Neutron spin precession near the p-wave resonance in ^{139}La

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The results of measurements of neutron spin precession near the p-wave resonance in ^{139}La at energy $E_p = 0.734$ eV are presented. The measurements were performed in a stationary reactor using a crystal-diffraction method. © *1995 American Institute of Physics.*

It is well known[1–6] that as polarized neutrons pass through matter, the weak interaction gives rise to neutron-optical phenomena — precession of the neutron spin around the neutron momentum ($\Phi_{pnc} > 0$ corresponds to rotation according to the right-hand rule)

$$\Phi_{pnc} = -\frac{4\pi}{k} nL \,\mathrm{Re}[f(0)_+ - f(0)_-] \tag{1}$$

and dichroism (spin-dependent absorption)

$$\Delta\sigma_{pnc} = \frac{4\pi}{k} \,\mathrm{Im}[f(0)_+ - f(0)_-], \tag{2}$$

where $f(0)_{+(-)}$ is the forward scattering amplitude for two opposite values of the neutron helicity, k is the wave number, n is the number of nuclei per cubic centimeter, and L is the target thickness.

The most striking example is the experimentally observed dichroism near the p-wave resonance in ^{139}La at an energy of 0.734 eV (Ref. 7). This effect was investigated using high-flux neutron pulsed sources[8–11] and a polarized proton filter for polarizing the neutron beam. The neutron spin precession for ^{139}La was measured only at the thermal point.[12] Near the p-wave resonance, however, the observation of this effect presents great experimental difficulties which are associated with the additional analysis of the polarization of the neutron beam behind the target and the need to ensure statistical accuracy of the measurements.

In our measurements we employed a stationary reactor and a crystal-diffraction method to produce and analyze the polarization of the neutron beam. This method has been used successfully to investigate parity violation in nuclear fission.[13] It also makes it possible to separate the energy of the neutron beam with energy resolution that is acceptable for the present problem. The high average flux of the stationary reactor, as well as the high polarizing and analyzing capability of the crystal-diffraction method ensure statistical accuracy.

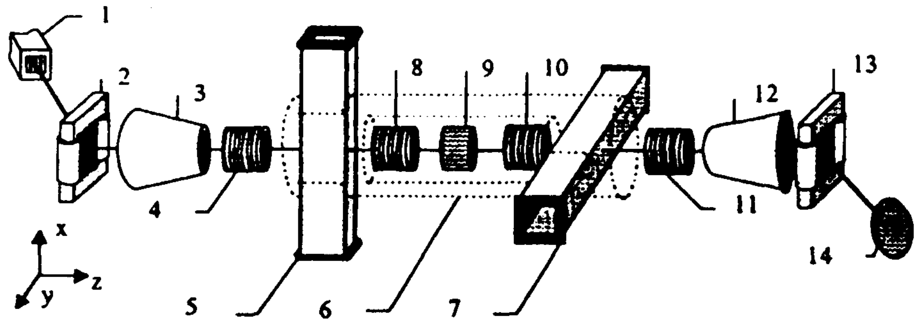

FIG. 1. Experimental arrangement. *1* — Multislit collimator; *2* — magnet with a polarizing crystal; *3* — adiabatic flipper; *4* — averaging coil; *5* — X-solenoid; *6* — two-layer magnetic screen; *7* — Y-solenoid; *8, 10* — Z-solenoid; *9* — ^{139}La target; *11* — averaging coil; *12* — adiabatic flipper; *13* — magnet with an analyzing crystal; *14* — neutron counter.

