Multilayer neutron monochromator-polarizer

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A multilayer neutron monochromator-polarizer is proposed, consisting of alternating layers of the alloy 66% Ni^{62}–34% Fe^{54} and of vanadium, obtained by thermal sputtering in vacuum. The concentration of the employed alloy prevents total neutron reflection from the proposed monochromator. The parameters of the neutron multilayer monochromator-polarizer are given: relative half-width of reflection 25%, maximum reflection coefficient 75%, polarizing efficiency $P \approx (90–95)\%$. The experimental dependences of the reflection coefficient and of the polarizing efficiency of the monochromator-polarizer on the neutron wavelength are also given.

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1. INTRODUCTION

There are published reports of interference mirror filters consisting of alternating plane-parallel layers of two substances having the same thickness and different amplitudes b_i of the coherent nuclear scattering, and correspondingly different refractive indices:

$$n_i = \left(1 - \frac{4\pi}{k_0^2} N_i b_i\right)^{1/2}, \qquad (1)$$

where $k_0 = 2\pi/\lambda$ is the wave vector of the neutrons in vacuum, λ is the wavelength, N_i is the density of the nuclei per unit volume. Filters of this kind were calculated for monochromatization of ultracold neutrons[1] and actually produced for thermal neutrons.[2]

Interest in the use of multilayer mirrors has greatly increased recently in connection with the possibility of extending the range of neutron total reflection angles,[3,4] a particularly important factor when it comes to development of neutron-guide systems.

If one type of layer of the multilayer structure is made magnetic, then it becomes possible to polarize the neutrons reflected by such a filter, as was experimentally demonstrated by Schoenborn[5] for periodic structures, and by Mezei[6] for aperiodic structures. A shortcoming of these multilayer periodic mirrors is that the magnetic layers employed are materials with positive coherent-scattering amplitude. In this case, besides the monochromatic neutrons, which undergo Bragg reflection from the periodic structure, the reflected beam contains an appreciable fraction of long-wave neutrons that experience total internal reflection.

If the magnetic layers are made of an alloy of the isotopes ^{62}Ni and ^{54}Fe, then by selecting the concentrations of these isotopes it is possible to obtain a negative resultant amplitude of the nuclear scattering, equal in magnitude to the magnetic amplitude. Estimates show that at weight concentrations 66% of ^{62}Ni and 34% of ^{54}Fe the resultant amplitude of the nuclear coherent scattering is $b_N = -3.91$ fm. For the same concentration, the effective magnetic amplitude is $b_m = 3.95$ fm. Thus, for one of the spin states of the neutron the magnetic layer acts as a negative potential barrier, while for the other spin states it is a barrier close to zero. By alternating layers of this alloy with layers of vanadium, which has a scattering amplitude $b_N = -0.5$ fm, it is possible to obtain the periodic structure shown in Fig. 1a. The effective interaction potential U of neutrons with such a structure is shown in Fig. 1b. For the spin state S_- which is negative with respect to the induction B, the effective potential constitutes periodically repeating potential wells. Neutrons with such a spin state will be reflected in a definite energy interval connected with the period and with the value of the potential. For the other spin state S_+, the potential U_+ does not change on going from one layer to another in the ideal case, or else changes little.

Thus, the proposed filter has no region of photoreflection for both spin states and produces upon reflection a monochromatic beam of polarized neutrons.

2. EXPERIMENTAL RESULTS

The multilayer mirror filters with periodically alternating layers of vanadium and the permalloy alloy 66% ^{62}Ni + 34% ^{54}Fe was prepared by vacuum thermal sputtering on a polished glass substrate measuring 210 × 80 × 5 mm. The technology was worked out on a permalloy alloy made of natural nickel and iron. In this case the resultant neutron scattering amplitudes were $b_N + b_m = 14.0$ fm and $b_N - b_m = 6.1$ fm for the S_+ and S_- spin states, respectively. The effective potential of such a multilayer structure is shown in Fig. 1c. In the course of development of the technology we prepared

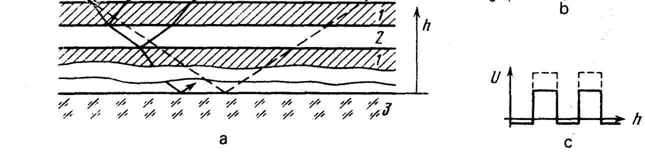

FIG. 1. Periodic filter mirror: a) arrangement of layers: 1—magnetic layers of permalloy 66% Ni + 34% Fe, 2—layers of vanadium, d—glass substrate. The form of the effective potential U for the spin state S_+ and S_- when using permalloy made of the isotopes ^{62}Ni and ^{54}Fe (b) and permalloy of natural Ni and Fe (c).

