Measurement of P-Violation in ^{139}La(n,γ)^{140}La – a first step towards a T-Violation search

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Abstract. We performed a polarized neutron transmission asymmetry measurement utilizing the ^{139}La(n, γ)^{140}La reaction. This measurement involved the use of a recently developed ^{3}He spin filter mounted on the J-PARC MLF beam line number 4 (BL04). The resulting value of the longitudinal asymmetry $A_L = (11.7 \pm 1.1)\%$ was found to be in good agreement with existing values in the literature suggesting that the method by which we polarize the neutron beam is not a significant source of uncertainty. This preliminary work represents a first step toward future measurements of the angular correlation in $(\vec{n}, \gamma)$ reactions necessary in the search for enhanced T-Violation in compound nuclei.

1. Introduction

When medium-heavy nuclei react with polarized epithermal neutrons, parity (P) violating asymmetries can be amplified by up to a factor of 10^6 with respect to the P-Violation observed in pp scattering [1]. This enhancement is due to interference of close-lying opposite-parity s and p states in the compound nucleus.

Within the framework of the compound nuclear model (CNM) including sp-mixing, it has been predicted by V.P. Gudkov that T-Violation will also be amplified in the compound nuclear state via the same mechanism as the P-Violation [2]. The relationship can be expressed as:

$$\Delta \sigma_T = \kappa(J) \frac{W_T}{W} \Delta \sigma_P, \tag{1}$$

where $\Delta \sigma_P$ and $\Delta \sigma_T$ are P and T violating cross section differences observed for two polarization states of the neutron inducing the compound nuclear reaction; W and W_T are P-violating and T-violating matrix elements; and $\kappa(J)$ is a spin factor. Since $\Delta \sigma_P$ has been measured for various nuclei in previous studies [1], the overall sensitivity of a T-Violation search in this system can be estimated if $\kappa(J)$ is known. This quantity is currently being

measured in various nuclides using angular distributions in (n, γ) reactions with unpolarized and polarized neutrons [3,4]. The analysis is based on a theoretical description of sp-mixing within the CNM [5]. The differential scattering cross section of the (n, γ) reaction is given by:

$$\frac{\mathrm{d}\sigma_{\mathrm{n}\gamma}^{\pm}(\theta)}{\mathrm{d}\Omega} = \frac{1}{2} \left[a_0 + a_1 \cos\theta + a_3 \left(\cos^2\theta - \frac{1}{3} \right) \right.$$
$$\left. + P_{\mathrm{n}}^{\pm} \left\{ a_{10} + \left(a_9 + \frac{2}{3} a_{12} \right) \cos\theta + a_{11} \left(\cos^2\theta - \frac{1}{3} \right) \right\} \right] \tag{2}$$

where $P_{\mathrm{n}}^{\pm}$ is the polarization in the two helicity states of the neutron, and θ is the angle between the directions of the incident neutron and the emitted γ-ray. The angular distribution of the γ-rays after capture of unpolarized neutrons by ^{139}La was measured by Okudaira et al., and analyzed within the CNM and the sp-mixing models [6,7]. However, no polarized-neutron measurement has yet been done with this nucleus. Since all corresponding correlation terms in Eq. (2) (a_9, a_{11}, a_{12}) depend on the final state, it is necessary to use a high-resolution γ-ray detector capable to distinguish single γ-ray transitions, in combination with a polarized neutron beam.
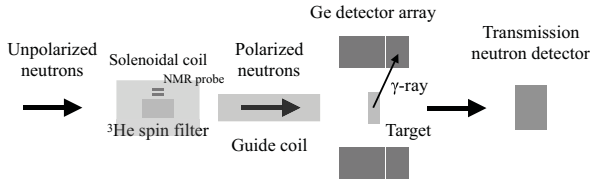
Figure 1. A schematic view of the experimental setup at BL04.

Figure 2. The ^{3}He gas cell.

