Study of an angular correlation of γ-rays emitted by ^{117}Sn(n,γ) reactions for T-violation search

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A discovery of violation of time-reversal symmetry (T-violation) can lead to a solution for an asymmetry between matter and antimatter in the current universe, which is one of the important problems in particle physics and astrophysics. An enhancement of T-violation is theoretically proposed in several compound nuclear reactions. The experimental sensitivity to find a T-violating effect depends on a spin factor $\kappa(J)$ which is different from each nuclide. It can be determined from an angular dependence of a differential cross section of neutron-nucleus reaction, and the experiments to measure this angular correlation have conducted at J-PARC. In this paper, the measurement result and the analysis status of experiments using the target nucleus ^{117}Sn are reported.

1. Introduction

An asymmetry between the number of matter and antimatter in the current universe is one of the important problems which should be solved in particle physics and astrophysics. A. Sakharov proposed that violation of charge conjugation and parity symmetry (CP-violation) stronger than expected within the Standard Model of particle physics is necessary to explain this asymmetry [1].

Compound nuclear reactions are expected as one of CP-violation search beyond the Standard Model under the assumption that the CPT theorem, which means that CP-violation is equal to the violation of time-reversal symmetry (T-violation), is correct. In several compound nuclear reactions, the violation of parity symmetry (P-violation) is observed with an enhancement factor of 10^6 compared to the proton-proton scattering [2]. This enhancement is theoretically explained as a *sp*-mixing model describing an interference between amplitudes of s-wave resonances and p-wave resonances. It is theoretically suggested that T-violation is enhanced by a similar mechanism in several nuclear reactions [3]. In addition, this theory proposes that an experimental sensitivity depends on each nuclides. One of the key parameters allowing to become good candidate nuclei is a spin factor $\kappa(J)$. Thus, there is a possibility that the magnitude of T-violating effect is enhanced if the value of $\kappa(J)$ is not small. The $\kappa(J)$ is related to neutron resonance partial widths via a mixing angle ϕ describing a superposition of different spin components. So far only ^{139}La has been determined the value of $\kappa(J)$ by Okudaira et al. [4]. To identify further candidates for T-violation search, other nuclei muse be measured.

The mixing angle ϕ can be determined by measuring an angular correlation of prompt γ-rays emitted from compound nucleus with respect to a direction of incident neutrons. According to Flambaum [5], the differential cross section for unpolarized neutrons is described as follows:

$$\frac{d\sigma}{d\Omega} = \frac{1}{2}\left\{a_0 + a_1\cos\theta_\gamma + a_3\left(\cos^2\theta_\gamma - \frac{1}{3}\right)\right\}, \tag{1}$$

where θ_γ is an angle between the flight directions of the emitted γ-rays and the incident neutrons. The a_0 term corresponds to the Briet-Wigner formula, while the a_1 and a_3 terms include the mixing angle ϕ. Equation (1) indicates the shape of p-wave resonance depends on the direction of emitted γ-rays with respect to the incident neutrons due to their terms. We can verify the *sp*-mixing model by measuring this angular dependence of p-wave resonance.

The isotope ^{117}Sn is one of the candidates for T-violation search. In this paper, the results of measurements of angular dependence of γ-ray emission around the 1.33 eV p-wave resonance, resonance parameters, and branching ratio of each resonance, which are essential values to calculate precisely the Eq. (1), is reported.

2. Experiment

2.1 Experimental setup

Our experiments were carried out with Accurate Neutron-Nucleus Measurement Instrument (ANNRI) in the Material and Life science experimental Facility (MLF) of the Japan Proton Accelerator Research Complex (J-PARC). ANNRI is installed at the neutron beam line BL04 to accept the pulsed neutron beam from spallation source of J-PARC MLF. Produced neutron beam was moderated by a liquid hydrogen moderator and supplied to the beam line at a repetition rate 25 Hz. The position of nuclear target is placed at 21.5 m from the moderator surface. Lead plates (in total 37.5 mm thickness) were installed at upstream to suppress background events stemmed from fast neutrons and γ-rays produced by spallation reactions. The disk choppers were operated synchronously with the proton-beam injection to avoid frame overlap due to low-energy neutrons.

