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Influence of multiple reflections on the polarization of nonmonochromatic neutron beams

A. F. Shchebetov, V. A. Kudryashov, V. P. Kharchenkov, and M. M. Agamalyan

B. P. Konstantinov Leningrad Institute of Nuclear Physics, USSR Academy of Sciences, Gatchina
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The influence of multiple reflections from ferromagnetic mirrors on the polarization of a nonmonochromatic neutron beam was demonstrated experimentally. The polarization increased with the number of reflections. The resultant polarization of a beam of neutrons with wavelengths λ from 1 to 4 Å was $P \geq 0.99$ (polarization ratio $R' = 240$). An analysis of the experimental results is given.

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The increase in the polarization of a neutron beam on increase in the number n of successive reflections from a ferromagnetic mirror can easily be predicted by considering the expression for the polarization P_n in terms of the reflection coefficients of the components of a monochromatic neutron beam parallel a_+ and antiparallel a_- to the magnetic field:

$$P_n = \frac{a_+^n - a_-^n}{a_+^n + a_-^n} = \frac{1-(a_-/a_+)^n}{1+(a_-/a_+)^n}. \quad (1)$$

The formula (1) does not allow for the beam depolarization on reflection,[1] which is valid in the case of complete magnetic saturation of the reflecting layer.[2] It is clear from the formula (1) that for $a_-/a_+ < 1$ the term $(a_-/a_+)^n$ tends to zero on increase of n at a rate which increases on reduction of the ratio a_-/a_+, i.e., the limiting value of the polarization obtained as a result of multiple reflections is $P_n = 1$.

Experimental investigations of the process of increase in the polarization and of the factors governing its limiting values after multiple successive reflections are desirable from the scientific and methodological points of view. Multiple reflections may explain the high values of the neutron beam polarization obtained at the exit from polarizing neutron channels (see, for example,[3,4]) when they contain a large number of neutrons reflected repeatedly at an angle θ much smaller than the critical value θ_c so that the increase in the polarization in each reflection is small.[5] The increase in the polarization by multiple reflection can be used in the construction of magnetic monochromators based on the Drabkin resonator[6,7] and in generation of nonmonochromatic neutron beams with a high degree of polarization in systems utilizing polarized neutrons. For example, in a system for testing newly developed polarizing mirrors we can determine directly the polarizability of such mirrors if we have a beam whose polarization does not differ by more than 1% from unity.

EXPERIMENTAL RESULTS

The experiments were carried out in a channel of a water-moderated water-cooled reactor (VVR-M) using a traditional double reflection system (Fig. 1b), which included a collimator 1, polarizer 2, spin-flipper 3,[8] analyzer 4, and detector 5. The polarizer was a straight reflecting channel 1 mm wide and 1260 mm long, formed by 40 Fe-60 Co mirrors on 85 Ti-15 Gd substrates.[5] The deviation of the mirror plane from ideal did not exceed 20″ in any part of the polarizer slit. A magnetic field produced by permanent magnets was H = 500 Oe. The polarizer was mounted on a common baseplate and it was inclined at an angle $\theta_p = 11'$ to the entry beam, which ensured four reflections of the beam inside the polarizer. The height of the neutron beam was limited to 5 mm to increase the probability of spin flip of neutrons in the flipper. The spectrum of

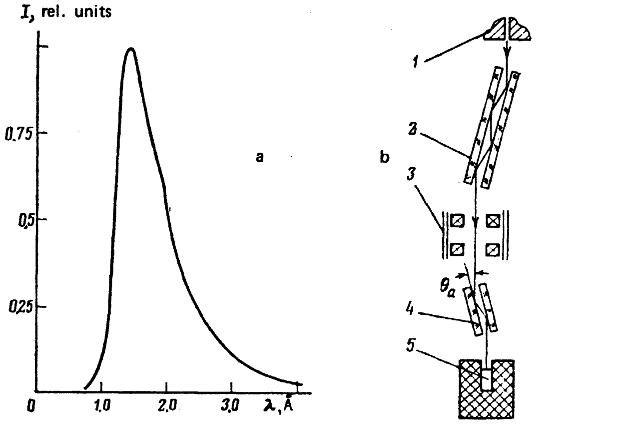

FIG. 1. Spectrum of a neutron beam after passing through the polarizer (a) and schematic diagram of the apparatus (b): 1) collimator; 2) mirror polarizer; 3) spin flipper; 4) mirror analyzer; 5) detector.