In the experiment reported here we determined the longitudinal asymmetry A_L given by:

$$A_L \equiv \frac{\sigma_{res}^+ - \sigma_{res}^-}{\sigma_{res}^+ + \sigma_{res}^-}, \tag{3}$$

where $\sigma_{res}^{\pm}$ are the total resonance cross sections for the two neutron helicity states. In Eq. (2), the longitudinal asymmetry A_L is represented by the term a_{10}. Since A_L has been well measured in previous experiments [7–9], we could use the known values as a benchmark to evaluate the neutron polarization of our beam [10]. Therefore, by confirming that A_L agrees with previous measurements, it can be concluded that the systematic error inherent in our setup is not significant and that a future (n, γ) measurement can be done using polarized neutrons.

2. Experiment

This experiment was carried out at the high-intensity proton accelerator facility at J-PARC on beam line number 4 (BL04) at the MLF spallation neutron source. The setup at BL04 is shown in Fig. 1. A ^{3}He spin filter was installed as a neutron polarizer 20 m away from the surface of the neutron moderator. It consists of a cylindrical glass cell with a diameter of 30 mm and a length of 50 mm filled with ^{3}He at approximately 3 atm (Fig. 2).

The spin filter was installed on the beam line after the ^{3}He was polarized using the spin exchange optical pumping (SEOP) method. The ^{3}He polarization was flipped approximately once every 2 hours using adiabatic fast passage (AFP), and its temporal decrease was monitored using an NMR signal.

A $40 \times 40 \times 3\,mm^3$, 99.9% pure lanthanum metal plate was used as the nuclear target located 21.5 m from the moderator surface. A guide coil served to maintain the neutron polarization between the spin filter and the target.

The γ-rays due to neutron capture reactions were detected by the germanium detector array surrounding
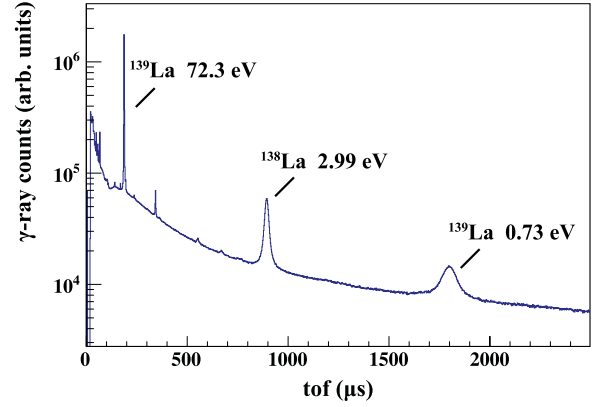
Figure 3. Neutron time-of-flight (TOF) spectrum measured with the lanthanum target.

the nuclear target. The detector array consisted of 22 germanium crystals, with two clusters of seven detectors located vertically above and below the target, and the remaining eight detectors surrounding the target in the horizontal plane [11]. For noise suppression, the threshold for the γ-ray detection was set at approximately 400 keV.

The neutrons that were transmitted through the lanthanum target of natural isotopic abundance then passed through a collimator and were detected by lithium scintillator detectors installed 28.7 m downstream from the moderator surface. Two types of lithium glass scintillators were used: GS20 enriched in ^{6}Li to 95% and GS30 enriched in ^{7}Li to 99.99%. Corresponding to the very different neutron absorption cross sections of these isotopes, GS20 is sensitive to both neutrons and γ-rays, whereas the GS30 is only sensitive to γ-rays; this allows one to monitor the γ-ray background in the GS20. The measurements were performed in June in 2017, accumulating 15.8 and 14.4 hours in the two opposite helicity states.

3. Analysis

The neutron energy information in this measurement was derived from time-of-flight (TOF). Figure 3 shows a typical TOF spectrum of the captured γ-rays. The proton beam bunch T0 was used to trigger the start of the spectrum. The peak around 1800 μs is due to the γ-rays emitted via the p-wave resonance in the compound system ^{139}La + n. It occurs at an incident neutron energy of 0.73 eV.