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ten multilayer mirror filters with permalloy layers of natural components. Their parameters are listed in the table. For eight mirrors, the multilayer structure was deposited directly on the glass substrate, while for mirrors Nos. 4 and 9 an absorbing sublayer of 85% Ti + 15% Gd, of thickness 8000 ± 1000 Å (Ref. 7) was placed between the multilayer structure and the glass. This sublayer should prevent total internal reflection of the neutron from the glass substrate. For each mirror we determined the reflection coefficients $R_+(\lambda)$ and $R_-(\lambda)$ as functions of the neutron wavelength λ at a fixed grazing angle θ_f. To this end we measured the spectra of the initial and reflected beams. The change of the direction of the spins in the initial beam of neutrons was effected with a spin flipper of Korneev's design. The measurements were made with a white beam of polarized neutrons by the standard time of flight procedure with a wavelength resolution $\Delta\lambda = (0.1-0.15)$ Å. The beam divergence in the reflection plane was not more than 15 minutes of angle, and the beam polarization degree was $p \gtrsim 0.99$. The magnetic field in which the investigated mirror was placed had an intensity $H = 500$ Oe.

Figure 2 shows the dependence of the reflection coefficients $R_+(\lambda)$ and $R_-(\lambda)$ on the wavelength and on the normal wavelength $\lambda_\perp = \lambda/\theta_f$ for mirror No. 2 at a glancing angle $\theta_f = 18'$. The maxima of the diffraction reflection, which are of interest to us, are observed near $\lambda = 2$ Å($\lambda_\perp = 380$ Å). At large wavelengths, a transition to total reflection of the neutrons from the magnetized permalloy is observed, with limiting wavelengths $\lambda_{\perp\mathrm{lim}} = 505$ Å and $\lambda^-_{\perp\mathrm{lim}} = 765$ Å. The picture of the total reflection near the diffraction maximum, however, as seen from the figure, is strongly distorted. It is also seen from the figure that the positions of the maxima of the reflection for the two spin directions do not coincide. This phenomenon is due to refraction of the neutrons when they pass through the alternating layers of the two substances with an interaction potential difference $\Delta U_\pm$ that depends on the spin orientation.

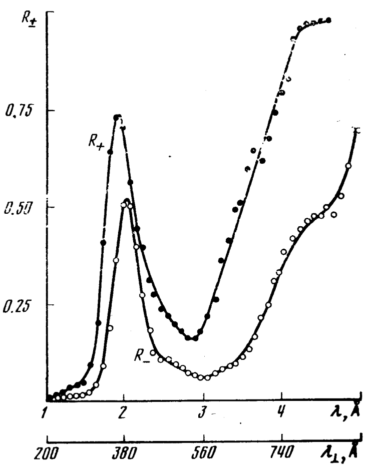

FIG. 2. Dependence of the reflection coefficients $R_+(\lambda)$ and $R_-(\lambda)$ for mirror-filter No. 2 based on natural permalloy, with layer thickness $d = 100$ Å and glancing angle $\theta_f = 18'$.

If the change of the potential ($\Delta U_\pm$) on going from layer to layer is small relative to $E_\perp = \hbar^2(2\pi)^2/2m\lambda_\perp^2$ (i.e., $\lambda_\perp < \lambda_{\perp\mathrm{lim}}$ at real $\lambda_{\perp\mathrm{lim}}$) then the position of the diffraction maximum can be estimated from the Bragg equation modified with allowance for refraction:

$$m\lambda_{\perp\,max} = 2(d_1+d_2) - \frac{\lambda^2_{\perp\,max}}{\pi}(d_1b_1N_1 + d_2b_2N_2), \qquad (2)$$

where m is the order of the reflection, d_1 and d_2 are the thickness of the alternating layers, and b_1 and b_2 are the resultant scattering amplitudes for a definite spin state, and N_1 and N_2 are the number of nuclei per unit volume for layers of type 1 and 2, respectively. To determine the exact values of the position of the peak, its half-width, and the shape of the diffraction curve $R(\lambda)$, it is necessary to use a matrix method for the calculation.[4]

