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Measurement of parity-nonconserving rotation of neutron spin in the 0.734-eV p-wave resonance of ^{139}La

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Abstract

The parity nonconserving spin rotation of neutrons in the 0.734-eV p-wave resonance of ^{139}La was measured with the neutron transmission method. Two optically polarized ^{3}He cells were used before and behind a 5-cm long ^{139}La target, each as a polarizer and an analyzer for neutron spin. The rotation angle was carefully measured by flipping the direction of ^{3}He polarization in the polarizer in sequence. The peak-to-peak value of the spin rotation was determined to be $(7.4 \pm 1.1) \times 10^{-3}$ rad/cm. The result is found to be consistent with the previous experiments, but the result was statistically improved. The s–p mixing model gives the weak matrix element as $xW = (1.71 \pm 0.25)$ meV. The value agrees well with the one deduced from the parity-nonconserving longitudinal asymmetry in the same resonance. © 2002 Elsevier Science B.V. All rights reserved.

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There have been a number of experimental studies concerning the effects of the weak interaction in hadronic systems. The ratio of the strength of the weak interaction to the strong interaction in such systems is estimated to be $G_F m_\pi^2 / 4\pi \sim 2 \times 10^{-7}$, where G_F and m_π are the Fermi coupling constant and the mass of pion, respectively. Observed longitudinal asymmetries of the cross sections for proton–proton scattering [1–3] are on the order of this estimate. However, it was found that parity-nonconserving effects are tremendously enhanced in p-wave resonances of neutron–nucleus systems. In particular, the helicity asymmetry of the cross section at the 0.734-eV p-wave resonance of ^{139}La was found to reach 10% [4–7]. As a theoretical explanation for such large parity-nonconserving (PNC) longitudinal asymmetries, a model based on the interference between the p-wave and its neighboring s-wave resonances was proposed [9].

The PNC effect appears in several measurable quantities in the neutron–nucleus system in addition to the longitudinal asymmetry of the total cross section of neutron–nucleus interaction. One of them is the rotation of neutron spin around the momentum vector during transmission in a target material while being through matter. According to the neutron optics, the forward scattering amplitude $f(0)$ for the neutron–nucleus scattering is expressed as

$$f(0) = F_0 + F_1 \boldsymbol{\sigma_n} \cdot \boldsymbol{I} + F_2 \boldsymbol{\sigma_n} \cdot (\hat{\boldsymbol{k}}_{\boldsymbol{n}} \times \boldsymbol{I}) + F_3 \boldsymbol{\sigma_n} \cdot \hat{\boldsymbol{k}}_{\boldsymbol{n}},$$
(1)

where $\boldsymbol{\sigma_n}$ denotes the Pauli spin matrices for the neutron, and $\boldsymbol{I}$ and $\hat{\boldsymbol{k}}_{\boldsymbol{n}}$ are unit vectors representing the directions of the target nuclear spin and the incident neutron momentum, respectively. The complex coefficients F_i ($i = 0, \dots, 3$) are functions of the neutron energy. The terms $\boldsymbol{\sigma_n} \cdot (\boldsymbol{I} \times \hat{\boldsymbol{k}}_{\boldsymbol{n}})$ and $\boldsymbol{\sigma_n} \cdot \hat{\boldsymbol{k}}_{\boldsymbol{n}}$ represent the parity nonconserving amplitudes. In the case of an unpolarized target, the terms with F_1 and F_2 vanish, and the forward scattering amplitude is simply described as

$$f(0) = F_0 + F_3 \boldsymbol{\sigma_n} \cdot \hat{\boldsymbol{k}}_{\boldsymbol{n}}.$$
(2)

The spin rotation angle around the momentum vector and the difference of the cross sections for the different neutron helicities are given as

$$\frac{\partial \phi}{\partial z} = -\frac{4\pi}{k_n} N \operatorname{Re} F_3,$$
(3)

and

$$\Delta \sigma = \frac{8\pi}{k_n} \operatorname{Im} F_3,$$
(4)

respectively, where N is the number density of the target nuclei and k_n is the wave number of the neutron. Accordingly, the longitudinal asymmetry and the spin-rotation angle are connected with each other through the forward scattering amplitude, F_3.