ANNRI has a germanium detector assembly shown in Fig. 1. It consists of two types of detector units: type-A and type-B. The type-A is an assembly of 7 germanium crystals, while the type-B has a germanium crystal, and it has 22 crystals in total. Each crystal is installed at 36.0, 70.9, 72.0, 90.0, 108.0, 109.1, and 144.0 degrees with respect to the neutron beam direction, respectively. This detector assembly enables us to measure the deposit energy and the detection time of γ-rays in each germanium crystal. When we focus on the prompt γ-rays from the nucleus target by (n,γ) reaction, the detection time can be regarded as time-of-flight (TOF) of neutrons from moderator surface to the target position because the time difference between neutron capture and the emission of a prompt γ-ray is negligible. The incident neutron energy is calculated from the TOF of the neutrons.

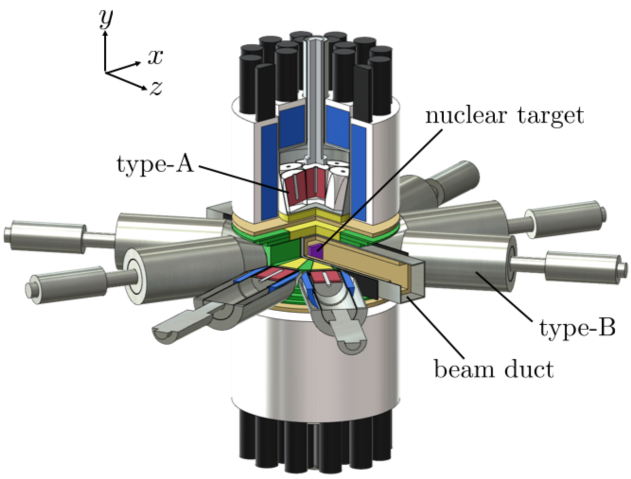

Fig. 1. Configuration of the germanium detector assembly in ANNRI.

2.2 *Measured data set*

We have conducted three experiments to measure (i) the angular dependence of the shape of p-wave resonance, (ii) resonance parameters, and (iii) branching ratio of each resonance. Here, the branching ratio means the transition ratio that the compound state decays to a final state of a specific energy level, which corresponds to the partial gamma width. Table I shows that each experimental condition. Target and measurement time are different in order to achieve each purpose.

Table I. Each experimental condition. Target and measurement time are different for each purpose. Proton beam power also depends on the date conducted in each experiment.

Purpose	Target	Size	Beam power	Measurement time
Angular dependence	^{nat}Sn	40×40×4 mm^3	150 kW	65 hours
Resonance paramter	^{117}Sn (86% enrich)	ϕ5 mm×6 mmt	525 kW	6 hours
Branching ratio	^{nat}Sn	40×40×1 mm^3	525 kW	100 hours

Figure 2 shows the spectrum of the energy deposit of γ-rays in all germanium detectors in the experiment (i). The γ-transition in the nucleus ^{118}Sn with an energy of 9327 keV and its single- and double-escape peaks can be observed clearly. It is known that the compound state in the p-wave resonance decays to the ground state of ^{118}Sn directly. Therefore, we focused the peak with 9327 keV and its single- and double-escape peaks for our analysis to examine the angular dependence of the shape of p-wave resonance and to determine the branching ratio that the compound state of ^{117}Sn + n system decays to the ground state of ^{118}Sn.