The table lists the principal characteristics of the reduced experimental reflection curves. The position of the reflection peak, its maximum value, and its relative width. The table gives also the positions of the peaks ($\lambda_{\perp max}$) calculated from Eq. (2). Notice should be taken of the considerable difference (~15%) between the experimental position of the maxima of the reflection and the calculated values estimated from the given layer thickness. This can be due either to an inaccurate determination of the absolute values of the thickness d of the layers obtained by sputtering, and to the angle error in the adjustment of the mirror relative to the initial beam. However, the relative displacement of the reflection peaks when the orientation of the spins in the initial beam is changed agrees well with the calculated one, since the $R_+(\lambda)$ and $R_-(\lambda)$ are measured in one setting of the mirror, thereby eliminating the influence of the inaccuracies in the adjustment of the mirror. Notice should also be taken of the difference between the maximum values of the reflection and the calculated value, which is close to unity. This indicates that the layers obtained by the employed sputtering technology were not of sufficiently good quality, and with decreasing layer thickness the quality becomes worse. By quality we mean here primarily sharpness of the boundaries and constancy of the layer thickness. Coating the glass substrate with an absorbing sublayer of 85% Ti + 50% Gd made the layers still worse (see the results for mirrors Nos. 4 and 9).

TABLE I.

Number of mirror filter	Number of layer pairs	Specified layer thickness d, Å	Characteristics of $R_+(\lambda)$ curve: $\lambda^+_{\perp max}$, Å (theory)	$\lambda^+_{\perp max}$, Å (experiment)	$\Delta\lambda^+_\perp/\lambda^+_{\perp max}$, %	R_{+max}	Characteristics of $R_-(\lambda)$ curve: $\lambda^-_{\perp max}$, Å (theory)	$\lambda^-_{\perp max}$, Å (experiment)	$\Delta\lambda^-_\perp/\lambda^-_{\perp max}$, %	R_{-max}
1	12	100	353	290	10	0.14	377	295	8	0.02
2	28	100	353	365	20	0.73	377	390	15	0.50
3	30	100	353	395	28	0.72	377	415	22	0.55
4*	28	100	353	400	10	0.08	377	425	8	0.04
5	30	60	228	245	15	0.49	235	250	13	0.12
6	30	60	228	220	16	0.24	235	225	17	0.08
7	30	60	228	220	14	0.34	235	225	13	0.12
8	30	60	228	215	16	0.36	235	216	13	0.08
9*	30	60	228	–	–	0	235	–	–	0.00
10	100	30	118	123	12	0.02	119	123	12	0.005

Note. The asterisks mark mirrors that have a absorbing sublayer of 85% Ti + 15% Gd, of thickness $d = 8000 \pm 1000$ Å.

For an ideal structure, as follows from the theory, the natural width $\Delta\lambda/\lambda$ of the reflection curve is determined by the ratio $\Delta U_{\pm}/E_{\perp}$. This means that if the effective inhomogeneity of the layer thickness $\langle\Delta d/d\rangle$ is less than the natural width of the reflection curve, then its width will be different for the two spin states. In the other case, when the thickness scatter $\langle\Delta d/d\rangle$ greatly exceeds the natural width $\Delta\lambda/\lambda$, the width of the reflection curve is determined by the value of $\langle\Delta d/d\rangle$ and does not depend on the spin state of the reflected neutrons. It is seen from the table that for layers with d= 60 Å and d= 30 Å practically no difference is observed in the width of the reflection peaks, this allows us to assume that the thickness inhomogeneity of the layers is ~15%, and the natural width $\Delta\lambda/\lambda$ is substantially less than this value. For monochromators with thicknesses d= 100 Å, a dependence of the half-width of the peak on the direction of polarization of the beam is observed. This is due to the fact that the natural width of the reflection peak, which is proportional to $\lambda_{\perp}^2 \sim d^2$, becomes comparable with $\Delta d/d$. We assume that $\Delta d/d$ does not change significantly when the lay thickness changes from 60 to 100 Å. Using the experimental half-widths for 60 and 100 Å layers we can estimate the natural half-width of the reflection curve for a monochromator of thickness 100 Å by the expression