The experimental arrangement is shown in Fig. 1. The neutron beam from the reactor passes through a multislit collimator (*1*) and strikes a crystal-polarizer (2) (single crystal of a Heusler alloy Cu_2MnAl; $2d_{111}=6.869$ Å), which is magnetized to saturation and placed in the Laue position. A vertically polarized neutron beam is formed as a result of diffraction: The average wavelength of the neutrons satisfies the Bragg condition. After the neutron beam passes through the target and a system of auxiliary magnetic fields, the polarization is analyzed using an identical crystal-analyzer *13*, tuned to the same wavelength, and a neutron detector *14*. The transition from vertical polarization to longitudinal and back to vertical polarization, as well as inversion of the polarization direction are performed with the aid of two adiabatic "flippers," *3* and *12*. Averaging coils, *4* and *11*, powered with a 50-Hz alternating current, were used to suppress the residual transverse polarization of the neutron beam. The amplitude of the alternating current was chosen in such a way that the time-averaged value of the transverse component of the neutron spin at the exit from the coil would be zero. The energy of the beam was changed by changing the angle of Bragg reflection from the crystals. The reflection coefficient of the crystals was equal to $\approx 2\%$ for $\approx 95\%$ polarization of the neutrons in first-order reflection. The admixture of second-order-reflection neutrons was equal to $\approx 50\%$ of the first-order intensity with a $\approx 30\%$ polarization.

The present experimental apparatus was developed to investigate possible spurious phenomena in the search for T-noninvariant effects.[14] The use of two additional crossed $\pi/2$ solenoids, *5* and *7*, makes it possible to switch from measurements with a longitudinally polarized beam to measurements with a transversely polarized beam and to investigate neutron spin precession.

In the precession measurements the neutron beam polarization vector, which after the beam has passed the "averaging" coil, *4*, is oriented along the Z axis, precesses by an angle of $\pi/2$ around the X axis in the range of the X solenoid, *5*, and acquires, within the experimental errors, an orientation along the Y axis with which is makes a small angle Φ in the XY plane. This angle can be determined by the method illustrated in Fig. 2a, which displays the neutron count as a function of the magnitude and direction of the

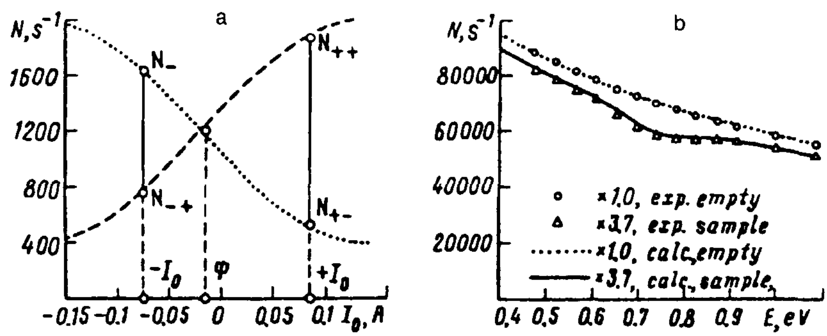

FIG. 2. a — Counting rate of the neutron counter as a function of the magnitude and direction of the current in the Z solenoid; b — experimentally measured counting rate of the detector plotted as a function of the neutron energy (dots) compared with the computed curves in the measurements with and without a sample in the beam.

current I in the Z solenoid (Fig. 1, positions *8* and *10*) for two directions of the current in the Y solenoid (Fig. 1, position *7*). It can be shown that the angle Φ is determined by the relation

$$\frac{\tan(\Phi)}{\tan(\beta I_0)}=\frac{(N_{++}-N_{+-})-(N_{--}-N_{-+})}{(N_{++}-N_{+-})+(N_{--}-N_{-+})}, \tag{3}$$

where the four quantities N_{ik} correspond to the counting rate of the neutron detector for two opposite directions of the current I_0 in the Z solenoid ($i=+,-$) and in the Y solenoid ($k=+,-$). The coefficient β, which fixes the phase of the transverse component of the polarization of the beam with a fixed current I_0, was calibrated by a separate measurement of the total rotation period of the polarization around the Z axis.

The phase shift $\Delta\Phi$ produced by the weak nucleon-nucleus interaction in the target was determined as the difference of the measurement of the phase with the target inserted and removed from the beam. The experimental apparatus and the experimental procedure will be described in greater detail in a separate publication.