3.1. Corrections

3.1.1. Proton beam current correction

Since the proton beam current incident on the mercury spallation target can vary from pulse to pulse, the amount of neutrons produced differs for each pulse. For analysis of our measurements the neutron beam intensities thus need to be normalized. For this we use the proton beam current as a reference, relying on the assumption of the proportionality of neutron and proton fluxes.

3.1.2. Background subtraction (Neutron detector)

The γ-ray background measured by the neutron and γ-ray sensitive GS20 scintillator was calibrated using the (only
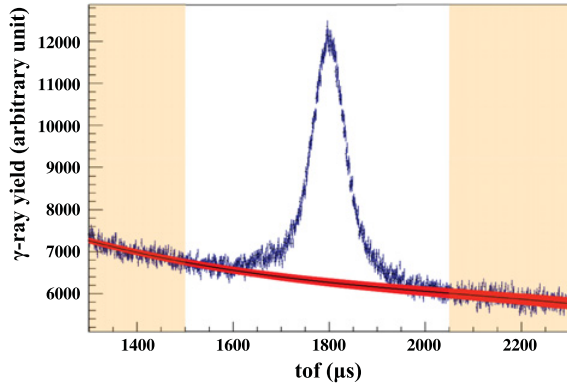
Figure 4. Background estimation at the 0.73 eV p-wave resonance. The orange shaded areas show the regions wherein a cubic polynomial was fit to the data. The red line shows the interpolated background fit with error.

γ-ray sensitive) GS30. A properly weighted difference of these two thus delivers the neutron spectrum. The events of the GS30 were subtracted from GS20's events, leaving only the neutron spectrum.

3.1.3. Background subtraction (Ge detectors)

For a quantitative analysis of the events in the p-wave resonance, a cubic polynomial was fitted to the γ-intensities in TOF regions nearby but excluding the resonance, i.e., between 1.3 ms and 1.5 ms, and between 2.05 ms and 2.3 ms (see Fig. 4). The fitted function was then subtracted from the data in the region of interest to obtain the resonance line corrected for background.
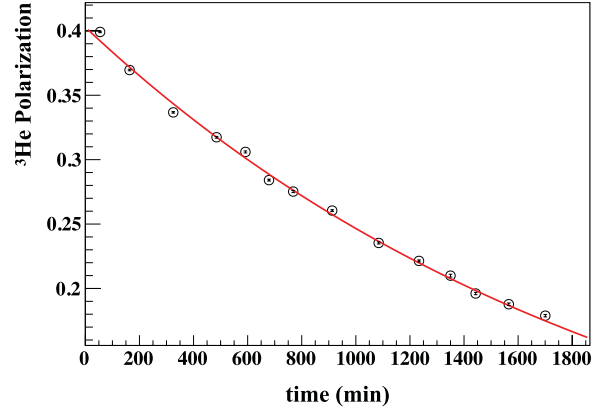
3.1.4. Polarization measurements

The polarization of the ^{3}He spin filter was determined using the ratio of the transmitted polarized neutrons N_{pol} to the transmitted unpolarized neutrons N_{unpol} through the filter via the relation

$$\frac{N_{\text{pol}}}{N_{\text{unpol}}} = \cosh\left(P_{\text{He}}\, nt\, \sigma_{\text{abs}}\right), \qquad (4)$$

where σ_{abs} is the nuclear absorption cross section for unpolarized neutron, n is the number density of the gas and t is the effective thickness of the ^{3}He gas. The product nt, was determined by measuring the transmission of unpolarized neutrons through the cell with and without the unpolarized gas.

Values of the ^{3}He polarization are plotted in Fig. 5 as a function of time, where the ^{3}He spin is flipped between each measurement. Each flip reduces the total polarization by a few percent, which was monitored using NMR. The time intervals between flips were chosen so that sufficient statistics were acquired in each spin state while minimizing the effect of the polarization reduction from flipping on the spin relaxation curve. In principle one could employ a neutron spin flipper to flip the neutron spin rather than the ^{3}He, which could be performed more frequently and avoid the depolarization from ^{3}He flipping. However, geometrical constraints on the beam line prevented us from doing so, as spin flippers capable of efficiently flipping eV neutrons require large coils placed along the beam line in an area where space was already very tight.