Now we examine the PNC effect on the forward scattering amplitude considering the case when an s-wave and a p-wave resonances contribute to a neutron transmission for which the measurement is made. Due to the presence of a weak matrix element W which connects the s- and p-states an incident neutron may be captured by the target nucleus in s-wave and re-emitted in p-wave, or vice versa. In this context, the interference between these two processes gives rise to the parity nonconserving amplitude F_3. Although the total angular momentum j of the p-wave neutron can have values 1/2 and 3/2, only the $j = 1/2$ component contributes to the interference because of the conservation of the total angular momentum. Thus the s–p mixing model gives F_3 as

$$F_3 = -\frac{g}{k_n} \frac{x W (\Gamma_s^n \Gamma_p^n)^{1/2}}{\left(E_n - E_s + \frac{i}{2}\Gamma_s\right)\left(E_n - E_p + \frac{i}{2}\Gamma_p\right)},$$
(5)

where E_n is the incident neutron energy and E_s (E_p), Γ_s (Γ_p), and Γ_s^n (Γ_p^n) are the energy, total width, and neutron width of the s-wave resonance (p-wave resonance) [10]. The spin statistical factor g is calculated from the spin of the target nucleus I and that of the resonance state J as

$$g = \frac{2J + 1}{2(2I + 1)}.$$
(6)

The factor x is defined as

$$x^2 = \frac{\Gamma_{p_{1/2}}^n}{\Gamma_p^n},$$
(7)

where $\Gamma_{p_{1/2}}^n$ is the partial neutron width for the p-wave neutron whose orbital and spin angular momenta make a total angular momentum $j = 1/2$. From Eqs. (3) and (5) and assuming $|E_p - E_s| \gg \Gamma_s$ and $\Gamma_s \sim \Gamma_p$, the PNC neutron-spin rotation is given as

$$\frac{\partial \phi}{\partial z} \simeq \frac{4\pi g N}{k_n^2} \frac{x W (\Gamma_s^n \Gamma_p^n)^{1/2}}{E_p - E_s} \frac{E_n - E_p}{(E_n - E_p)^2 + \frac{1}{4}\Gamma_p^2}.$$
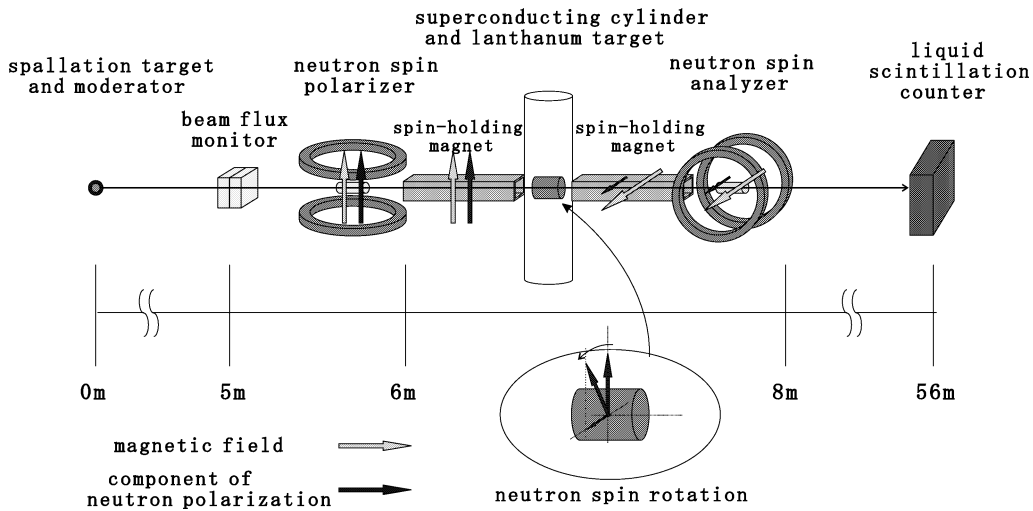(8)

Fig. 1. Experimental setup.

An attempt to measure the neutron spin rotation angle covering the 0.734-eV p-wave resonance of ^{139}La was performed at KEK as reported in Ref. [12]. They used a superconducting neutron polarimeter, which comprised a neutron spin polarizer of polarized protons, a neutron spin analyzer of polarized ^{3}He nuclei and Meissner sheets [13]. They found that the energy dependence of the rotation angle has a dispersive behavior changing its sign at the center of the p-wave resonance, as expected from the s–p mixing model. They deduced the value of xW to be (1.04 ± 0.40) meV. The value is consistent with those obtained from the longitudinal asymmetries of the cross section [4,6] within the errors. Serebrov et al. measured the neutron spin rotation angles at several energies around 0.734-eV with a ^{139}La target at Gatchina [7] and ILL [8]. They used a crystal-diffraction method to produce a polarized neutron beam and to analyze the neutron polarization after the target. They also obtained the result that the spin rotation angle shows a dispersion curve.