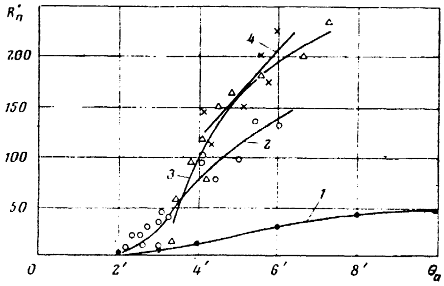

FIG. 2. Dependences of the experimental values of the polarization ration R_n' on the glancing angle θ_a of neutrons incident on the analyzer, plotted for different numbers of reflections n: 1) single reflection (•); 2) double reflection (○); 3) triple reflection (△); 4) quadruple reflection (×).

the polarized beam (Fig. 1a) was recorded by the time-of-flight method. The maximum of the spectrum corresponded to the neutron wavelength $\lambda = 1.5$ Å. The apparatus made it possible to determine the polarization ratio R', which was related to the characteristics of the polarizer, spin flipper, and analyzer by[9,10]

$$\frac{R'-1}{1-R'(1-2f)} = P_p P_a \leqslant 1, \qquad (2)$$

where f is the probability of spin flip in the nonadiabatic region between the polarizer and analyzer, created by the spin flipper; $R' = I_{ad}/I_{na}$ is the polarization ratio or the ratio of the intensities at the detector in the presence of adiabatic (I_{ad}) and nonadiabatic (I_{na}) regions; P_p is the polarization of the beam after the polarizer; P_a is the polarizability of the investigated analyzer.

The experiments involved determination of the dependence of the polarization ratio R_n' of Eq. (2) on the glancing angle of neutrons on the analyzer mirror for a different number of reflections in the analyzer. The analyzer consisted of two mirrors 210 mm long with interchangeable spacers, whose range of thicknesses made it possible to obtain the required number of reflections for a given glancing angle and a given slit width. In this way the experimental values of the polarization ratio R_n' were obtained for 1, 2, 3, and 4 reflections in the range of angles $\theta_a = 2-10'$. The results are presented in Fig. 2. The numbers of the curves 1, 2, 3, and 4 represent the number of reflections.

It is clear from Fig. 2 that, firstly, the polarization ratio rises on increase of the number of reflections in the analyzer; secondly, the rise is observed up to a certain limit beyond which there is no further increase in R_n' when the number of reflections is increased and this limit varies with the angle; thirdly, the maximum value of the ratio is $R_n' = 240$ for $\theta_a = 7'$ after three reflections.

ANALYSIS OF EXPERIMENTAL RESULTS

Since only the polarizing ability of the analyzer changes during the experiment and the beam polarization beyond the polarizer remains constant, the polarization can be described by

$$P_p = (I_0^+ - I_0^-)/(I_0^+ + I_0^-), \qquad (3)$$

where I_0^+ and I_0^- are the neutron intensities in a beam with spins which are, respectively, parallel and antiparallel to the field. We can show that the formula (2), deduced for single reflection, is also valid in the case when P_a is given by Eq. (1). This allows us to make certain estimates. When the experimental value is $R_n' = 240$, it follows from Eq. (2) that

$$f \geqslant 0.996, \quad P_a \geqslant 0.99, \quad P_p \geqslant 0.99.$$

Then, in accordance with Eq. (3), the incident beam is characterized by the ratio $I_0^+ : I_0^- \geqslant 240:1$.

After n reflections without allowance for depolarization, the polarization ratio R_n' is given by the following expression:

$$R_n' = \frac{I_0^+ b_+^n + I_0^- b_-^n}{A b_+^n + B b_-^n}, \qquad (4)$$

where b_+ and b_- are the coefficients of reflection of the relevant component from the analyzer mirror, and

$$A = I_0^- f + I_0^+ (1-f), \quad B = I_0^+ f + I_0^- (1-f).$$

If we ignore quantities of the second order of smallness and make the necessary transformation, Eq. (4) becomes

$$R_n' = \frac{1}{f(b_-/b_+)^n + C_1}, \qquad (5)$$

where $C_1 = 1 - f(1 - I_0^-/I_0^+)$.

It is clear from Eq. (5) that an increase in the number n of the reflections in the analyzer makes it possible to attain the limiting value R_n' governed only by the quantity C_1, i.e., by the properties of the spin flipper and the degree of polarization of the beam after the polarizer. This means that the limiting value of R_n' should be the same for all angles θ_a, i.e., it should not be less than 240, which is in conflict with the experimental results. A comparison of the experimental values of R_n' and those calculated from Eq. (5), using the values of C_1 and the ratio b_-/b_+ from curve 1 (Fig. 2) in the case when $\theta_a = 4-6$, shows that there is no quantitative agreement because the experimental value of R_n' increases from 90 to 210.