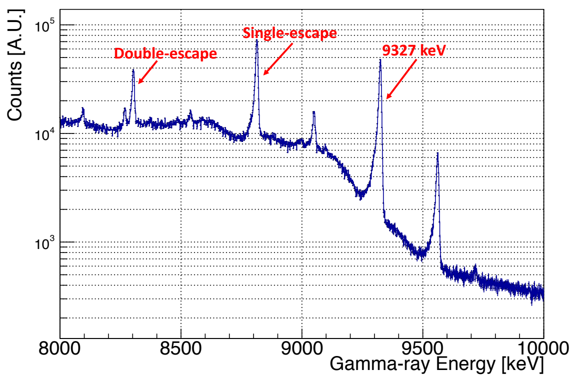

Fig. 2. Gamma-ray spectrum by neutron capture reactions in the experiment (i) at the range of 8 - 10 MeV. The peak with an energy deposit of 9327 keV and its single- and double-escape peaks due to ^{117}Sn(n,γ) reactions in the target can be observed clearly.

3. Analysis

3.1 *Background subtraction and beam intensity normalization*

The neutron energy spectrum gated with events from signal regions (9327 keV, its single- and double-escape peaks) includes background events from other sources. There are two kinds of background events. One is caused by the Compoton scattering of the 9563 keV γ-rays emitted from the compound state of ^{116}Sn. The other stems from pileup events due to simultaneous detection of multi γ-rays. These background events must be subtracted. First, the number of background events in the signal regions was estimated using a GEANT4 simulation [6], which enables us to obtain a spectrum convoluted a response function of the germanium detector for monoenergetic γ-rays [7]. Spectra geted with the background regions (9563 keV peak and energies higher than 9600 keV) were scaled that number of events matched that of GEANT4 calculated ones. After that, they were subtracted from spectra gated with the signal regions. The procedure of this subtraction was conducted for the analysis of the experiment (i) and (iii). On the other hand, this was not conducted for the analysis of the experiment (ii) because the spectrum for determining resonance parameters was not gated with the energies of γ-rays.

In the energy region of epithermal neutrons, the intensity of neutron beam increases for lower neutron energies as a result of moderation. The energy spectrum of neutrons captured by the target must be normalized in order to compare the measured spectrum and the calculated cross section. We used the spectrum gated with the 477.6 keV γ-rays from ^{10}B(n,$\alpha\gamma$)^{7}Li reactions because the cross section of this reaction has no resonance at the epithermal energy region [8]. This normalization was conducted for all analysis, and the beam intensity was measured in each experiment.

3.2 Angular dependence

Figure 3 shows spectra of the neutron energy dependent on the angle of the γ-rays emitted from the compound states of ^{118}Sn. An angular dependence of the shape of the p-wave resonance has clearly been observed. To evaluate quantitatively, we defined an asymmetry value A_{LH} as

$$A_{\mathrm{LH}} = \frac{N_{\mathrm{L}} - N_{\mathrm{H}}}{N_{\mathrm{L}} + N_{\mathrm{H}}}, \tag{2}$$

where N_{L} and N_{H} are the integrated values in a lower (L) and a higher (H) energy region of the p-wave resonance, respectively. The integral regions were defined using the p-wave resonance energy E_{p} and the resonance width Γ_{p} as follows: $E_{\mathrm{p}} - 2\Gamma_{\mathrm{p}} < E_{\mathrm{n}} < E_{\mathrm{p}}$ for N_{L} and $E_{\mathrm{p}} < E_{\mathrm{n}} < E_{\mathrm{p}} + 2\Gamma_{\mathrm{p}}$ for N_{H}. The value of A_{LH} in each angle is plotted in Fig. 4. Based on the Flambaum's formalism, the angular dependence can be written as

$$A_{\mathrm{LH}} = A\cos\theta_{\gamma} + B, \tag{3}$$

The expression was fitted to the experimental data, with the result:

$$A = 0.494 \pm 0.043,\ B = 0.040 \pm 0.018. \tag{4}$$

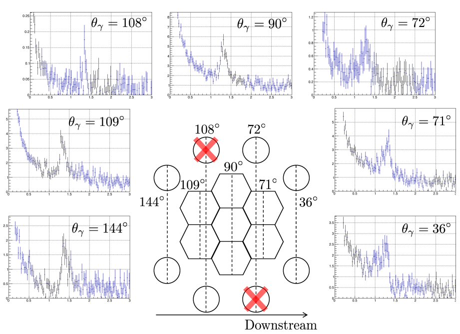

Fig. 3. The neutron energy spectrum around the 1.33 eV p-wave resonance, for variable angles accessible at ANNRI. The central figure shows the placement and the shape of each crystal. Two detectors marked by crosses were not available for the experiment (i).