We measured the parity-nonconserving rotation of neutron spin in the p-wave resonance of ^{139}La with a high intensity pulsed neutron beam. The experiment was performed at Manuel Lujan Jr. Neutron Scattering Center in Los Alamos Neutron Science Center. The beamline and experimental setup are schematically shown in Fig. 1. The rotation angle was observed via the polarization in the axis orthogonal to that of the incident neutron that appeared after transmission

through a lanthanum target, by means of two optically polarized ^{3}He neutron spin filters. One was used as a neutron beam polarizer and the other to analyze the transmitted neutron beam polarization.

We used a cylindrical lanthanum target of 5 cm in length along the beam direction and 3 cm in diameter. The target was suspended by a rod inside a niobium cylinder which was placed in the neutron-beam path. The niobium cylinder was cooled with liquid helium to the superconducting state so that it completely excluded the magnetic field in the cylinder. The magnetic field seen by the neutron changed nonadiabatically at the boundary of the cylinder and the neutron spin did not experience any rotation when entering or exiting the cylinder. The method and the device were developed and used in the experiment at KEK [12,13].

The method used to polarize and to analyze the neutron spins was based on the spin-dependent absorption in the polarized ^{3}He gas [14,15]. The polarizer and the analyzer of the neutron spins were placed before and behind of the lanthanum target, respectively. Both spin filters consisted of ^{3}He gas of 6 atm enclosed in cylindrical glass cells. A small amount of rubidium was introduced in the cells and optically pumped by a circularly polarized light of the wavelength of 795 nm in a magnetic field of about 20 gauss. We used frequency stabilized diode laser arrays. The polarization of Rb atoms were transferred to the ^{3}He nuclear spins by hyperfine interactions upon atomic collisions.

Since the neutron absorption in ^{3}He is essentially associated with the 0^+ compound state at low neutron energies, ^{3}He absorbs only neutron with its spin antiparallel to the ^{3}He spin and lets neutron with parallel spin go through. The polarization axes of the two spin filters were set transverse to the beam direction and perpendicular to each other. Using the adiabatic fast passage method of NMR, the ^{3}He polarization of the polarizer was flipped every 7 minutes to minimize the systematic errors. Flipping was carried out with an eight-step sequence of $+ - - + - + + -$, where '+' and '−' denote the direction of the ^{3}He polarization in the polarizer rotated around the beamline by $+90°$ or $-90°$ with respect to the direction of the polarization of ^{3}He of the analyzer. The neutron transmission was measured with 4800 beam bursts for each flipped state.

The values of absolute polarizations of the ^{3}He filters were obtained from the transmission enhancement through the polarized ^{3}He gas. ^{3}He polarizations of the polarizer and analyzer were monitored by measuring amplitudes of NMR signals of ^{3}He. The direction of the polarization of the analyzer was fixed during the measurement. The transmissions of neutrons whose spin is parallel and antiparallel to the ^{3}He polarization are expressed as $\exp(-(1 - P_{3\text{He}})\sigma_{3\text{He}}Nl)$ and $\exp(-(1 + P_{3\text{He}})\sigma_{3\text{He}}Nl)$, respectively, where $P_{3\text{He}}$, $\sigma_{3\text{He}}$, N, and l are the polarization, the neutron cross section, the number density of the ^{3}He nuclei and the thickness of the cell. Accordingly the transmission of unpolarized neutrons is $\exp(-\sigma_{3\text{He}}Nl)\cosh(P_{3\text{He}}\sigma_{3\text{He}}Nl)$. Thus, the neutron transmission through a polarized ^{3}He gas is enhanced over the transmission through an unpolarized ^{3}He gas, with an enhancement factor $\cosh(P_{3\text{He}}\sigma_{3\text{He}}Nl)$.

The neutron transmission enhancement for each spin filter was measured without the lanthanum target. Typical polarizations of ^{3}He in the polarizer and the analyzer were 56% and 29%, respectively.

The "flipping ratio" is defined as the asymmetry of the neutron transmissions for two directions of the polarizer. It is written as the product of the rotation angle of neutron spin and the total analyzing power determined by the ^{3}He polarizations. The latter is given as $\tanh(P_{\text{pol}}\sigma_{3\text{He}}N_{\text{pol}}l_{\text{pol}})\tanh(P_{\text{ana}}\sigma_{3\text{He}}N_{\text{ana}}l_{\text{ana}})$, where P_{pol}, N_{pol} and l_{pol} are the polarization, neutron cross section, number density and length of the ^{3}He polarizer, respectively, and P_{ana}, N_{ana} and l_{ana} are those of

the analyzer. Actually we determined the factors given by the hyperbolic functions experimentally from the neutron transmission enhancement and NMR signals.

