4.8×10^{-2} rad. The total length of the neutron guide was 4 meters. The tube material was the alloy 50N (50% iron, 50% nickel), $a_n=0.995\times 10^{-12}$ cm, and $N=0.881\times 10^{23}$ nuclei/cm^3. Coils wound on the neutron guide produced a solenoidal magnetic field whose strength in the course of all the experiments was such that saturation induction, equal to 10^4 G for this alloy, was always attained. The quality of the reflecting surface corresponded to a finish to class 11. We determined the reflection coefficient R in a straight neutron guide from the relation $G_c R^{\bar{n}}=G_e$, where G_c is the calculated intensity gain, determined by the transmission of the direct neutron guide for the given value of λ, $\bar{n}$ is the average number of collisions of the neutrons of given wavelength in the neutron guide, and G_e is the experimentally obtained intensity gain, constituting the ratio of the intensities when the neutron guide was placed in the beam to the corresponding intensity when the neutron guide was replaced by a nonreflecting collimator having the same cross section. The values of the reflection coefficient in the entire wavelength range accessible to the measurement are shown in Fig. 1. The measurements were performed by the time-of-flight method. The spectra of the neutrons leaving the unmagnetized and magnetized neutron guides are shown in Fig. 2. From these spectra we determined the values $\lambda_0=11.0$ Å and $\lambda_+=9.8$ Å, the resolution over the entire spectrum being 0.3 Å. The spectrum was determined with a fluoroplogopite single crystal at $\lambda<19$ Å and by the time-of-flight method at $\lambda>19$ Å.

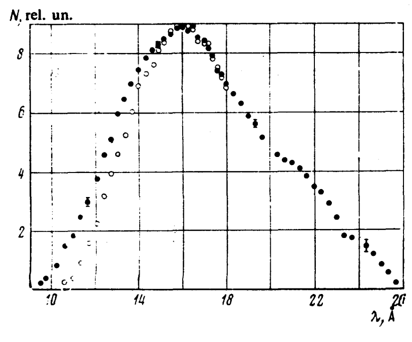

FIG. 2. Spectra of neutrons at the exit from the unmagnetized (○) and magnetized (●) neutron guide.

It was necessary to determine the value of k from λ_0 (see (1)), inasmuch as in all the experiments with neutron guides its value was always less than 0.707. Thus, our earlier study[3] yielded $k=0.4$, while Farnoux *et al.*[2] obtained $k=0.5$. For our neutron guide $k=0.38\pm 0.01$. From formulas (3) and (4) we determined the values a_m, which were equal within the limits of errors, the average being $a_m=(0.25\pm 0.01)\times 10^{-12}$ cm. Formula (2) yielded a value $\lambda_-=12.7$ Å.

The position of the "hidden cutoff" was determined also from the dependence of the half-width of the angular divergences on the neutron wavelength (see Fig. 3). The discontinuity in the half-width takes place at $\lambda_-=12.9$ Å. In practice, the entire wavelength band was divided into three segments: the segment $9.8\text{ Å}<\lambda<12.6$ Å with high degree of polarization, the transition segment with $12.6\text{ Å}<\lambda<13.0$ Å, due to the finite resolution, and the segment $\lambda>13.0$ Å, where $\alpha_0=\alpha$ and therefore the polarizing ability is determined by formulas (8), inasmuch as $R^n_{n+m}/R^n_{n-m}\geq 0.97$. Figure 3 shows the three indicated regions. The angular distributions were obtained with a single-axis spectrometer by the ω method. When collimators with respective divergences α and γ were placed ahead and past the monochromator, the reflection curve could be represented as a convolution of Gaussian functions, determined by the divergences α and γ and by the effective mosaic width of the crystal β. The total width at the midpoint of the ordinate of the diffraction curve is then represented in the form

$$w={}^1/_2(\alpha^2+\gamma^2+4\beta^2)^{1/2}. \tag{9}$$

From the known γ and β we determined the divergence of the neutron beam at the exit from the neutron guide. The monochromator crystal was rotated relative to the given Bragg position with the aid of an automatic system. For a given λ, the reflection curve was plotted several times. Corrections were introduced for the background and for the multiple incoherent scattering.

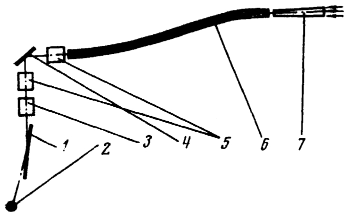

FIG. 4. Experimental setup. 1—analyzer mirror, 2—detector, 3—nonadiabatic region, 4—monochromator crystal, 5—adiabatic region, 6—polarizing neutron guide, 7—collimators.

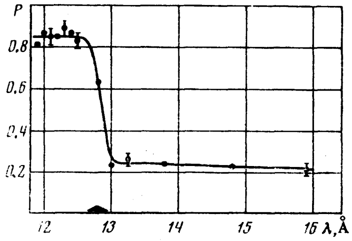

FIG. 5. Dependence of the degree of polarization of the neutrons on the wavelength.

To measure the degree of polarization of the neutron beam we used the well known method of double reflection, and the shim method. The analyzer was a Co–Fe mirror with Ti–Gd sublayer.[1] The nonadiabatic regions, with spinflip probabilities 1 and 0.5, were produced by the solenoidal fields of two coils connected to buck each other, and by the shim, respectively. The analyzer mirror was also placed in a longitudinal magnetic field. The coils were surrounded by metal screens. The experimental setup is illustrated in Fig. 4.

The results of the measurements of the degree of polarization by the two methods agree within the limits of error (see Fig. 5). As expected, one can see distinctly three bands, the same as in Fig. 3, namely, $\lambda < 12.6$ Å, where the average degree of polarization is 0.85 ± 0.04, the transition region 12.6 Å $< \lambda < 13.0$ Å, and the region $\lambda > 13.0$ Å where the average degree of polarization is 0.22 ± 0.03.

The results of the experiments show that a doubly bent neutron guide made of a ferromagnetic material can be used to polarize effectively neutrons even in the case when the magnetic scattering amplitude is several times smaller than the nuclear amplitude of coherent scattering. Such a neutron guide has a polarizing ability close to unity in a certain range of neutron wavelengths (λ_-, λ_+).

The authors are sincerely grateful to G. M. Drabkin for constructive criticism, to V. A. Trunov and A. F. Shchebetov for the opportunity of working with the analyzer mirror, and to the Chief Engineer of the Radio Engineering Institute of the Moscow Engineering Physics Institute A. P. Kryukov for constant attention and support.

[1]G. M. Grabkin, A. I. Okorokov, A. F. Shchebetov, N. V. Borovikova, A. G. Gukasov, A. I. Egorov, and V. V. Runov, Zh. Eksp. Teor. Fiz. 69, 1916 (1975) [Sov. Phys. JETP 42, 972 (1976)].
[2]B. Farnoux, B. Hennion, and J. Fagot, Fourth Symposium on Neutron Inelastic Scattering, II, 1968, p. 353.
[3]V. E. Zhitarev, F. M. Zelenyuk, S. B. Stepanov, and A. V. Timakov, Prib. Tekh. Eksp. No. 4, 43 (1973).

Translated by J. G. Adashko