The difference effect $\Delta\Phi$ or the precession angle of a neutron spin in a weak pseudomagnetic field of the target is shown in Fig. 3b as a function of the neutron-beam energy. Figure 3a shows the results of the weak-dichroism measurements

$$nL\Delta\sigma_{pnc}=\frac{N_+-N_-}{N_++N_-}, \tag{4}$$

performed in a separate experiment. In these measurements the crystal-analyzer was removed, the X and Y solenoids were switched off, and the neutron detector was placed on the Z axis. The quantities N_+, N_-, and $\Delta\sigma_{pnc}$ in expression (4) correspond to the counting rates of the neutron detector and the difference of the cross sections for two opposite helicities of the neutron beam incident on the target.

Despite its advantages of high luminosity and simplicity, with respect to energy resolution, the crystal-diffraction method loses its advantage, in terms of the energy resolution, to the time-of-flight method using a pulsed neutron source. Consequently, the

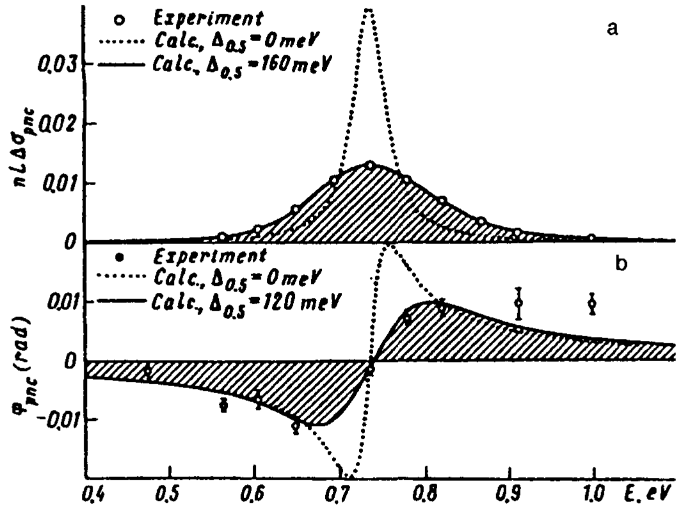

FIG. 3. Main experimental results (dots) compared with the theoretical prediction (curves): a) P-odd dichroism; b) P-odd precession. The dashed line corresponds to ideal energy resolution of the apparatus; the solid line corresponds to the real resolution.

measured effects are found to be distorted by the instrumental resolution function of the apparatus. However, this problem can be solved by using the well-developed theory of neutron diffraction[15] and the well-known parameters of the p-wave resonance.[16]

The counting rate of the detector in measurements with and without a target in the resolution range can be expressed as follows:

$$N_0(E_n)=\text{const}\int \omega(E)\eta(E)R(E)\mathscr{R}(E_n,E)dE, \tag{5}$$

$$N_t(E_n)=\text{const}\int \omega(E)\exp[-nL\sigma(E)]\eta(E)R(E)\mathscr{R}(E_n,E)dE, \tag{6}$$

where $\omega(E) \propto 1/E$ is the neutron flux density from the reactor, $\eta(E) \propto 1-\exp(-a/\sqrt{E})$ is the detector efficiency, $R(E) \propto 1/E$ is the integral reflectance of an ideal crystal,[15]

$$\mathscr{R}(E_n,E)\propto\exp\left[-\frac{1}{2\Delta_{0.5}^2}\left(\frac{1}{\sqrt{E_n}}-\frac{1}{\sqrt{E}}\right)^2\right]$$

is the resolution function, which is determined under the assumption that the crystal has a highly mosaic structure, that the distribution of the separate blocks around the Bragg position is Gaussian,[15] and that $\sigma(E)$ is the total cross section for the interaction of neutrons with the target.

Figure 2b shows the experimental measurements of the transmission of a ^{139}La sample ($L=5$ cm) compared with the transmission calculated according to (5) and (6). The energy resolution was determined by comparing the half-width of the experimental cross section of the resonance ($E_p=0.734$ eV) with the computed cross section. It was found to be 0.160 eV. This value includes the intrinsic resolution of the crystal-polarizer and the Doppler broadening of the resonance.

The energy resolution of the apparatus for a scheme with two crystals was determined assuming that the resolution of the polarizer is equal to that of the analyzer. It was found to be 0.120 eV. This characteristic can be improved, in principle, by using more perfect crystals based on the alloys FeCo and FeSi.