The neutron spin was kept in the same direction as a spin-holding magnet between the polarizer and the target, and also as another magnet between the analyzer and the target. The neutron beam was defined by brass collimators with apertures of 23 mm in diameter. The collimators were placed upstream of the polarizer and downstream of the analyzer. Transmitted neutrons were detected with ^{10}B loaded liquid scintillation counters located 56-m downstream of the spallation target. The liquid scintillator was enclosed in a flat cylinder with diameter of 43 cm and thickness of 4 cm. Scintillation photons were detected with 55 photomultiplier tubes of 2 inches in diameter (Amprex XP2262B). The detection efficiency for 0.734-eV neutrons was nearly 100% [16]. The signals were counted by multi-channel scalers (EG&G ORTEC Turbo MCS) after passing through discriminators. The energies of neutrons were determined by time-of-flight (TOF) measurements. The start signal for the TOF measurements was given by the proton pulse incident to the spallation target. The resolution of the neutron energy at 0.734 eV was about 5 meV.

The neutron detector was sensitive also to γ-rays and neutrons which were scattered with collimators and walls. They showed wrong TOF timing. We studied the background in the detected neutrons by inserting foil absorbers of tantalum, indium, and cadmium in the neutron beam downstream of the analyzer. The thicknesses of the foils were selected so that neutrons in the resonances of 0.18 eV for ^{113}Cd, 1.46 eV for ^{115}In and 4.3 eV for ^{181}Ta were completely absorbed, so these being black resonances in the measurement. Thus detector counts at these resonance energies came entirely from the background. The background levels at three black resonances were estimated by interpolating the count rates at the three black resonances.

The neutron flux was monitored with a pair of ion chambers placed upstream of the polarizer. One of them was filled with ^{3}He gas, while the other with ^{4}He. Both of the chambers were operated at the pressure of 1 atm. Each chamber had a charge collection plate at the center, which was sandwiched between two anode plates held at about $+600$ V. The thickness of the sensitive area between the two anodes was 2 cm.

Difference in currents between the two chambers gives the neutron flux without γ-ray contribution, since the ^{3}He chamber is sensitive to both neutrons and γ-rays, whereas the ^{4}He chamber is sensitive only to γ-rays.

The spin rotation angle Φ measured with the lanthanum target was fitted with a function

$$\Phi = \phi \, \frac{\frac{E_n - E_p}{\Gamma_p/2}}{1 + \left(\frac{E_n - E_p}{\Gamma_p/2}\right)^2} + C + S\Phi_{\mathrm{bg}}, \qquad (9)$$

where ϕ, C, S are fitting parameters. The first term represents the energy dependence of the neutron spin rotation. The second term, C, is the constant which indicates the error in the fine adjustment of the direction of polarization of the polarizer and analyzer. The third term, Φ_{bg}, represents a misalignment effect, which originates from the field inhomogeneity. A transverse component of the neutron polarization to the spin holding field appears upon passage through the region where field direction rapidly varies. We measured Φ_{bg} without the lanthanum target. However, the experimental condition might be changed when we placed a thick target. For example, slight deflections of the neutron beam path due to multiple small-angle scatterings, or a failure in ^{3}He polarization monitor probably caused a small change in Φ_{bg}. We assumed that S, whose deviation from unity represents the change in Φ_{bg}, is independent of the neutron time of flight. According to Eq. (8) ϕ is related to the weak matrix element W by the equation

$$\phi = \frac{8\pi g N l}{k_n^2 \Gamma_p} \, \frac{x W (\Gamma_s^n \Gamma_p^n)^{1/2}}{E_p - E_s}. \qquad (10)$$

The misalignment effect, Φ_{bg}, depends on the neutron time of flight. The dependence is affected by the holding field distribution in the neutron beam path. The fitting was carried out for the two sets of data. They were obtained with magnetic field of 20 and 15 gauss at the spin-holding magnets and their net data-acquisition times were 13.9 and 6.4 hours, respectively. The absolute values of Φ_{bg} were smaller than 0.17 and 0.26 rad, respectively. In the higher-field case, the fitting parameters were obtained as

$$\phi = (3.99 \pm 0.55) \times 10^{-2} \text{ rad},$$
$$C = (3.79 \pm 0.95) \times 10^{-3},$$
$$\text{and} \quad S = 1.115 \pm 0.012. \qquad (11)$$