This discrepancy between the quantitative estimates may be explained by the fact that the beam used in the experiments is nonmonochromatic (Fig. 1a) and the above discussion makes no allowance for depolarization by reflection. The beam depolarization may be included by representing the reflection coefficients b_+ and b_- in the form[1]

$$b_+=b_{++}+b_{-+},\quad b_-=b_{--}+b_{+-},\tag{6}$$

where b_{++} and b_{--} are the reflection coefficients of the parallel and antiparallel (to the magnetic field) components, which represent the reflection of neutrons without a change in the spin state; b_{+-} and b_{-+} are the depolarization coefficients of the parallel and antiparallel components, which govern the contribution of the reflection of neutrons accompanied by a change in the spin orientation. It is natural to assume that $b_{+-}=b_{-+}$.

The expression for the polarization ratio R_n' is best written out in the matrix form because its analytic form is very cumbersome. In the case of an adiabatic region between the analyzer and polarizer, this can be done by representing the original incident beam as a sum of two completely polarized beams of the $I_0^+ + I_0^-$ intensity. After the first reflection from the analyzer mirror there is a change in the intensities of these spin states, which can be described by the single-reflection matrix $\hat{B}$ relating the incident and reflected beams, as follows:

$$\hat{I}_1=\hat{B}\hat{I}_0.\tag{7}$$

$$\hat{I}_1=\begin{pmatrix}I_1^+\\ I_1^-\end{pmatrix},\quad \hat{I}_0=\begin{pmatrix}I_0^+\\ I_0^-\end{pmatrix},\quad \hat{B}=\begin{pmatrix}b_{++}, & b_{+-}\\ b_{+-}, & b_{--}\end{pmatrix}.$$

After n reflections the state of polarization is described by

$$\hat{I}_n=\hat{B}^n\hat{I}_0.\tag{8}$$

When the flipper is activated, the adiabatic region becomes nonadiabatic with a spin-flip probability f. The original beam then transforms to

$$\tilde{I}_0^+=I_0^-f+I_0^+(1-f),\quad \tilde{I}_0^-=I_0^+f+I_0^-(1-f),$$

which can be expressed in the matrix form

$$\hat{\tilde{I}}_0=\hat{F}\hat{I}_0.\tag{9}$$

$$\hat{F}=\begin{pmatrix}1-f, & f\\ f, & 1-f\end{pmatrix}.$$

After the first reflection we then obtain

$$\hat{\tilde{I}}_1=\hat{B}\hat{\tilde{I}}_0=\hat{B}\hat{F}\hat{I}_0,\tag{10}$$

and after n reflections,

$$\hat{\tilde{I}}_n=\hat{B}^n\hat{\tilde{I}}_0=\hat{B}^n\hat{F}\hat{I}_0.\tag{11}$$

As a result of n reflections from the analyzer mirror the polarization ratio R_n' can be described by

$$R'=(I_n^+ + I_n^-)/(\tilde{I}_n^+ + \tilde{I}_n^-).\tag{12}$$

An analysis of Eqs. (2) and (12) shows that Eq. (2) is still valid. In dealing with the expression for R_n' we shall ignore quantities of the second order of smallness and transform Eq. (12). Then, the expression for R_n' becomes

$$R_n'=\frac{1+C_2b_{+-}/b_{++}}{f(b_{--}/b_{++})^n+C_1+C_2(b_{+-}/b_{++})},\tag{13}$$

where $C_2=1+I_0^-/I_0^+$.

The expressions (12) and (13) differ from Eqs. (4) and (5) by the fact that their numerators and denominators contain terms depending on the coefficient b_{+-}. Consequently, the limiting value of R_n' obtained by increasing the number of reflections n is governed by the value of the ratio b_{+-}/b_{++}, which occurs in Eq. (13) in the first power, and by the constants C_1 and C_2. The experimental curves representing the polarization ratio R_n' (Fig. 2) in combination with Eq. (13) show that the coefficient b_{+-} decreases on increase of the glancing angle θ.