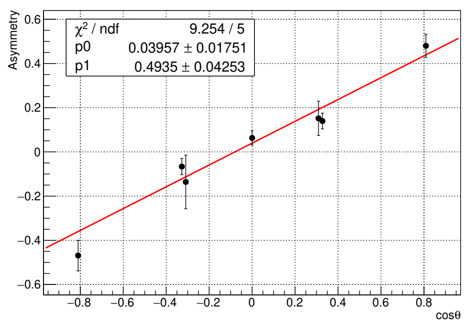

Fig. 4. The angular dependence of A_{LH}. The solid line shows the fitting result using the function of Eq. (3).

3.3 Resonance parameters and branching ratios

Resonance parameters are determined by fitting to the neutron energy spectrum gated with γ-rays of more than 2 MeV to suppress background events in low γ-rays' energy region. Fitting function is the Briet-Wigner formula convoluted the doppler broadening effect [9] and a time structure of pulsed beam [10]. Figure 5 shows the neutron energy spectrum around the p-wave resonance and fitting result. The resonance parameters in this p-wave resonance were determined as

$$E_{\mathrm{p}} = 1.331 \pm 0.002\,[\mathrm{eV}],\ \Gamma_{\mathrm{p}}^{\gamma} = 133 \pm 5\,[\mathrm{meV}]. \tag{5}$$

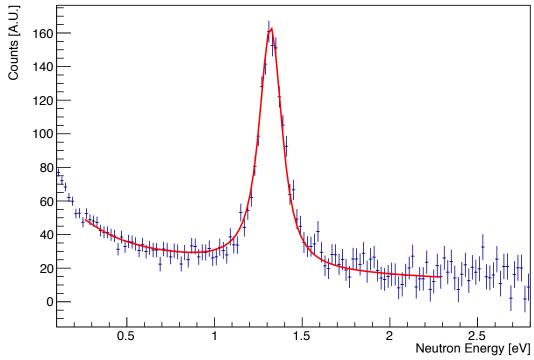

Fig. 5. The neutron energy spectrum gated with an γ-rays' energy regions of more than 2 MeV around p-wave resonance in the experiment (ii). The solid line shows the best fit line.

In s-wave resonances, an influence of self-shielding can be considered. In general, the cross sections of s-wave resonances is very larger than those of p-wave resonances, so that neutron beam cannot reach deeply inside the target. This causes a shortage of the number of neutrons which interact with nuclei. As this result, the shapes of resonances can be changed, and this effect must be considered. At the moment, the estimation of this effect by a Monte Carlo simulation is ongoing.

Branching ratio of each resonance can be determined by fitting like the determination of resonance parameters. In this analysis, the spectrum which should be fitted must be gated with the signal regions. In this case, a fitting function has a branching ratio as an only free parameter, while other parameters are fixed as follows: $f(E_{\mathrm{n}}) = C\sigma(E_{\mathrm{n}})$, where $\sigma(E_{\mathrm{n}})$ is the Briet-Wigner formula with fixed resonance parameters and C is the free parameter corresponding to the branching ratio of its resonance. Thus, branching ratios are able to be determined after the determination of their resonance parameters. In the near future, branching ratio of each resonance will be determined.

4. Summary

CP-violation (T-violation) is one of the essential contents to explain the dominance of matter over antimatter in the current universe. For the preparation of T-violation search using compound nuclei, one has to determine the spin factor $\kappa(J)$ which directly relates to the experimental sensitivity. The angular correlation of γ-rays emitted from the compound states of ^{118}Sn in the p-wave resonance can be clearly observed by the measurement at ANNRI in J-PARC MLF. In addition, the experiments to measure the resonance parameters and the branching ratios have been conducted and the analysis is ongoing. In the near future, the mixing angle ϕ, and hence the value of $\kappa(J)$ will be determined.

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