The values obtained for the resolution were used to describe, as a function of the energy, the weak dichroism and the neutron spin precession. For an apparatus with the ideal resolution ($\Delta_{0.5}=0$) these effects are described by the formulas[5]

$$\Delta\sigma_{pnc}=\frac{2\pi g}{k^2}\frac{xw(\Gamma_s^n\Gamma_p^n)^{1/2}}{[s][p]}[(E-E_s)\Gamma_p+(E-E_p)\Gamma], \tag{7}$$

$$\frac{d\Phi}{dz}=\frac{4\pi n g}{k^2}\frac{xw(\Gamma_s^n\Gamma_p^n)^{1/2}}{[s][p]}\left[(E-E_s)(E-E_p)-\frac{1}{4}\Gamma_s\Gamma_p\right], \tag{8}$$

where $g=(2J+1)/2(2I+1)$ is a statistical factor; $E_{s,p}$, $\Gamma_{s,p}$, and $\Gamma_{s,p}^n$ are, respectively, the energy and the total and neutron widths of s and p compound resonances, respectively; w is the matrix element of the weak P-odd interaction between these resonances; $[s][p]=(E-E_{s,p})^2+\frac{1}{4}\Gamma_{s,p}^2$; $x=\sqrt{\Gamma_p^n(1/2)/\Gamma_p^n}$ is the mixing parameter of the channels [$\Gamma_p^n(1/2)$ is the partial width of the p-wave neutron with the total angular momentum $j=1/2$]. It follows from Eqs. (7) and (8) that the maximum dichroism is equal to the total amplitude of the precession:

$$P_{\max}=n\Delta\sigma_{pnc}(E_p)L=\Phi_{\max}(E_p-\Gamma_p/2)-\Phi_{\max}(E_p+\Gamma_p/2). \tag{9}$$

Substituting expression (7) into (6) and using Eq. (4), we obtain a model of the weak-dichroism experiment with one free parameter — xw, which must be determined. It was found to be

$$xw=(1.77\pm0.13)\ \text{meV} \quad \text{or} \quad \Delta\sigma_{pnc}/\sigma_p=(10.2\pm0.8)\%,$$

where the accuracy of the measurements of the magnitude of the effect is limited by the accuracy of the measurements of the polarization of the beam and by how accurately the second-order-reflection intensity is taken into account.

The form of the dependence of the dichroism on the energy of the incident neutrons with the resolution of the apparatus equal to 0.160 eV is shown in Fig. 3a (solid line). The experimental points agree well with the function calculated according to the model described above.

Using the computed value of the energy resolution, equal to 0.120 eV for the two-crystal experimental arrangement, and the quantity xw determined from the dichroism measurements, we calculated in a similar manner the expected magnitude and form of the energy dependence of the neutron spin precession. The results are shown in Fig. 3b (solid line). A comparison with the experimentally measured values shows that the theoretical prediction generally agrees with the experimental results: 1) The measured neutron spin precession effect changes sign at the resonance in accordance with expression (8) and

2) the total amplitude of the effect corresponds to that expected according to Eq. (9). To analyze the more detailed form of the effect, specifically, on the right-hand shoulder of the curve, more careful measurements with improved statistical accuracy must be performed. More accurate comparative measurements of the two effects will be performed under identical experimental conditions with an improved experimental apparatus.

In the measurements performed the maximum experimental dichroism effect at resonance (7×10^{-3}) was determined with a statistical accuracy of 2% in a time of 20 min. The measurement time of the precession effect was longer because it was necessary to use the two-crystal scheme. The time was equal to 12 h at each point for the position with the target and 4 h for the position without the target. It should be noted that the data acquisition rate can be increased by a factor of 100–300 by using a neutron beam from the hot-neutron source of the ILL high flux beam reactor (Grenoble).

The results presented here are preliminary, but they nonetheless illustrate clearly the possibilities of the crystal-diffraction method for use in stationary reactors for investigating P- and T-invariance in neutron reactions.

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