$$\left(\frac{\Delta\lambda}{\lambda}\right)^{\mathrm{nat}} = \left[\left(\frac{\Delta\lambda}{\lambda}\right)^{\mathrm{exp}}_{100\text{Å}} - \left(\frac{\Delta\lambda}{\lambda}\right)^{\mathrm{exp}}_{60\text{Å}}\right]^{1/2}, \quad (3)$$

which yields for the spin states the values $(\Delta\lambda/\lambda)^{\mathrm{nat}}_{+} \approx 20\%$ and $(\Delta\lambda/\lambda)^{\mathrm{nat}}_{-} \approx 10\%$.

After developing the technology of preparing periodic multilayer mirrors from natural components, we prepared mirrors with the isotopic alloy 66% ^{62}Ni + 34% ^{54}Fe. We deposited 35 pairs of vanadium-permalloy layers directly on the glass substrate, each layer having a thickness d= 100 Å. Figure 3 shows the spectra of the beams incident on the mirror and reflected from it. The asymmetry in the reflection spectrum, as well the singularities at small wavelengths, is due to reflections of higher order, which have reflection coefficient ~1%.

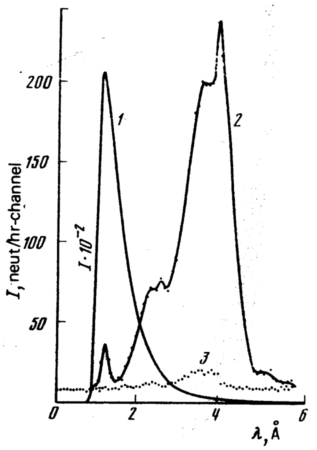

FIG. 3. Spectral dependences of the intensity I for an isotopic-permalloy filter mirror, layer thickness d=100 Å, glancing angle θ_f=30′. 1—spectrum of initial beam incident on the mirror, 2—spectrum of beam reflected in the S_- state, 3—spectrum of beam reflected in S_+ state.

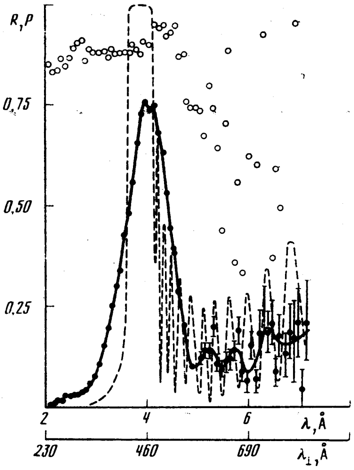

FIG. 4. Dependence of the reflection coefficient $R_-(\lambda)$ for filter mirror based on isotopic permalloy with layer thickness d =100 Å and glancing angle θ_f=30′. Solid curve—experiment, dashed—theoretical calculation. Points—experimental dependence of the polarization efficiency P on λ.

Figure 4 shows the experimental and theoretical plots of the reflection coefficient $R_-(\lambda)$ and the experimental dependence of the polarizing ability $P(\lambda)$ at a grazing angle equal to 30′. The relative width of the experimental reflection curve amounts to 25% at a resolution $\Delta\lambda/\lambda = \Delta\lambda_{\perp}/\lambda_{\perp} \approx 5\%$ for λ= 4 Å and θ_f= 30′. The theoretical value of the relative width of the curve is 17%, which agrees with experiment when account is taken of d/d and of the resolution $\Delta\lambda/\lambda$. The minimum value of $R_-(\lambda)$ is 75%, the polarizing ability $P(\lambda)$ near the reflection peak is ~90–95%. The integral polarizing ability in the wavelength range λ= 1–10 Å is 85%.

3. CONCLUSION

The investigation of the multilayer periodic structure allows us to draw the following conclusions.

1. A monochromator-polarizer was proposed for thermal neutrons, made up of alternating layers of isotopic permalloy alloy and vanadium.