In the lower-field case, the results were

$$\phi = (3.42 \pm 0.76) \times 10^{-2} \text{ rad},$$
$$C = (-3.26 \pm 1.42) \times 10^{-3},$$
$$\text{and} \quad S = 1.041 \pm 0.011. \qquad (12)$$

The errors shown above were statistical ones from the fittings. It should be mentioned that in the present analysis the systematic error caused by the ^{3}He polarization measurement is not explicitly shown. However, the possible error in the fitting caused by the ambiguity originating from the polarization measurement are negligible compared to the error due to the ambiguities of the fitting parameters. The systematic errors originate from the uncertainties in the NMR sensitivity and in the angular settings of axes for the two spin filters.

The two values of ϕ for the two holding field conditions were consistent with each other. We took the average value of these results for ϕ. The neutron spin rotation angle in the p-wave resonance of ^{139}La target is shown as a function of the neutron energy in Fig. 2. The difference between the maximum and the minimum values of the rotation angle in a target of a unit length was obtained as $(7.4 \pm 1.1) \times 10^{-3}$ rad/cm.

In order to extract $x W$ from the rotation angle, the energy E_p and the width Γ_p of the resonance were determined from this experiment. The width of the s-wave resonance Γ_s was considered to be negligible with respect to $(E_n - E_s)$ in the vicinity of the p-wave resonance. We used the values listed in [17] for the other parameters. With these values, we obtained

$$x W = (1.71 \pm 0.25) \text{ meV}. \qquad (13)$$

In summary, the observed spin rotation angle ϕ exhibits a dispersion curve which conforms well with the center and width values that were independently determined from the neutron absorption experiment. The value of $x W$ shows good agreement with those obtained from the PNC longitudinal asymmetries in the same resonance as shown in Table 1. In the present experiment we have confirmed that the large enhancement of PNC effect in the p-wave resonance of ^{139}La exists also in the neutron spin rotation. The enhancements in the longitudinal asymmetry and the spin rotation are described consistently by the s–p mixing model.
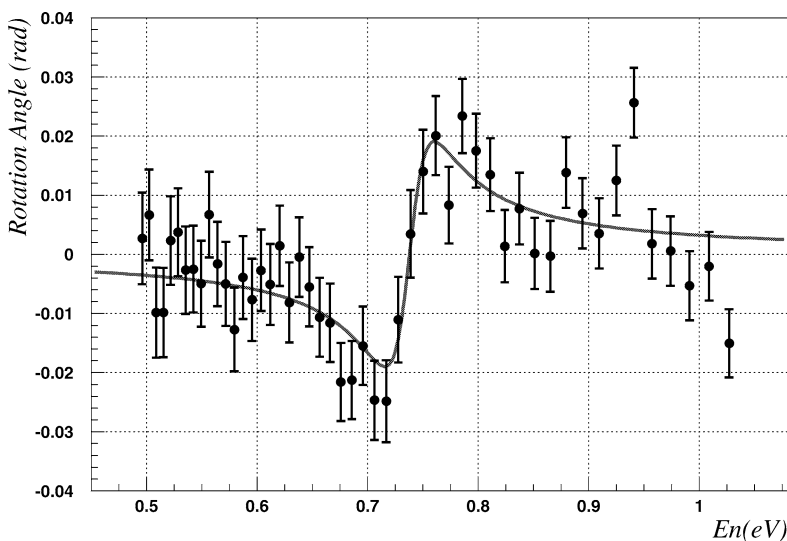
Fig. 2. The neutron-spin rotation angle in the 0.734-eV p-wave resonance of ^{139}La. Statistical errors of the rotation angle are shown as bars. The solid line represents the best fit of the first term of Eq. (9) to the experimental values which were obtained by averaging the data taken in the two different magnetic fields. The difference between the maximum and the minimum of the solid line is $(3.72 \pm 0.55) \times 10^{-2}$ rad after subtracting $S\Phi_{bg}$.

Table 1
Experimental values of xW for 0.734-eV p-wave resonance of ^{139}La

xW (meV)	Observable	Energy region	Reference
1.7 ± 0.1	Im F_3	resonance	[6]
1.68 ± 0.06	Im F_3	resonance	[5]
1.77 ± 0.13	Im F_3	resonance	[7]
1.63 ± 0.21	Re F_3	cold	[11]
1.04 ± 0.40	Re F_3	resonance	[12]
1.71 ± 0.25	Re F_3	resonance	present work

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