Figure 5. Relaxation of the ^{3}He polarization as a function of time, derived from NMR measurements. The spin of the ^{3}He is flipped between each measurement.

The known $1/v$ dependence of σ_{abs} in the thermal neutron region was assumed to extend to the epithermal neutron energy region in our analysis. The time constant obtained from a fit of a single exponential function to this data is (33.0 ± 0.1) h. The neutron polarization can then be determined using the relation

$$P_n = \tanh\left(P_{\text{He}}\, nt\, \sigma_{\text{abs}}\right), \qquad (5)$$

where the uncertainties consist of counting statistics in the determination of P_{He} via Eq. (4), measurement of nt, and uncertainty in the absorption cross section.

3.2. Asymmetry

The following expression relates the experimental asymmetry ε defined by the γ-ray yields for the two neutron helicity states (including the corrections discussed before) with A'_L, which is the sought asymmetry value still uncorrected for multiple scattering events:

$$\varepsilon = \frac{N'^+_{\text{res}} - N'^-_{\text{res}}}{N'^+_{\text{res}} + N'^-_{\text{res}}} = \frac{A'_L\left(P_{n^+} + P_{n^-}\right)}{2 + A'_L\left(P_{n^+} - P_{n^-}\right)}, \qquad (6)$$

where $N'^{\pm}_{\text{res}}$ are the corrected γ-yields within the full-width-at-half-maximum (FWHM) region of the p-wave resonance peak, and $P_{n^\pm}$ denote the neutron polarization values for each neutron helicity. The result is $A'_L = (10.9 \pm 1.0)\%$.

Neutron scattering in the target prior to absorption in the p-wave resonance alters the neutron momentum vector and hence impacts the asymmetry. Taking such scattering events into account, A'_L is given by:

$$A'_L \equiv \frac{(\sigma^+_{\text{res}} + \sigma_{\text{sng}}) - (\sigma^-_{\text{res}} + \sigma_{\text{sng}})}{(\sigma^+_{\text{res}} + \sigma_{\text{sng}}) + (\sigma^-_{\text{res}} + \sigma_{\text{sng}})}, \qquad (7)$$

where σ_{sng} represents the absorption cross-section after scattering in the target. Therefore, A_L and A'_L can be related by:

$$A_L = A'_L\left(1 + \frac{\sigma_{\text{sng}}}{\sigma_{\text{res}}}\right), \qquad (8)$$

where σ_{res} is defined as $\frac{\sigma^+_{\text{res}} + \sigma^-_{\text{res}}}{2}$. The ratio $\frac{\sigma_{\text{sng}}}{\sigma_{\text{res}}}$ was estimated using a Monte Carlo simulation. After this

Table 1. Values of A_L as measured in previous studies.

$A_L(\%)$	Method	Group
9.5 ± 0.3	Capture γ-rays	KEK(a) [8]
9.7 ± 0.5	Transmission	KEK(b) [8]
9.2 ± 1.7	Transmission	Los Alamos [9]
10.15 ± 0.45	Transmission	LANSCE(a) [10]
9.55 ± 0.35	Transmission	LANSCE(b) [10]
11.7 ± 1.1	Capture γ-rays	This work

correction, the value of the longitudinal asymmetry was found to be $A_L = (11.7 \pm 1.1)\%$. The largest uncertainty in this measurement was the statistical error, and it is expected that a more precise measurement becomes possible by the improvement of the performance of the ^{3}He spin filter (larger effective thickness of ^{3}He and longer relaxation time).

4. Summary

Table 1 shows that our value of A_L agrees within 2σ to values measured in previous experiments. This confirms

that it will be possible to measure the angular distribution of the (n, γ) reaction using polarized neutrons and high energy resolution detectors at BL04.

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