2. The experimental results obtained with the test samples confirm its high reflectivity and polarizing ability. However, there are discrepancies between the experimental and theoretical estimates of the monochromator parameters; these can apparently be attributed to imperfection of the technology used to obtain the layers.

3. When the proosed filters are used in physical installations, for example in small-angle scattering, the required resolution is $\Delta\lambda_{\perp}/\lambda_{\perp} \approx 5$–10%. Such a resolution can be obtained, as shown by calculation, at a layer thickness ~60 Å. The results obtained using natural permalloy with layer thickness 60 Å indicate that such mirrors can be produced.

4. To obtain high values of the reflection coefficient and of the polarizing efficiency at the diffraction max-

imum, further improvement of the technology of the multilayer monochromator-polarizer is necessary.

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Nuclear level shift and radiative transitions in a proton-antiproton atom

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A formula is obtained for the Coulomb shifts of the levels of proton-antiproton atoms in terms of the length of scattering by a strong potential V_s (without the use of perturbation theory, i.e., without assuming the shift to be small compared with the distance between the neighboring levels). The restructuring of the atomic spectrum following the formation of a bound state in the potential V_s is discussed on the basis of this formula. The connection between the level shift and the expansion of the effective radius is indicated. The average radius of the s state is calculated for an arbitrary value of the shift and for an arbitrary probability of the radiative $E1$ transition between the p and s levels. The experimental data [M. Izycki and G. Backenstoss, paper contributed to the Fourth European Antiproton Symposium, Barr, France, 1978; CERN, Geneva, 1978] on the shift of the 1s level of the $p\bar{p}$ atom indicate that a bound QS state (quasinuclear meson) can exist in the $p\bar{p}$ system with binding energy $\varepsilon \approx 1$ MeV and width $\Gamma \lesssim 200$ keV. Calculation shows that the probabilities of the radiative transitions $2p \to 1s$ and $2p \to Qs$ are comparable. This points to a possibility of experimentally observing the Qs level by investigating the spectrum of the γ rays produced in transitions between the levels of the $p\bar{p}$ atom.

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§ 1. INTRODUCTION

Investigations of the interaction of antinucleons with nucleons yield valuable information on the nuclear forces. This information is of particular interest in connection with the existence of bound and resonant states in the $N\bar{N}$ system (quasinuclear mesons, predicted theoretically in the papers of Shapiro and coworkers[1]; references to subsequent papers and a survey of the present status of the $N\bar{N}$ problem can be found in later papers by Shapiro[2,3]). Besides quasinuclear mesons[1)] with binding energy ≈50–300 MeV, there exist in the $p\bar{p}$ system atomic levels of the hydrogen type, due to the Coulomb interaction, with a characteristic energy on the order of several keV. These levels cannot be described by the known Balmer formula, but they experience shifts and broadening on account of strong interaction and annihilation. So long as the level shift is small, perturbation theory in terms of the scattering length is applicable[2)]:

$$\Delta E_{nl} = \frac{2(n+l)!}{(l!)^2 (n-l-1)!\, n^{2l+4}} a_l, \qquad (1.1)$$

where a_l is the length of scattering by the nuclear potential V_s (see Refs. 4–6). When the potential V_s has a near-zero real or virtual level with angular momentum l, the scattering length a_l becomes large and the perturbation-theory equation (1.1) no longer holds. At the instant when the level is produced in the strong potential V_s, a restructuring of the atomic spectrum takes place[3,7] (a similar behavior of the s and p levels was observed[8] in the electrodynamics of strong ($Z > 137$) Coulomb fields—near the critical charge of the nucleus $Z = Z_{cr}$, corresponding to the entry of the level $1s_{1/2}$ into the lower continuum).

Several strong-interaction model potentials (square well, separable potential) were used in Ref. 7 to describe the restructuring of the level spectrum of the atom. The qualitative aspect of the problem was explained, but the solved models did not indicate that the restructuring is universal and independent of the form of the potential V_s, and made it necessary to resort to numerical calculations of the level spectrum in each concrete case. It will be shown below that the presence in the problem of the small parameter r_0/a_B (amounting to ≈1/30 for the $p\bar{p}$ atom) makes it possible to develop an analytic theory of the level shift and to describe the

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