CONCLUSIONS

1. Successive reflections of a nonmonochromatic neutron beam from ferromagnetic mirrors increase the beam polarization.

2. For each set of the coefficients b_{++}, b_{--}, and b_{+-} there is a specific number of reflections n corresponding to the limiting value of the polarization. A further increase in n simply results in a loss of the intensity because of the reduction in the value of b_{++}^n. The limiting value of n is governed by the values of b_{++}, b_{--}, and b_{+-}, which generally depend on the angle and spectrum of the polarized beam.

3. It is possible, using the increase in the polarization in successive reflections and employing a monochromatic neutron beam, to determine the mirror characteristics $b_{++}(\theta)$, $b_{--}(\theta)$, and $b_{+-}(\theta)$ for various materials, solving Eq. (12) with the experimental values of R_n'.

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Optical activity of thallium and lead vapors near suppressed $M1$ transitions

O. P. Sushkov, V. V. Flambaum, and I. B. Khriplovich

Institute of Nuclear Physics, Siberian Branch of the USSR Academy of Sciences
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The magnitude of parity nonconservation effects in the $6p_{1/2}\to 7p_{3/2}$ transition in thallium is calculated and the feasibility of an experimental search for an optical activity is pointed out. A similar calculation is carried out for the $6p^2\ {}^3P'_0\to 6p7p\ {}^3D'_1$ transition in lead.

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Several groups of investigators are currently searching for parity nonconservation in atomic transitions.[1-5] These experiments are attracting considerable interest because the results will be critical in checking theoretical schemes describing in a unified manner both electromagnetic and weak interactions of elementary particles. The most promising approach is the search for an optical activity in heavy metal vapors,[3-5] which has already resulted in considerable narrowing of the possible ranges of the parameters of such schemes.

So far, discussions of the possibility of finding an optical activity have always been concerned with the usual $M1$ transitions between the levels in the same configuration. These discussions have been concerned specifically with the $6p_{1/2}\to 6p_{3/2}$ transitions in thallium, between the levels of the $6p^2$ configuration in lead, and those of the $6p^3$ configuration in bismuth. All the experiments have been carried out so far on bismuth.

The possibility, in principle, of searching for an optical activity near the suppressed $6p_{1/2}\to 7p_{3/2}$ transition of the $M1$ type in thallium was pointed out in [6]. However, a pessimistic view was taken there of the chance of detecting this activity. We shall report a calculation of the degree of circular polarization of photons in this transition, and of the corresponding angles of rotation of the plane of polarization of light in thallium vapor. In our view, these results indicate that the chance of observing an optical activity near this transition is quite realistic. We shall also give the results of a calculation of an optical activity in a similar transition in lead.

We shall begin with the amplitude of the $M1$ $6p_{1/2}\to 7p_{3/2}$ transition in thallium. A numerical calculation[6] shows that, in spite of the difference between the principal quantum number of the initial and final states, this amplitude is suppressed only by an order of magnitude. Its value can easily be found also analytically. The spin-orbit interaction mixes the $6p$ and $7p$ states:

$$|7p_{3/2}\rangle'=|7p_{3/2}\rangle+\frac{1}{2}\frac{\zeta_{6,7}}{E(7p_{3/2})-E(6p_{3/2})}|6p_{3/2}\rangle,$$
$$|6p_{1/2}\rangle'=|6p_{1/2}\rangle-\frac{\zeta_{6,7}}{E(6p_{1/2})-E(7p_{1/2})}|7p_{1/2}\rangle. \qquad (1)$$

Here, $\zeta_{n,n'}$ is the radial matrix element of the spin-orbit interaction. Since the main contribution to this element comes from the region of short distances from the nucleus, where the $6p$ and $7p$ wave functions differ only in respect of the normalization, it follows that $\zeta_{6,7}\approx(\zeta_{6,6}\zeta_{7,7})^{1/2}$ (we are assuming that all the radial functions are positive in the limit $r\to 0$). Hence, using the experimental values of the energies of the relevant states, we obtain

$$\left\langle 7p_{3/2}j_z=\frac{1}{2}|M_z|6p_{1/2}j_z=\frac{1}{2}\right\rangle=\frac{\sqrt{2}}{3}\cdot 0.09|\mu_B|. \qquad (2)$$

The absolute value of the matrix elements is in agreement with the value given in the cited calculation[6] but the results differ in respect of the sign.

The $6p_{1/2}\to 7p_{3/2}$ transition in thallium can also be of electric quadrupole nature. A numerical calculation gives $\langle 7p_{3/2}|r^2|6p_{1/2}\rangle=-6.7a_B^2$.[6] Consequently, the

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